Functional balance assessment in recreational college-aged individuals with a concussion history

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ABSTRACT

Objectives: Despite evidence for increased musculoskeletal injury after concussion recovery, there is a lack of dynamic balance assessments that could inform management and research into this increased injury risk post-concussion. Our purpose was to identify tandem gait dynamic balance deficits in recreational athletes with a concussion history within the past 18-months compared to matched controls.
Design: Cross-sectional, laboratory study.
Methods: Fifteen participants with a concussion history (age: 19.7 ± 0.9 years; 9 females; median time since concussion 126 days, range 28–432 days), and 15 matched controls (19.7 ± 1.6 years; 9 females) with no recent concussion history participated. We measured center-of-pressure (COP) outcomes (velocity, path length, speed, dual-task cost) under 4 tandem gait conditions: (1) tandem gait, (2) tandem gait, eyes closed, (3) tandem gait, eyes open, cognitive distraction, and (4) tandem gait, eyes closed, cognitive distraction.
Results: The concussion history group demonstrated slower tandem gait velocity compared to the control group (4.0 cm/s difference), thus velocity was used as a covariate when analyzing COP path length and speed. The concussion history group (23.5%) demonstrated greater COP speed dual-task cost than the control group (16.3%) during the eyes closed dual-task condition. No other comparisons were statistically significant.
Conclusions: There may be subtle dynamic balance differences during tandem gait that are detectable after return-to-activity following concussion, but the clinical significance of these findings is unclear. Longitudinal investigations should identify acute movement deficits in varying visual and cognitive scenarios after concussion in comparison with recovery on traditional concussion assessment tools while also recording musculoskeletal injury outcomes.

Practical implications

- Recently concussed individuals walked slower than healthy individuals, indicating timed tandem gait assessment may have clinical utility.
- Recently concussed individuals did not appear to suffer tandem gait balance impairments as compared to healthy individuals, although it is possible the instrumentation used in this study was not sensitive enough to detect potentially subtle differences.
- Overall, the clinical significance of our findings is not clear, although this study adds to the growing body of literature suggesting tandem gait testing after concussion may provide clinicians with important information that is not commonly assessed post-concussion.

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1. Introduction

Concussion is a complex pathophysiologic process that can affect many areas of cognition and motor control.[1] Clinicians often rely on athlete self-report of concussion symptoms, but athletes may fail to report or not notice concussion symptoms, leading to a high rate of undiagnosed concussion in sports.[2–4] Several concussion evaluation tools have been developed and validated, including graded symptom checklists,[5] neurocognitive measures,[6] and static balance assessments.[7] Using these clinically based tools as injury recovery markers, over 85% of concussed college-aged individuals demonstrate recovery within 7 days of injury.[8]

Evidence detailing increased concussion risk, functional abnormalities, and increased musculoskeletal injury risk post-concussion calls into question the long-held clinical working assumption that concussed individuals are truly "recovered" when they return to baseline function on these measures. Those who have suffered a concussion are 3–6 times more likely to suffer a subsequent concussion.[9,10] Innovative neurophysiological assessment tools such as transcranial magnetic stimulation[11] and electroencephalography[12] indicate that functional brain abnormalities remain after clinical recovery. Growing scientific literature suggests there are associations between concussion and musculoskeletal injury[13–15], and that retired professional football players with a concussion history may have a higher prevalence of osteoarthritis.[16] Taken together, these studies raise the possibility there may be lingering functional impairments during dynamic movements such as poor movement control or execution when traditional neurocognitive and static balance measures have demonstrated recovery. However, alternate explanations, such as factors associated with care-seeking and/or risk-taking behavior, may also account for these associations.

Numerous studies suggest that dynamic balance measures during gait may be sensitive to brain injury even after recovery on traditional measures,[17,18] with one study detailing gait deficits in a cohort that was assessed more than 6 years after sustaining concussion.[19] Dynamic balance deficits during gait appear to be more pronounced when individuals perform in dual-task situations (motor and cognitive task performed concurrently).[17,20] These results have only been observed during standard gait in laboratory settings, and have not addressed the translational challenges of clinically implementing these findings.

Tandem gait has been suggested as a valid, cost-effective, and clinician friendly means of objectively identifying post-concussion deficits.[1,21] Though the evidence is limited, researchers have reported slower tandem gait velocities,[22] longer time to task completion,[23,24] and lower tandem gait cadence following concussion.[23] Importantly, these deficits appear to linger beyond traditional concussion recovery, but no studies have assessed tandem gait beyond approximately two months post-injury.

The purpose of this investigation was to determine whether there are differences in tandem gait dynamic balance between recreational athletes with a concussion history within the past 18-months as compared to matched non-concussed recreational athletes. Our hypothesis was that a sport-related concussion history would be associated with dynamic balance deficits during tandem gait due to lingering motor control deficits from the injury that are unaccounted for by conventional concussion assessment tools.

2. Methods

We recruited a convenience sample of 30 college-aged recreational athletes. There were two groups (15 participants per group): (1) concussion history group (median time since concussion 126 days, range 28–432 days), and (2) matched control group with no recent concussion history. Control participants were matched to each injured participant based on sex, age (±1 year), mass (±10%), and height (±5%). Concussed history group participants must have sustained a concussion diagnosed by a medical professional within the last 18 months. Any participant reporting any concussion-related symptoms at the time of testing or those who were not fully cleared by a medical provider by the time testing was scheduled were excluded from participating. Matched control group participants must have been without diagnosed concussion for at least 3 years. Participants were excluded for any of the following: attention deficit hyperactivity disorder, seizure disorders, lower extremity injury resulting in physical activity time loss ≥3 days within the last 6 months, any lower extremity or low back surgery history, concussion requiring hospital admission, any current concussion symptoms, or a previous history of >3 concussions. Our Institutional Review Board approved the study and all participants signed an informed consent document prior to testing.

The Zeno Walkway (ProtoKinetics, Havertown, PA) was used to collect center of pressure (COP) data during tandem gait assessment. The 4.9 m long by 0.6 m wide Zeno Walkway contains a 16-level pressure sensing pad and circuitry inside a low-profile housing. ProtoKinetics Movement Analysis Software allows for recording and analysis of spatiotemporal and dynamic balance variables, demonstrating excellent test-retest reliability and strong correlation to force plate technology.[25]

All data collection took place in a single session. Tandem gait testing consisted of 4 randomized conditions: (1) single-task, eyes open (STEO), (2) single-task, eyes closed (STEC), (3) dual-task, eyes open (DTEO), and 4) dual-task, eyes closed (DTEC). Prior to testing, each participant familiarized her/himself with the 4 conditions by completing a minimum of 1 practice trial of each. Participants were instructed to complete tandem gait as fast as possible while maintaining their best balance. Participants started with both feet together at one end of the walkway and were required to touch their toes to their heel on each step. Participants completed 3 trials of each condition, with a trial defined as one pass of the walkway.

The cognitive task used during the dual-task conditions was the Brooks Visuospatial Task,[26] which has been previously used to investigate dual-task effects on gait following concussion.[19] Each participant had one minute to memorize the order of digits 1 through 8 on a 4 × 4 grid. After the memorization period, the participant identified the position in the grid of each consecutive digit (1–8) without looking at the grid. During dual-task conditions, participants were instructed to focus on maintaining fast and balanced tandem gait while trying to accurately complete the cognitive task. Error frequency and time taken to complete the Brooks Visuospatial Task were recorded during all trials. Prior to any tandem gait trials, each participant completed 3 baseline Brooks Visuospatial Task trials while seated.

A custom Matlab (Matlab v8.0, The MathWorks Inc., Natick, MA) program was created to reduce the data and calculate tandem gait velocity (cm/s; sagittal plane COP path divided by time), COP speed (cm/s; COP path divided by time), and COP path length (cm). The first 140 cm of each trial were analyzed. This was necessary because trials were stopped when the participant finished the Brooks Visuospatial Task during conditions 3 and 4. Several cut-points were explored, and the 140 cm cut-point resulted in the least amount of discarded trials (n = 1) while still capturing multiple footfalls during a given trial. This distance allowed for at least 4 footfalls per trial per participant, which is more than has been analyzed and previously reported in several standard gait protocols,[17,27] and is similar to a recently published tandem gait protocol.[23]

The average values across all 3 trials for each condition were used for statistical analyses. To explore tandem gait velocity, COP speed, and COP path, we utilized a 4 (condition) × 2 (group) mixed-

Table 1
Group demographics and statistical comparisons.

	Concussion history (n = 15)	Control (n = 15)	P-value
Age (years)	19.7 (0.9)	19.7 (1.6)	0.89
Height (cm)	169.2 (9.4)	172.3 (10.8)	0.41
Mass (kg)	66.0 (12.8)	71.0 (10.4)	0.25
Female (n)	9 (60.0%)	9 (60.0%)	–
Male (n)	6 (40.0%)	6 (40.0%)	–
Days since concussion[a]	126 (28–432)	–[b]	–
Total concussions[a]	1 (1–3)	0 (0–2)[b]	–

All variables are represented by the mean (SD) unless otherwise noted.
[a] Reported as median (range).
[b] One control participant had experienced 2 concussions, their most recent concussion was 1103 days prior to testing. No other control participants had a history of concussion. Healthy controls were matched to each injured participant based on sex, age (±1 year), mass (±10%), and height (±5%).

model analysis of covariance (ANCOVA). Brooks Visuospatial Task time to task completion was analyzed using a 3 (condition: single-task, dual-task eyes open, and dual-task eyes closed) × 2 (group) mixed-model ANCOVA. Bonferroni corrected t tests were used to analyze any significant interactions or main effects. Separate between-subjects ANCOVAs were used to compare eyes open dual-task cost and eyes closed dual-task cost. Because gait velocity was statistically different between groups, it was used as a covariate when investigating COP speed and COP path as well as all COP dual-task outcomes. Additionally, we covaried for the number of days between the last concussion and the testing session in the injured group. The number of days post-injury for each concussion history group participant was subtracted from the group mean days since concussion (177 days). Control participants were assigned a value of zero. This created a mean-centered days since concussion value, which was used as a covariate in all statistical models. An a priori alpha value of 0.05 was established.

Dual-task cost was calculated separately for eyes open and eyes closed conditions by calculating a percent change between dual- and single-task conditions. When interpreting dual-task cost, positive values indicate worse performance during dual-task conditions. To investigate dual-task effects on cognitive performance, errors on the Brooks Visuospatial Task were converted to percent of correct responses. Because there were no errors in the majority of Brooks Visuospatial Task trials, errors were combined with time to complete the Brooks Visuospatial Task to form a single combined dual-task cost outcome for the cognitive task.

3. Results

Independent t-tests revealed no statistically significant group demographics. Median days since concussion in the concussion history group was 126 days (range 28–432 days). One participant in the control group reported a history of 2 concussions, the most recent of which was 1103 days prior to testing (Table 1).

No significant interactions were observed for COP path ($F_{3,83} = 1.10$; $p = 0.353$), velocity ($F_{3,83} = 0.45$; $p = 0.715$), or COP speed ($F_{3,83} = 0.32$; $p = 0.810$). We observed a significant group main effect for velocity ($F_{1,27} = 4.26$; $p = 0.049$; ES = 0.38), with the concussion history group (25.2 cm/s, 95% CI: 22.3–28.0) walking significantly slower than the control group (29.2 cm/s, 95% CI: 26.4–32.0; Table 2).

Significant condition main effects were observed for COP path ($F_{3,83} = 13.21$; $p < 0.001$), velocity ($F_{3,83} = 147.67$; $p < 0.001$), and speed ($F_{3,83} = 29.65$; $p < 0.001$). Center of pressure path was longer during DTEC (197.3 cm) compared to STEO (177.2 cm; $p = 0.009$) and DTEO (168.0 cm: $p < 0.001$). Additionally, greater COP path was noted during STEC (188.8 cm) compared to DTEO ($p = 0.001$). Center of pressure speed was faster during STEC (35.7 cm/s) compared to both STEO (33.2 cm/s; $p < 0.001$) and DTEO (32.1 cm/s; $p < 0.001$). Greater COP speed was also noted during DTEC (35.1 cm/s) compared to DTEO ($p < 0.001$). Velocity was greater during STEO (34.4 cm/s) compared to all other conditions ($p < 0.001$), while slower velocity was noted during DTEC (21.3 cm/s) compared to all other conditions ($p < 0.001$). Velocity was greater during DTEO (24.1 cm/s) as compared to STEC (28.9 cm/s; $p < 0.001$; Table 2).

Center of pressure speed dual-task cost was significantly different between groups during eyes closed trials ($F_{3,26} = 5.13$; $p = 0.032$) such that the concussion history group (23.5%) reduced their COP speed to a greater extent than did the control group (16.3%) during DTEC. No other dual-task cost differences were significant ($p > 0.068$; Fig. 1).

No significant interactions were noted for Brooks Visuospatial Task time ($F_{2,56} = 1.36$; $p = 0.266$). There were no main effects for group ($F_{1,27} = 4.07$; $p = 0.054$; ES = 0.37), but we did observe a significant main effect for condition ($F_{2,56} = 17.22$; $p < 0.001$) such that DTEO (12.4 s; $t_{56} = 4.69$; $p < 0.001$) and DTEC (12.7 s; $t_{56} = 5.40$; $p < 0.001$) trials took longer to complete than baseline Brooks Visuospatial Task trials (10.4 s).

No group differences were observed for Brooks Visuospatial Task combined dual-task cost during eyes open ($F_{3,27} = 1.11$; $p = 0.301$; concussion history group = 32.4%, 95% CI:15.5–9.3; control group = 20.1%, 95% CI: 3.2–37.0) or eyes closed conditions ($F_{2,27} = 1.98$; $p = 0.170$; concussion history group = 37.5%, 95% CI: 21.9–53.1; control group = 22.4%, 95% CI: 6.8–38.0).

4. Discussion

We are among the first to study tandem gait outcomes after concussion,[22–24] even though international concussion experts recommended a tandem gait assessment following concussion more than 5 years ago.[21] Our goal was to explore differences in tandem gait dynamic balance between recreational athletes with a concussion history within the past 18-months as compared to matched non-concussed recreational athletes in a preliminary manner, hopefully leading to more in-depth study of these potentially important clinical outcomes using novel methodology. We failed to reject the null hypotheses for most variables, but we did observe slower tandem gait velocity and greater COP speed dual-task cost in those with a concussion history as compared to healthy controls. Since participants were instructed to move as quickly as possible, the strategy adopted by concussion history participants (i.e., slower velocity and COP speed compared to non-concussed individuals) during eyes closed dual-task trials likely reflects a more conservative approach to tandem gait. As Brooks Visuospatial Task performance did not change between groups, it appears concussion history participants prioritized gait balance control in order to retain cognitive task accuracy and speed, whereas control participants we able to retain cognitive performance without sacrificing as much COP speed. Our findings must be regarded as tentative, as we lack pre-injury data on our participants. Thus, we cannot eliminate the possibility that these two groups may have differed on tandem gait conditions prior to injury onset.

Our findings are consistent with two previous investigations. Sambasivan et al.[22] studied a cohort of children (8–17 years old) who were deemed clinically recovered from concussion and were an average of 42.9 ± 25.4 days post-injury. The authors reported significantly slower tandem gait velocity relative to controls but did not report any balance outcomes. Howell et al.[23] studied a small cohort of college-aged individuals at multiple time points following injury, and reported concussed participants walked slower during single- and dual-task conditions at 72 h post-concussion and had a lower dual-task cadence overall compared to controls. Like our study, these findings suggest a conservative adaptation to dual-task

Table 2
Tandem gait outcomes between groups for each condition adjusted for average days since concussion and sagittal plane velocity.

Condition	Center of pressure outcome variables					
	Path length (cm)		Speed (cm/s)		Velocity (cm/s)	
	Mean (95% CI)	ES[a]	Mean (95% CI)	ES[a]	Mean (95% CI)	ES[a]
Tandem gait (TG)						
Concussion history	176.7 (164.6, 188.8)	0.02	33.5 (32.0, 34.9)	0.09	32.5 (29.5, 35.5)	0.33
Control	177.7 (163.9, 191.4)		33.0 (31.3, 34.6)		36.4 (33.4, 39.3)	
TG w/eyes closed (EC)						
Concussion history	193.2 (182.0, 204.4)	0.20	36.1 (34.8, 37.5)	0.16	27.3 (24.3, 30.3)	0.28
Control	184.4 (172.9, 196.0)		35.3 (33.9, 36.7)		30.5 (27.5, 33.5)	
TG w/Brooks						
Concussion history	172.0 (159.9, 184.1)	0.18	32.5 (31.1, 34.0)	0.14	21.9 (18.9, 24.9)	0.37
Control	164.1 (152.9, 175.3)		31.7 (30.4, 36.4)		26.3 (23.3, 29.3)	
TG w/EC and Brooks						
Concussion history	205.6 (192.3, 218.9)	0.37	35.1 (33.5, 36.7)	0.02	18.9 (15.9, 21.9)	0.41
Control	189.0 (177.4, 200.6)		35.0 (33.6, 36.4)		23.6 (20.6, 26.6)	

CI = confidence interval, ES = effect size, TG = tandem gait, EC = eyes closed, Brooks = Brooks Visuospatial Task.
[a] Effect size was calculated as Cohen's *d*.

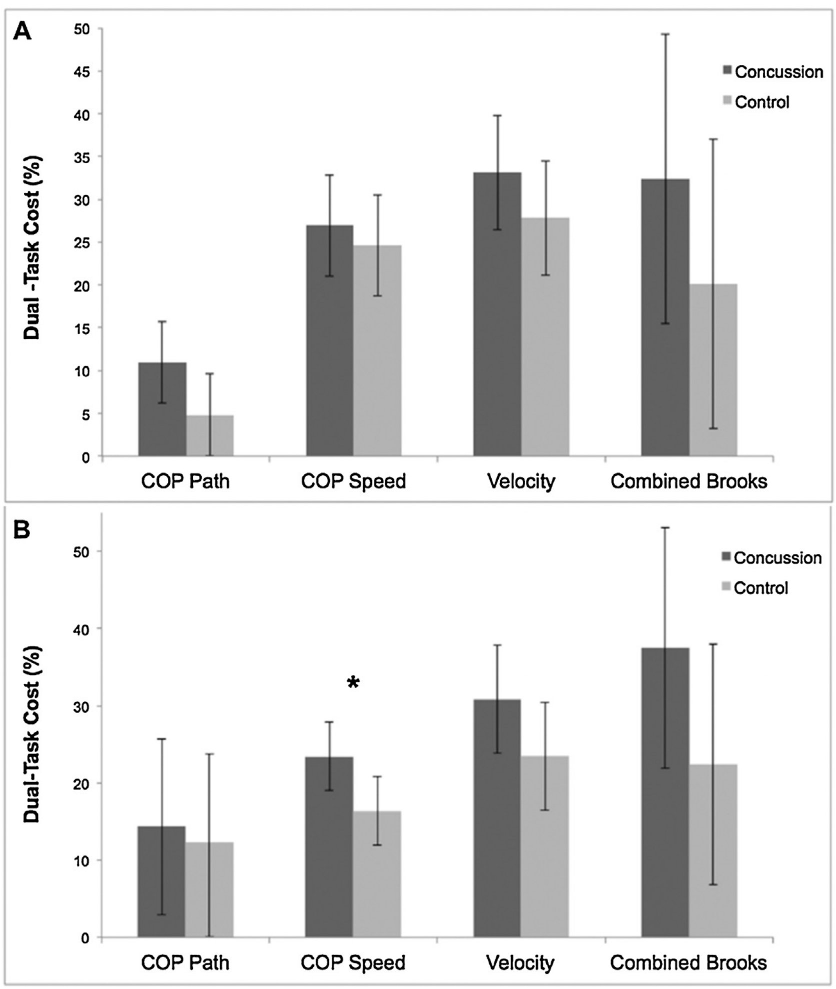

Fig. 1. (A) Dual-task cost during eyes open tandem gait conditions. None of the between group differences were statistically significant. COP = center of pressure; combined Brooks = percent correct answers and time to complete the Brooks Visuospatial Task combined. (B) Dual-task cost during eyes closed tandem gait conditions. *Indicates significant group difference ($F_{3,26} = 5.13$; $p = 0.032$). Error bars represent the 95% confidence intervals. COP = center of pressure; combined Brooks = percent correct answers and time to complete the Brooks Visuospatial Task combined.

tandem gait in participants with a concussion history as compared to control individuals.

A current shortfall in concussion management is the lack of a clinical test to identify dynamic balance deficits that may be contributing to the relative high re-injury rate among athletes who have returned to play after concussion. Differences between healthy and concussed individuals in standard gait, while apparent using sophisticated laboratory equipment, are minimal. It is likely that clinicians are not able to objectively observe such slight center of mass perturbations. Increasing the neuromechanical constraints of standard gait, such as tandem gait that is not motor program based, may exaggerate dynamic balance deficits, leading to easier observation by clinicians. Although we used fairly expensive equipment here to measure center of pressure, we believe tandem gait assessment can be feasibly evaluated by translating our work into non-technical clinical assessments. There are few published tandem gait investigations,[22–24] but there are many describing post-concussion deficits during standard gait.[17–20] Direct comparisons between our tandem gait findings and standard gait outcomes is challenging. Proportional mean differences, obtained by dividing the observed group difference by the overall mean velocity and then multiplying by 100, may provide some insight to this discussion. Using this standardization, we observed a 15% proportional tandem gait velocity mean difference between groups. Previous reports of standard gait following concussion report statistically significant between group velocity mean differences, but proportionately the differences are around 7 or 8%.[19,28] Our proportional difference was about twice as much, but the clinical significance of this finding is unclear. Though more research is needed, tandem gait appears to be reliable[29] and may be more sensitive to concussion than common clinical balance assessments.[23,24]

We found increased time to complete the Brooks Visuospatial Task while walking compared to sitting, suggesting slower cognitive performance during walking (in both groups). Plummer et al.[30] describe several potential cognitive-motor interference outcomes during dual-task. While many combinations are possible, our results suggest a mutual interference pattern during dual-task tandem gait. Mutual interference represents a worsening cognitive performance accompanied by a simultaneous worsening motor performance in the dual-task compared to the single-task. We also found increased COP path length and decreased COP speed during dual-task conditions, suggesting a dual-task related decline in balance performance. Our data provide evidence for mutual interference in both previously concussed and non-concussed matched individuals, however, the previously concussed individuals demonstrated a greater cost, especially for the combined cognitive outcome variable. Thus, it may be possible this same mutual interference occurs in dynamic athletic settings. If so, athletic performance might be decreased and musculoskeletal injury risk increased. Although our data show trends toward worse performance in the concussion history group, we lacked statistical significance for most between-group differences. While this may be related to issues with statistical power, we cannot ignore the plausible outcome that true differences in the selected dependent variables do not exist between recently concussed individuals with no current symptoms and matched athletes with no recent concussion history. Further study should include sport performance and injury risk outcomes, allowing for further clinical interpretation as to the effects of mutual interference in the sport setting.

We observed wide between-subject variability in task performance, especially during dual-task conditions, similar to a previous investigation.[19] The wide-ranging performance on the Brooks Visuospatial Task may have limited our ability to detect significant cognitive performance differences between groups, if they exist. The Brooks Visuospatial Task appears effective in distracting subjects from the motor task, based on our observed motor dual-task effects. However, due to the large amount of between-subject variability during the Brooks Visuospatial Task, it may not be useful for detecting true cognitive group differences. Additionally, we cannot say if other cognitive deficits remain besides those associated with visuospatial memory, as they were not assessed in this study. We were limited by a cross-sectional study design. It is possible that any group differences in dynamic balance that were acutely present following concussion had recovered before we were able to measure these outcomes in our study sample given the median post-injury duration of 126 days. Longitudinally measuring related outcomes is necessary to understand dynamic balance after concussion. We did not examine any frontal plane outcomes due to data collection instrumentation limitations. Frontal plane outcomes may give insight into dynamic balance control following concussion. We only assessed 140 cm of tandem gait data, which limited the duration and number of steps available for analysis. In the future, incorporating continuous cognitive tasks, such as counting backwards by sevens, may be important to study balance during tandem gait over longer durations and distances. Despite this limitation, we feel our methodology was appropriate as many previously published standard gait investigations have been limited to analysis of a single gait cycle per trial,[17,27] less than the 4 steps we observed here.

5. Conclusion

We observed significantly slower tandem gait velocities in the concussion history group as compared to the control group but failed to reject the null hypotheses in many cases. This implies that dynamic balance in recently concussed individuals may not be impaired, at least as measured in this investigation. Due to several limitations discussed above, our findings should be interpreted cautiously. These preliminary data are intended to encourage future work aimed at longitudinally assessing dynamic balance utilizing novel assessment methods following concussion.

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