Original research

Objective clinical tests of dual-task dynamic postural control in youth athletes with concussion

David R. Howell [a,b,c,*], Julie C. Wilson [a,b], Anna N. Brilliant [c,d], Andrew J. Gardner [e,f], Grant L. Iverson [g,h], William P. Meehan III [c,d,i]

[a] Sports Medicine Center, Children's Hospital Colorado, USA
[b] Department of Orthopedics, University of Colorado School of Medicine, USA
[c] The Micheli Center for Sports Injury Prevention, USA
[d] Division of Sports Medicine, Department of Orthopaedics, Boston Children's Hospital, USA
[e] Hunter New England Local Health District Sport Concussion Program, Australia
[f] Centre for Stroke and Brain Injury, School of Medicine and Public Health, Faculty of Health & Medicine, University of Newcastle, Australia
[g] Department of Physical Medicine and Rehabilitation, Harvard Medical School, USA
[h] Spaulding Rehabilitation Hospital, MassGeneral Hospital for Children™ Sports Concussion Program, Home Base, A Red Sox Foundation and Massachusetts General Hospital Program, USA
[i] Departments of Pediatrics and Orthopaedic Surgery, Harvard Medical School, USA

ARTICLE INFO

ABSTRACT

Objectives: To prospectively evaluate single/dual-task timed-up-and-go (TUG) and tandem gait performance among children and adolescents with concussion and healthy controls.

Design: Repeated measures.

Methods: Participants with concussion (n = 23; age = 14.1 ± 2.5 years; 52% female) completed single/dual-task TUG, tandem gait, and symptom assessments 6.7 ± 2.6 and 23.3 ± 6.1 days post injury. The control group (n = 27; age = 14.1 ± 2.3 years; 48% female) completed the same protocol initially and 10.7 ± 16.1 days later. All participants completed single-task (undivided attention) and dual-task (divided attention) tests. The primary outcome variable was test completion time.

Results: The concussion group completed single-task (concussion group mean = 11.1 ± 1.9 vs. control group mean 9.9 ± 1.4 s, p = 0.027) and dual-task (concussion group mean = 14.4 ± 3.3 vs. control group mean 12.7 ± 1.9 s, p = 0.047) TUG tests slower than the control group across both time points. The concussion group completed dual-task tandem gait tests slower than the control group at both time points (21.3 ± 6.3 vs. 16.8 ± 5.5 s, p = 0.006), and were slower in the single-task condition at the first test (19.8 ± 5.4 vs. 13.8 ± 4.4 s, p = 0.003). Symptoms were significantly worse for the concussion group compared to the control group at the first (34.1 ± 21.4 vs. 3.9 ± 9.1, p < 0.001), but not the second test (9.1 ± 12.0 vs. 2.2 ± 6.8; p = 0.08).

Conclusions: Slower dual-task TUG and tandem gait times were detected across both time points for the concussion group relative to the control group. In contrast, single-task tandem gait deficits appeared to improve in a similar fashion as symptoms, suggesting increased complexity from the addition of a cognitive task allows for the detection of persistent post-concussion deficits that might take longer to resolve.

© 2018 Sports Medicine Australia. Published by Elsevier Ltd. All rights reserved.

1. Introduction

Sport-related concussion can affect many different brain areas and their associated functions, making accurate evaluation of post-injury deficits and subsequent clinical recovery difficult.[1] Thus, a multifaceted approach to measuring post-concussion function is recommended.[2] Among the many potential deficits that can arise following injury, balance problems have been reported as a common post-concussion deficit.[3–5] Because multiple sensory systems are needed for adequate balance control, assessing balance in a multimodal and objective fashion can help healthcare providers monitor recovery following concussion.[2,6]

The most common form of assessment used to determine postural stability is the Balance Error Scoring System (BESS) test.[7]

* Corresponding author.
E-mail address: David.Howell@ucdenver.edu (D.R. Howell).

An easily implemented test, the BESS is useful in the acute post-concussion stages, but spontaneous recovery and learning or practice effects may contribute to diminishing value during serial evaluations more than a week after a concussion.[8,9] Some researchers have used more sophisticated measurement systems such as optical motion analysis to quantify post-concussion postural control deficits.[4,6] Although this approach allows for an accurate movement evaluation, the required cost, personnel, and space demands prohibits its use across most clinical settings. Thus, there is a need to identify sensitive tests that can objectively measure postural control and are feasible across diverse clinical settings.

The increased task complexity of dual-task paradigms for measuring post-concussion deficits has been recognized in prior studies.[10–13] These reports suggest that abnormal gait is present following a concussion and generally resolves over time, but the inconsistency of findings, small sample sizes, and limited literature prohibit specific recommendations for measuring gait in clinical settings.[10–13] Dual-tasks may be more sensitive for detecting persistent deficits after a concussion compared to single-task paradigms, symptom inventories, and computerized neurocognitive tests.[6,14,15] Although dual-task paradigms can range from laboratory-based[4] to clinically-based,[16] their relative ease of use can make them well suited for concussion assessments.

Two clinical tests used within the dual-task framework are the timed-up-and-go (TUG)[17] and tandem gait tests.[18] The TUG test is a well-established assessment of both gait and postural control that measures the time it takes for an individual to stand up from a chair, walk a set distance, turn around and sit back down.[17] It has been used in several studies as an objective measure to evaluate functional mobility,[19] and to determine the efficacy of a vestibular rehabilitation program for patients with persistent post-concussion symptoms.[3] The tandem gait test assesses how fast a patient can walk a set distance along a line while approximating their heel and toe together during locomotion.[18,20] It had a higher sensitivity and specificity compared to the BESS in the acute post-concussion stage in one study,[20] and it has been identified as a proxy measure for instrumented single-task and dual-task gait evaluations.[18]

Our objective was to prospectively evaluate single-task and dual-task TUG and tandem gait performance among a group of children and adolescents with concussion compared to healthy controls. Based on prior studies,[14,21] we hypothesized that the concussion group would have slower single-task TUG and tandem gait times at the initial post-injury test only, and that they would have slower dual-task TUG and tandem gait times than controls at both testing time points relative to a group of healthy control participants.

2. Methods

We conducted a prospective investigation of children and adolescents between the ages of 8–18 years who completed the testing protocol on two occasions. Those with a concussion were tested initially within the first ten days of injury (time 1), and again approximately 3 weeks post injury (time 2). Follow-up test timing was selected as the time where we expected the majority of participants would no longer be experiencing concussion symptoms. The control group completed their initial examination (time 1) and returned for their second test approximately two weeks later (time 2). Concussion group participants were recruited from a sport concussion clinic associated with a tertiary-care regional children's hospital between July 1, 2016 and February 1, 2018. After injury, concussion participants self-referred to the clinic, or were referred from an emergency department or their primary healthcare provider. Control group participants were identified from an

injury prevention center where they were completing an injury prevention evaluation or a personal training session, or from children of hospital employees. Control participants were matched individually to concussion participants based on the age, sex, and body size of concussion group participants. We assessed prior concussion history, documented the time of the most recent concussion, and excluded potential participants who had sustained a concussion within 6 months of initial testing or if they were still experiencing concussion symptoms.

We defined concussion consistent with the Consensus Statement on Concussion in Sport as a brain injury caused by a direct blow to the head, face, neck or elsewhere on the body, resulting in the rapid onset of impairment of neurological function.[22] A board-certified sports medicine physician diagnosed each concussion participant with a concussion prior to enrollment in the study. The Institutional Review Board approved this study prior to commencement. All participants and their parent/guardian assented/consented to participate in the study through a written informed consent procedure. Potential participants were excluded if they had an existing lower extremity injury that may affect normal gait or balance control, a documented learning disability, or developmental delay. Only those who sustained a concussion during sports or by a mechanism involving forces similar to sports, such as falling from ground level or being injured during recreational activities, were included in the study. Patients with more severe injury mechanisms, such as falling from a height or sustaining an injury during a motor vehicle collision, or those with structural abnormalities visible with neuroimaging, were excluded. Tests were administered by a single trained research assistant.

The primary TUG outcome variable was the time required to complete the test in single- and dual-task conditions. During the test, participants were seated with their back against the back of a chair and were not wearing shoes. They were instructed to stand up from a chair without using the arm rests, walk a distance of 3 m at their normal pace, turn at approximately 180° where a piece of tape on the ground marked the turnaround point, then walk and sit back down, again without the use of the chair's arm rests. TUG test completion time was acquired and automatically calculated using a set of instrumented inertial sensors (Opal Sensor, APDM Inc., Portland, OR[23,24]) consisting of one sensor at the level of the lumbosacral junction and one sensor on the dorsum of both feet, attached with an elastic strap. This experimental setup has been previously used to calculate instrumented TUG test time with a greater sensitivity to subtle changes than hand-timing.[25] Mobility Lab version 2.0 software was used to automatically calculate TUG outcome variables in single-task and dual-task conditions separately. One TUG trial was performed per condition. During the dual-task TUG, a cognitive test was simultaneously performed based upon a previous dual-task TUG study where participants were asked to subtract by 6 s or 7 s from a randomly presented 2-digit number.[17] They were given instructions prior to task initiation, began once cued by the test administrator, and continued completing both tasks (motor and cognitive) throughout the trial.

Consistent with previously published studies,[18,21,26] participants also completed the single-task and dual-task timed tandem gait test. The primary outcome variable from this assessment is the time required to complete the test, averaged across three trials completed in each condition. During both conditions, participants completed the tandem gait test consistent with standardized instructions,[27] where they walked without shoes with an alternate heel-to-toe gait along a 3 m length of sports tape. While completing the test, instructions were given to approximate their heel and toe, walk beyond the end of the 3 m line, make a 180° turn and return to the original starting point while walking in the same heel-to-toe fashion. Test administrators timed each trial using a standard stopwatch or smartphone to the nearest hundredth of a second.

Failed trials were defined as an overt separation of heel and toe, stepping off the tape, or touching the test administrator. If a participant failed a trial, they repeated the test until they successfully completed three trials. All participants were able to successfully complete three tandem gait trials.

During the dual-task condition, participants were asked to simultaneously complete one of three different cognitive test forms: spelling a five-letter word backwards, serial subtraction by 6 s or 7 s from a randomly presented 2-digit number, or reciting the months in reverse order starting from a randomly selected month. Prior to trial commencement, participants were given the task to complete during the trial and instructed to begin doing both tasks (i.e. walk and talk) simultaneously throughout the duration of the gait trial. The same test form was not used consecutively to avoid practice effects from one trial to the next. This cognitive test has been used in prior studies of dual-task tandem gait.[18,21,26]

All participants completed a symptom assessment using the Post-Concussion Symptom Scale (PCSS), which has been previously used in adolescents with concussion to assess the number and severity of concussion symptoms present at the time of testing.[28,29] On the PCSS, participants rate 22 concussion symptoms on a scale from 0 to 6, where zero indicates that the patient is not experiencing the listed symptom, and six indicates the maximum severity for that symptom. Thus, a higher score indicates worse concussion symptoms experienced by the participant.

Continuous variables are presented as means (standard deviation) and medians [interquartile range], and categorical variables are presented as the number included and corresponding percentages. Differences in participant demographic and injury history characteristics between concussion and control groups were analyzed using independent samples t-tests for continuous variables, and chi-square analyses for categorical variables.

To compare TUG and tandem gait test outcomes between groups (between-subject independent variable) and across time (within-subject independent variable), we used a repeated measures mixed effects analyses of covariance (ANCOVA). To account for potential confounding variables, we entered covariates into the model consisting of participant characteristics with potential differences between groups, defined as $p < 0.20$. Using this approach, we investigated the interactions and main effects of group (concussion vs. control) and time (time 1 vs. time 2) for each of the dynamic postural control outcome variables (TUG, tandem gait times) in single-task and dual-task conditions, and symptom severity. If we detected a significant interaction, we performed post-hoc pairwise comparisons between groups at both time points, and statistical significance was defined as $p < 0.01$ to adjust for multiple comparisons. In addition, we analyzed the test–retest correlation of each test in single-task and dual-task conditions for the concussion and control groups separately using Spearman's rho correlations. All statistical analyses were two-sided, and performed with Statistical Package for the Social Sciences (version 24, IBM Inc., Armonk, NY).

3. Results

There were 50 total participants who completed the study: 23 with a concussion and 27 control participants (Table 1). Four concussion group participants were lost to follow-up, thus their data were not included in our analyses. The concussion group completed the first assessment at a mean of 6.7 ± 2.6 days post concussion, and the second assessment 23.3 ± 6.1 days following injury. The control group completed the initial assessment, and returned for the second assessment 10.7 ± 16.1 days later. The concussion group reported a significantly greater number of prior lifetime concussions than the controls (Table 1), and this variable was subsequently included in the ANCOVA models.

For single-task TUG completion time, participants with a concussion completed the test slower than controls across both time points (Table 2; $p = 0.027$; $\eta_p^2 = 0.10$). Both groups completed the single-task TUG faster at the second time point than the first ($p = 0.028$; $\eta_p^2 = 0.10$). Similarly, for dual-task TUG completion time, participants with a concussion completed the test slower than controls across both time points (Table 2; $p = 0.047$; $\eta_p^2 = 0.08$). Both groups completed the dual-task TUG faster at the second time point relative to the first ($p = 0.001$; $\eta_p^2 = 0.22$).

During the single-task condition of the tandem gait test, the control group completed the test faster than the concussion group at the first test (Table 2; $p = 0.001$), but not at the second time point ($p = 0.035$). For the dual-task tandem gait test, the concussion group completed the test slower than controls across both time points (Table 2; $p = 0.006$; $\eta_p^2 = 0.22$); both groups completed the test faster at the second time point relative to the first ($p = 0.010$; $\eta_p^2 = 0.21$).

As would be expected, the concussion group had significantly worse symptoms than the control group at time 1 (Table 2; $p < 0.001$), but not at time 2 ($p = 0.02$). There was a trend toward the concussion group reporting more symptoms at time 2, and there was considerable variability among individuals within the concussion group in their symptom reporting at that time period. The concussion group PCSS scores significantly decreased from time 1 to time 2 ($p < 0.001$). The control group PCSS scores remained similar at each time point.

4. Discussion

Slower dual-task TUG and tandem gait completion times continued to persist at follow up testing among some athletes with a recent concussion. In contrast, single-task tandem gait deficits resolved more quickly. Thus, the increased complexity induced by the addition of a cognitive task completed concurrently during the tandem gait test may have allowed for the detection of continual post-concussion deficits. Overall, these findings indicate the potential clinical applicability for the objective detection of postural control deficits after concussion using dual-task tests with relatively few equipment demands, including a chair, strip of tape, tape measure, and standard stopwatch.

Within the framework of dual-task TUG testing, a recent study reported excellent test–retest reliability among healthy collegiate student athletes.[17] Our findings build upon this work by comparing a group of children and adolescents with concussion to a healthy control group of children and adolescents. The control group showed relative consistency across time, while those with a concussion exhibited slower TUG completion times on average in both testing conditions across the two testing points. While these between-group deficits continued, the concussion group appeared to resolve the majority of their symptoms, although some remained symptomatic. In a different setting, Alsalaheen et al. observed that among patients with persistent dizziness and gait/balance dysfunction, vestibular rehabilitation resulted in significantly faster TUG times.[3] Taken together with our findings, this suggests that the TUG test may be useful in measuring the efficacy of rehabilitation protocols that provides information beyond symptom inventories.

The single-task timed tandem gait test is included as one component of the SCAT-3.[30] All participants in our study were able to successfully complete three trials in both single-task and dual-task conditions. Thus, the inclusion of a timed component of the test allows for clinicians to obtain objective and continuous outcome variable information regarding postural stability, whereas the recommended pass/fail criteria put forth by the SCAT-5 can be subjective and may only be able to detect overt motor deficits. Furthermore, the inclusion of a dual-task condition allowed us to

Table 1
Demographic characteristics of study participants (mean, SD or n, %).

Variable	Concussion group (n = 23)	Control group (n = 27)	p Value	Cohen's d
Age (years)	14.1 (2.5)	14.1 (2.3)	0.98	0.01
Height (cm)	160.6 (14.5)	160.2 (12.0)	0.93	0.03
Weight (kg)	57.6 (16.9)	52.4 (13.4)	0.24	0.34
Female sex	12 (52%)	13 (48%)	0.78	N/A
Prior history of concussion	10 (43%)	4 (15%)	0.04	N/A
LOC at time of injury?	1 (4%)	N/A	N/A	N/A

Table 2
Test completion times (seconds) for single- and dual-task TUG and TG, and total symptom severity scores at each assessment.

Test	Group	Condition	Assessment 1		Assessment 2		Test–retest Spearman r
			Mean (SD)	Median [IQR]	Mean (SD)	Median [IQR]	
TUG time	Concussion	Single	11.7 (2.1)	11.4 [10.5–13.6]	10.5 (1.7)	10.9 [9.0–11.6]	0.40
		Dual	15.2 (3.7)	13.7 [12.7–17.2]	13.4 (2.9)	13.1 [12.0–14.4]	0.60
	Control	Single	10.0 (1.7)	9.7 [8.7–11.1]	9.7 (1.2)	9.8 [9.0–10.5]	0.49
		Dual	13.1 (2.1)	13.1 [11.9–14.6]	12.3 (1.8)	12.1 [11.3–13.8]	0.77
Tandem gait time	Concussion	Single	19.8 (5.4)	17.2 [16.8–23.5]	15.7 (3.8)	14.5 [13.3–17.1]	0.46
		Dual	23.3 (6.4)	21.2 [20.1–24.4]	18.8 (5.9)	17.8 [14.4–23.0]	0.80
	Control	Single	13.8 (4.4)	12.8 [11.9–15.6]	13.5 (4.4)	13.3 [10.6–14.4]	0.47
		Dual	17.4 (6.7)	16.0 [12.9–22.4]	16.9 (5.2)	15.9 [13.5–18.3]	0.66
PCSS Score	Concussion		34.1 (21.4)	31 [17–45]	9.1 (12.0)	3 [0–17]	0.39
	Control		4.1 (4.5)	1 [0–5]	2.3 (6.9)	0 [0–2]	0.63

detect between-group differences for a longer duration of time than the single-task form, consistent with prior observations.[14,21] Because the tandem gait test provides a higher level of sensitivity and specificity than other concussion tests of postural stability,[20] and is a relevant proxy measure for more sophisticated dual-task gait examinations,[18] monitoring recovery from concussion with the tandem gait test may be appropriate in clinical settings. Further work among individuals in different populations than our study should be explored to better determine the utility of this type of testing paradigm. Furthermore, future studies should directly compare the practicality of both the tandem gait and TUG tests in different clinical environments to determine their clinical utility.

Our study had limitations. The sample size of both participants groups was relatively small and participants were tested only on two occasions. We recruited and tested participants from a single clinical environment. Our participant sample consisted of adolescent athletes who reported to a specialty care center. Thus, they may have represented a cohort of individuals with more severe injuries than what is typically seen in an acute care setting and our findings may not be generalizable to other locations or study populations. There may have been practice effects that we could not account for with the administration of the tests, because there was not a counter-balanced presentation of tasks. Further, the follow-up test time varied somewhat between groups and may have affected our observed outcomes. There were a variable number of minimum trials per task, thus, our study lacked standardization between TUG and tandem gait assessments, particularly under dual-task conditions. Finally, we did not record the presence, duration, or absence of post-traumatic amnesia at the time of injury in concussed participants.

5. Conclusion

In conclusion, we identified dynamic postural control differences between concussion and control groups using objective and clinically feasible dual-task tests. The inclusion of a dual-task into these paradigms may allow clinicians to identify otherwise unnoticed deficits, and should be considered as adjunct evaluative techniques in addition to the established battery of cognitive, vestibulo-ocular, and balance tests commonly used across different clinical settings.

Practical implications

- We identified differences between adolescents and children with a concussion compared to controls using two different objective dynamic postural control tasks.
- Slower dual-task TUG and tandem gait completion times continued to persist at follow up testing among some athletes with a recent concussion.
- Implementation of dual-task postural control tests is possible using standard equipment such as a chair, strip of tape, tape measure, and standard stopwatch.

References

1. Toledo E, Lebel A, Becerra L et al. The young brain and concussion: imaging as a biomarker for diagnosis and prognosis. *Neurosci Biobehav Rev* 2012; 36(6):1510–1531. http://dx.doi.org/10.1016/j.neubiorev.2012.03.007.

2. Littleton A, Guskiewicz K. Current concepts in sport concussion management: a multifaceted approach. *J Sport Health Sci* 2013; 2(4):227–235. http://dx.doi.org/10.1016/j.jshs.2013.04.003.

3. 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. http://dx.doi.org/10.1097/NPT.0b013e3181dde568.

4. Howell DR, Osternig LR, Chou L-S. Dual-task effect on gait balance control in adolescents with concussion. *Arch Phys Med Rehabil* 2013; 94(8):1513–1520. http://dx.doi.org/10.1016/j.apmr.2013.04.015.

5. King LA, Mancini M, Fino PC et al. Sensor-based balance measures outperform modified balance error scoring system in identifying acute concussion. *Ann Biomed Eng* 2017; 45(9):2135–2145. http://dx.doi.org/10.1007/s10439-017-1856-y.

6. Howell DR, Osternig LR, Chou LS. Detection of acute and long-term effects of concussion: dual-task gait balance control vs. computerized neurocognitive test. *Arch Phys Med Rehab* 2018; 99(7):1318–1324.

7. Baugh CM, Kroshus E, Stamm JM et al. Clinical practices in collegiate concussion management. *Am J Sports Med* 2016; 44(6):1391–1399. http://dx.doi.org/10.1177/0363546516635639.

8. Valovich McLeod TC, Perrin DH, Guskiewicz KM et al. Serial administration of clinical concussion assessments and learning effects in healthy young athletes. *Clin J Sport Med* 2004; 14(5):287–295.

9. Buckley TA, Munkasy BA, Clouse BP. Sensitivity and specificity of the modified balance error scoring system in concussed collegiate student athletes. *Clin J Sport Med* 2018; 28(2):174–176. http://dx.doi.org/10.1097/JSM.0000000000000426.

10. Fino PC, Parrington L, Pitt W et al. Detecting gait abnormalities after concussion or mild traumatic brain injury: a systematic review of single-task, dual-task, and complex gait. *Gait Posture* 2018; 62:157–166. http://dx.doi.org/10.1016/j.gaitpost.2018.03.021.

11. Grants L, Powell B, Gessel C et al. Gait deficits under dual-task conditions in the concussed adolescent and young athlete population: a systematic review. *Int J Sports Phys Ther* 2017; 12(7):1011–1022.

12. Manaseer TS, Gross DP, Dennett L et al. Gait deviations associated with concussion: a systematic review. *Clin J Sport Med* 2017. http://dx.doi.org/10.1097/JSM.0000000000000537. Epub ahead of print.

13. Howell DR, Lynall RC, Buckley TA et al. Neuromuscular control deficits and the risk of subsequent injury after a concussion: a scoping review. *Sports Med* 2018; 48(5):1097–1115. http://dx.doi.org/10.1007/s40279-018-0871-y.

14. Berkner J, Meehan WP, Master CL et al. Gait and quiet-stance performance among adolescents after concussion symptom resolution. *J Athl Train* 2017; 52(12):1089–1095. http://dx.doi.org/10.4085/1062-6050-52.11.23.

15. Howell DR, Osternig LR, Koester MC et al. The effect of cognitive task complexity on gait stability in adolescents following concussion. *Exp Brain Res* 2014; 232(6):1773–1782. http://dx.doi.org/10.1007/s00221-014-3869-1.

16. Stephens J, Nicholson R, Slomine B et al. Development and pilot testing of the dual task screen in healthy adolescents. *Am J Occup Ther* 2018; 72(3):1–6. http://dx.doi.org/10.5014/ajot.2018.025361.

17. Tamura K, Kocher M, Finer L et al. Reliability of clinically feasible dual-task tests: expanded timed get up and go test as a motor task on young healthy individuals. *Gait Posture* 2017; 60:22–27. http://dx.doi.org/10.1016/j.gaitpost.2017.11.002.

18. Howell DR, Oldham JR, Meehan WP et al. Dual-task tandem gait and average walking speed in healthy collegiate athletes. *Clin J Sport Med* 2017. http://dx.doi.org/10.1097/JSM.0000000000000509. E-pub ahead of print.

19. Nicolini-Panisson RD, Donadio MVF. Timed "up & go" test in children and adolescents. *Rev Paul Pediatr* 2013; 31(3):377–383. http://dx.doi.org/10.1590/S0103-05822013000300016.

20. Oldham JR, DiFabio MS, Kaminski TW et al. Efficacy of tandem gait to identify impaired postural control following concussion. *Med Sci Sports Exerc* 2018; 50(6):1162–1168. http://dx.doi.org/10.1249/MSS.0000000000001540.

21. Howell DR, Osternig LR, Chou L-S. Single-task and dual-task tandem gait test performance after concussion. *J Sci Med Sport* 2017; 20(7):622–626. http://dx.doi.org/10.1016/j.jsams.2016.11.020.

22. McCrory P, Meeuwisse W, Dvorak J et al. Consensus statement on concussion in sport—the 5th international conference on concussion in sport held in Berlin, October 2016. *Br J Sports Med* 2017; 51(11):838–847. http://dx.doi.org/10.1136/bjsports-2017-097699.

23. Horak F, King L, Mancini M. Role of body-worn movement monitor technology for balance and gait rehabilitation. *Phys Ther* 2015; 95(3):461–470. http://dx.doi.org/10.2522/ptj.20140253.

24. Mancini M, Salarian A, Carlson-Kuhta P et al. ISway: a sensitive, valid and reliable measure of postural control. *J Neuroeng Rehabil* 2012; 9:59. http://dx.doi.org/10.1186/1743-0003-9-59.

25. Salarian A, Horak FB, Zampieri C et al. iTUG, a sensitive and reliable measure of mobility. *IEEE Trans Neural Syst Rehabil Eng* 2010; 18(3):303–310. http://dx.doi.org/10.1109/TNSRE.2010.2047606.

26. Howell DR, Berkstresser B, Wang F et al. Self-reported sleep duration affects tandem gait, but not steady-state gait outcomes among healthy collegiate athletes. *Gait Posture* 2018; 62:291–296. http://dx.doi.org/10.1016/j.gaitpost.2018.03.038.

27. Echemendia RJ, Meeuwisse W, McCrory P et al. The sport concussion assessment tool 5th edition (SCAT5). *Br J Sports Med* 2017; 51:848–850. http://dx.doi.org/10.1136/bjsports-2017-097506.

28. 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(3):166–174. http://dx.doi.org/10.1207/s15324826an1303_4.

29. Howell DR, Mannix RC, Quinn B et al. Physical activity level and symptom duration are not associated after concussion. *Am J Sports Med* 2016; 44(4):1040–1046. http://dx.doi.org/10.1177/0363546515625045.

30. Chin EY, Nelson LD, Barr WB et al. Reliability and validity of the sport concussion assessment tool-3 (SCAT3) in high school and collegiate athletes. *Am J Sports Med* 2016; 44(9):2276–2285. http://dx.doi.org/10.1177/0363546516648141.