Cognition Uniquely Influences Dual-Task Tandem Gait Performance Among Athletes With a Concussion History

Eric J. Shumski, MS,*† Julianne D. Schmidt, PhD, ATC,† and Robert C. Lynall, PhD, ATC†

Background: After a concussion, there are unique associations between static balance and landing with cognition. Previous research has explored these unique correlations, but the factor of time, dual-task, and different motor tasks leave gaps within the literature. The purpose of this study was to determine the associations between cognition and tandem gait performance.

Hypothesis: We hypothesized that athletes with a concussion history would display stronger associations compared with athletes without a concussion history between cognition and tandem gait.

Study Design: Cross-sectional.

Level of Evidence: Level 3.

Methods: A total of 126 athletes without (56.3% female; age, 18.8 ± 1.3 years; height, 176.7 ± 12.3 cm; mass, 74.8 ± 19.0 kg) and 42 athletes with (40.5% female; age, 18.8 ± 1.3 years; height, 179.3 ± 11.9 cm; mass, 81.0 ± 25.1 kg) concussion history participated. Cognitive performance was assessed with CNS Vital Signs. Tandem gait was performed on a 3-meter walkway. Dual-task tandem gait included a concurrent cognitive task of serial subtraction, reciting months backward, or spelling words backward.

Results: Athletes with a concussion history exhibited a larger number of significant correlations compared with athletes without a concussion history for cognition and dual-task gait time (4 significant correlations: rho-range, -0.377 to 0.358 vs 2 significant correlations: rho, -0.233 to 0.179) and dual-task cost gait time (4 correlations: rho range, -0.344 to 0.392 vs 1 correlation: rho, -0.315). The time between concussion and testing did significantly moderate any associations (P = 0.11-0.63). Athletes with a concussion history displayed better dual-task cost response rate (P = 0.01). There were no other group differences for any cognitive (P = 0.13-0.97) or tandem gait (P = 0.20-0.92) outcomes.

Conclusion: Athletes with a concussion history display unique correlations between tandem gait and cognition. These correlations are unaffected by the time since concussion.

Clinical Relevance: These unique correlations may represent shared neural resources between cognition and movement that are only present for athletes with a concussion history. Time does not influence these outcomes, indicating the moderating effect of concussion on the correlations persists long-term after the initial injury.

Keywords: cognitive load; mild traumatic brain injury; musculoskeletal injury; neurocognition; walking

From †UGA Concussion Research Laboratory, Department of Kinesiology, University of Georgia, Athens, Georgia

*Address correspondence to Eric J. Shumski, MS, UGA Concussion Research Laboratory, Department of Kinesiology, University of Georgia, Ramsey Student Center, 330 River Rd., Athens, GA 30602 (email: eric.shumski@uga.edu).

The following authors declared potential conflicts of interest: E.J.S. is a paid consultant for ASPIRE Clinic and has received grant support from NCAA, DoD, Andee's Army, and Georgia Clinical and Translational Science Alliance and education payments from Impact Inc. R.C.L. has received grant support from NFL, DoD.

DOI: 10.1177/19417381231183413

Concussions account for a large portion of injuries among National Collegiate Athletic Association (NCAA) athletes.[61] Across the globe, the World Health Organization reports 600 concussions per every 100,000 people.[9] A plethora of symptoms (eg, headache, sensitivity to light, and difficulty concentrating) are commonly reported postconcussion but other deficits often exist, including balance, cognitive, and vestibular problems.[30,41,42]

Balance can be assessed through static and dynamic means, with the Balance Error Scoring System being one of the more common static assessments.[27] Dynamic methods include normal gait and tandem gait.[58] Both static and dynamic measures may be important postconcussion, and dynamic balance typically resolves slower than static balance. Tandem gait resolves at the return-to-play clinical milestone,[44] and normal gait resolves approximately 2 months after initial injury under dual-task conditions.[8] However, the exact recovery timeline reported in the literature is mixed.[16,34,41]

Cognition after a concussion is assessed on the sideline and throughout the return-to-play protocols. The Standardized Assessment of Concussion is a common sideline assessment that assesses attention and memory[37] but does not reveal cognitive deficits beyond 48 hours.[36] Computerized cognitive tests provide a more comprehensive assessment due to the inclusion of multiple cognitive domains, including composite memory, verbal memory, visual memory, psychomotor speed, reaction time, complex attention, cognitive flexibility, processing speed, executive function, simple attention, and motor speed.[20] In general, the recovery of cognition occurs around 10 to 14 days postconcussion. However, impairments in verbal memory are commonly impaired at the end range of 14 days,[35] and reaction time is impaired for up to 2-months postconcussion.[30]

Motor function and cognition are correlated with each other. Among healthy athletes, better cognition is linked to safer jump/drop landing mechanics.[2,22,47,55] For example, athletes in the high-performing group, as categorized by the Concussion Resolution Index (an assessment of reaction time and processing speed), display smaller anterior tibial shear forces, smaller knee abduction moments, and smaller knee abduction angles compared with the lower-performing group.[22] In addition, athletes without a concussion history have greater verbal memory and faster visual motor speed correlated with greater knee flexion, lower eye-hand coordination scores correlated with smaller knee extension moments, greater multiple object tracking scores correlated with smaller ankle dorsiflexion angles and smaller knee abduction moments,[7] and slower functional visuomotor reaction correlated with smaller knee extension moments.[2] However, after a musculoskeletal injury such as an anterior cruciate ligament tear, the relationship between cognition and movement becomes skewed, with the injured population relying more on vision and visual-spatial ability to perform movements.[12,43] This skewness of association has been reported repeatedly after musculoskeletal injury,[12,43] concussion,[2] and among healthy older adults compared with matched young adults.[45]

Further, structural and functional brain studies among healthy and pathologic populations give insight into the relationship between cognition and movement. For instance, the cerebellum is responsible for voluntary movements such as gait,[1,15] and cognitive aspects such as spatial cognition, working memory, and verbal fluency (as revealed in a study of people with isolated cerebellar disease).[52] Facilitation of the dorsolateral prefrontal cortex via noninvasive brain stimulation improved cognitive (eg, dual-tasking, reaction time, working memory, and processing speed) and motor tasks (eg, gait speed) among both healthy and people with neurologic pathologies.[17,18,21,28,32,33,39,40,59] This demonstrates specific parts of the brain are involved in both cognition and movement and improving one may lead to associated changes in the other (positively or negatively).

A similar association between cognition and better motor function occurs postconcussion. During an acute postconcussion static balance assessment, athletes displayed 5 significant correlations between cognition and balance, while before the concussion the same athletes displayed no significant correlations.[57] During a landing task, athletes an average of 461 days postconcussion displayed 13 significant correlations between cognition and common high-risk landing biomechanics compared with matched, nonconcussed controls, who displayed 8 significant correlations.[2] As movement and cognition are correlated, potentially, any task requiring the use of both simultaneously (ie, dual-task) will lead to performance deficits in either both or one of the tasks themselves.[26] Sports require constant dual-tasking (tracking the ball and defender simultaneously while running and cutting). However, neither of the previous studies assessed whether there was an influence of time or the effect of dual-task (concurrent cognitive task) during the motor task on any of these outcomes. Insight into whether greater correlations exist may open avenues for more comprehensive active management techniques.

Therefore, it is critical to understand the association between clinically feasible dynamic balance assessments and cognition. The purpose of this study was to (1) determine the associations between cognition (as assessed with CNS Vital Signs) and single- and dual-task tandem gait time and dual-task cost tandem gait time, (2) determine whether the time between concussion and gait testing (days) moderates the relationship between cognition and single- and dual-task tandem gait time and dual-task cost tandem gait time, and (3) compare cognitive and tandem gait (single-task, dual-task, dual-task cost for response rate, percent correct, and tandem gait time) outcomes between athletes with and without a concussion history. We hypothesized that (1) athletes with a concussion history would display stronger associations compared with athletes without a concussion history between cognition and single- and dual-task and dual-task cost tandem gait time, (2) athletes testing closer to the concussion would display stronger associations that those further removed from their concussion, and (3) there would be no differences between cognitive outcomes between athletes with and without a concussion history.

Table 1. CNS Vital Signs cognitive domains interpretations

Domain	Interpretation[a]
Composite memory	How well a subject can recognize, remember, and retrieve words and geometric figures
Verbal memory	How well a subject can recognize, remember, and retrieve words
Visual memory	How well a subject can recognize, remember, and retrieve geometric figures
Psychomotor speed	How well a subject perceives, attends, responds to visual-perceptual information, and performs motor speed and fine motor coordination
Reaction time[b]	How quickly a subject can react, in milliseconds, to a simple and increasingly complex direction set
Complex attention[b]	Ability to track and respond to a variety of stimuli over lengthy periods of time and/or perform mental tasks requiring vigilance quickly and accurately
Cognitive flexibility	How well a subject is able to adapt to rapidly changing and increasingly complex set of directions and/or to manipulate the information
Processing speed	How well a subject recognizes and processes information (ie, perceiving, attending/responding to incoming information, motor speed, fine motor coordination, and visual-perceptual ability
Executive function	How well a subject recognizes rules, categories, and manages or navigates rapid decision-making
Simple attention	Ability to track and respond to a single defined stimulus over length periods of time while performance vigilance and response inhibit quickly and accurately
Motor speed	Ability to perform movements to produce and satisfy an intention toward a manual action and goal

[a] Interpretation is verbatim from page 13 of the CNS Vital Signs interpretation guide (https://www.cnsvs.com/WhitePapers/CNSVS-BriefInterpretationGuide.pdf).
[b] Lower scores are better.

METHODS

Data from 168 NCAA student-athletes were analyzed during baseline concussion testing. A total of 126 (75.0%) athletes did not have a concussion history and 42 (25.0%) athletes did have a concussion history. Participants were included if they were NCAA athletes, ≥18 years old, and provided written and informed consent. Participants were excluded if they self-reported attention deficit hyperactivity disorder, attention deficit disorder, dyslexia, or memory disorder. All methods were approved by the University of Georgia's institutional review board (PROJECT00001979).

Self-reported concussion history was collected with the University of Michigan National Institute of Health sport-related concussion common data element form during concussion baseline testing.[6] Demographic information such as age, height, mass, and shoe size were self-reported during concussion baseline testing.

A computerized cognitive assessment (CNS Vital Signs) was completed as part of a baseline concussion assessment program for all athletes before the start of their season.[20] We used athletes' first assessment for all analyses, except if an athlete's test was deemed invalid by the computerized testing platform or if ≥2 domains were below the 5th percentile. In these cases (7.1% of all participants), a subsequent assessment (median [interquartile range] =13 [8-22] days after initial testing) was completed and used for analysis.

The computerized assessment, CNS Vital Signs, was completed in a well-lit room while seated at a desk.[49] CNS Vital Signs provides outcome scores for composite memory, verbal memory, visual memory, psychomotor speed, reaction time, complex attention, cognitive flexibility, processing speed, executive function, simple attention, and motor speed. Full details of each cognitive domains' calculation and interpretation can be found elsewhere,[10] but Table 1 provides a brief interpretation. Raw CNS Vital Signs scores were used for analyses.

Tandem gait was performed on a 3-meter walkway. Athletes were instructed to walk heel-to-toe to one end of the walkway, turn around, and walk back as fast as possible (total 6-meter distance).[25] Single-task tandem gait was performed first, then alternating between single- and dual-task tandem gait until 5 trials of each condition were completed. During dual-task tandem gait, participants completed a concurrent cognitive task administered in a random order including (1) reciting the months backward, (2) spelling words backward, or (3) serial subtraction by 6 or 7.[25] All tandem gait assessments were performed by research team members and certified athletic trainers; however, all baseline testing (of which tandem gait is a part) is overseen by certified athletic trainers. Furthermore, the research team collectively conducts over 100 assessments (CNS Vital Signs, tandem gait, Balance Error Scoring System, and other baseline concussion battery tests) per year. A standard set of instructions is given to all participants to decrease interpersonal variability.

Single-task measures of reciting the months backward, spelling words backward, or serial subtraction by 6 or 7 were completed before all tandem gait trials while standing still. Athletes completed 1 to 2 trials of each task under single-task (no tandem gait) conditions. Athletes were instructed to complete the task as quickly and as accurately as possible for 20 seconds.

Single- and dual-task tandem gait cognitive tasks were scored for accuracy (percent correct) and response rate (responses per second). Outcomes were averaged across all cognitive tasks. Tandem gait times (seconds) were collected with a stopwatch and all trials were averaged respectively to their condition.

Dual-task costs were calculated in the typical manner such that negative values represent a decrease in performance during the dual-task condition relative to the single-task condition[24]:

$$\text{Dual-task cost} = \left(\frac{\left(\text{Dual-task condition}\right) - \left(\text{Single-task condition}\right)}{\left(\text{Single-task condition}\right)}\right) \quad (1)$$

Of the 18 dependent variables (cognitive domains [Table 1] and gait outcomes [response rate, percent correct, and gait time for single- and dual-task; dual-task cost response rate, dual-task cost percent correct, dual-task cost gait time]), 8 (44.4%) and 16 (88.9%) were not normally distributed for athletes with and without a concussion history, respectively, per the Shapiro-Wilk's test ($P < 0.05$). Therefore, aim (1) was assessed with Pearson *r* and Spearman rho correlations were used for parametric and nonparametric correlations. Aim (2) was assessed with linear regressions including an interaction term between significant correlations from aim (1) and days between concussion and gait testing. Aim (3) was assessed with independent *t* tests and Mann-Whitney *U* tests to compare dual-task cost outcomes between groups. Separate 2 (group) × 2 (condition [single-task, dual-task]) nonparametric mixed model analyses of variance (ANOVA) were used for not normally distributed variables. The nonparametric mixed model analyses were conducted with an aligned ranked transformation ANOVA from the R package "ARTool."[60] Analyses were completed with R statistical software (Version 4.0.3). An alpha level of 0.05 was established a priori with post hoc Bonferroni adjustments.

We explored potential confounders on single- and dual-task gait outcomes to include as potential covariates in our analyses. Variables such as sex, age, height, mass, shoe size (standardized to men's shoe size), total number of concussions, and time between concussion and baseline testing were assessed for significant correlations with single- and dual-task tandem gait and dual-task gait cost. There were no significant correlations ($P = 0.12$ to 0.95; r/rho range, -0.130 to 0.098) and no demographic group differences (Table 2); therefore, none of these variables were included as covariates.

Demographic information was compared with a series of independent samples *t* tests. Shoe size was compared with a Mann-Whitney *U* test. The proportion of male to female athletes between groups was compared with a chi-square test (Table 2). Pearson's *r* and Spearman rho correlation coefficients were interpreted as negligible (≤0.10), weak (0.11-0.39), moderate (0.40-0.69), strong (0.70-0.89), and very strong (≥0.90).[53] Normally distributed variables' effect sizes were calculated with Hedge's *g* and interpreted as small (<0.20), medium (0.20-0.80), and large (>0.80).[11] Non-normally distributed variables' effect sizes were calculated with Cliff's Delta and interpreted as small (≤0.33), medium (0.34-0.47), and large (≥0.48).[51]

RESULTS

There were no significant demographic differences between athletes with and without a concussion history (Table 2).

Concussion Cognitive and Tandem Gait Correlations

Motor speed (rho = -0.317; $P < 0.01$) and psychomotor speed (rho = -0.283; $P < 0.01$) were weakly, significantly correlated with single-task tandem gait time for athletes without a concussion history. Motor speed ($r = -0.309$; $P = 0.05$) was weakly, significantly correlated with faster single-task tandem gait time for athletes with a concussion history (Table 3).

Processing speed (rho = -0.233; $P < 0.01$), psychomotor speed (rho = -0.305; $P < 0.01$), and reaction time (rho = 0.179; $P = 0.04$) were weakly, significantly correlated with dual-task gait time for athletes without a concussion history. Executive function (rho = -0.377; $P = 0.01$), cognitive flexibility (rho = -0.351; $P = 0.02$), complex attention (rho = -0.342; $P = 0.03$), and (rho = 0.358, $P = 0.02$) were weakly, significantly correlated with dual-task tandem gait time (Table 3).

Processing speed (rho = -0.315; $P < 0.01$) was weakly, significantly correlated with dual-task cost tandem gait time for athletes without a concussion history. Complex attention (rho = -0.392; $P = 0.01$), cognitive flexibility (rho = 0.344; $P = 0.03$), executive function (rho = 0.338; $P = 0.03$), and simple attention (rho = 0.323; $P = 0.04$) were weakly, significantly correlated with dual-task cost tandem gait time for athletes with a concussion history (Table 3).

Cognitive Outcomes Moderated by Time Since Concussion

The median number of days between concussion and testing was 1394.0 days (range, 192.0-4456.0 days). Three athletes only reported the year of the concussion and were removed from this analysis.

The time between concussion and testing did not significantly moderate the relationship between single-task gait time and motor speed ($F_{3,35} = 2.2$; $P = 0.11$; $R^2 = 0.156$). The time

Table 2. Participant demographics

	Concussion History (n = 42)	No History (n = 126)	*P*
Sex, % (female)[a]	40.5	56.3	0.07
Age, y[a]	18.8 (1.3)	18.8 (1.3)	0.91
Height, cm[a]	179.3 (11.9)	176.7 (12.3)	0.22
Mass, kg[a]	81.0 (25.1)	74.8 (19.0)	0.09
Shoe size[b,c]	11.0 (4.0)	9.0 (5.0)	0.27
Total number of concussions[c]	1.5 [0.5]	-	-
Time between concussion and testing, days[c]	1394.00 [1786.00]	-	-

[a] Mean (SD).

[b] Shoe size standardized to male shoe size.

[c] Median [interquartile range], full range reported in Results.

Table 3. Correlations between cognition and tandem gait time

	Concussion History[a]			No History[a]		
	Single-Task	Dual-Task	Dual-Task Cost	Single-Task	Dual-Task	Dual-Task Cost
Composite memory	−0.096	−0.158	−0.011	0.089	0.046	−0.006
Verbal memory	−0.054	−0.038	−0.025	0.059	0.049	−0.003
Visual memory	−0.106[b]	−0.100	0.044	0.062	0.027	0.020
Psychomotor speed	−0.216[b]	−0.115	0.127	**−0.283**	−0.305	−0.092
Reaction time	0.258[b]	**0.358**	0.115	0.102	**0.179**	0.049
Complex attention	0.173[b]	**0.342**	**0.392**	0.033	−0.041	−0.060
Cognitive flexibility	−0.239[b]	**−0.351**	**−0.344**	−0.089	0.021	0.112
Processing speed	0.122	−0.034	−0.224	−0.012	**−0.233**	**−0.315**
Executive function	−0.268[b]	**−0.377**	**−0.338**	−0.144	−0.029	0.095
Simple attention	−0.168	−0.290	**−0.323**	−0.043	−0.089	−0.118
Motor speed	**−0.309**[b]	−0.024	0.291	**−0.317**	−0.171	0.113

[a] Bold values indicate significant correlation coefficients ($P < 0.05$). Spearman rho correlation used for analysis unless otherwise indicated.

[b] Pearson *r* correlation used for analysis.

between concussion and testing did not moderate the relationship between dual-task gait time and reaction time ($F_{3,35} = 0.7$; $P = 0.55$; $R^2 = 0.057$), cognitive flexibility ($F_{3,35} = 2.1$; $P = 0.11$; $R^2 = 0.155$), or executive function ($F_{3,35} = 2.4$; $P = 0.08$; $R^2 = 0.172$). The overall model for complex attention and dual-task gait time ($F_{3,35} = 3.0$; $P = 0.04$; $R^2 = 0.207$) was significant, but none of the individual predictors of executive function raw score ($P = 0.57$; $R^2 = 0.158$), days between concussion and testing ($P = 0.17$; $R^2 = 0.022$), or their interaction ($P = 0.28$; $R^2 = 0.027$) were significant.

Table 4. CNS Vital Signs

	Concussion History (n = 42)	No History (n = 126)	*P*	Effect Size
Composite memory[a]	101.5 (13.0)	101.0 (10.0)	0.82	0.023
Verbal memory[a]	53.0 (9.0)	54.0 (7.0)	0.16	0.144
Visual memory[a]	49.0 (9.0)	47.0 (8.0)	0.13	0.156
Psychomotor speed[b]	177.7 (15.6)	179.1 (18.2)	0.80	0.074
Reaction time[ac]	624.5 (150.0)	621.0 (94.0)	0.86	0.019
Complex attention[ac]	9.0 (8.0)	8.0 (5.0)	0.76	0.032
Cognitive flexibility[a]	50.0 (10.0)	48.5 (13.0)	0.63	0.049
Processing speed[a]	58.0 (13.0)	62.0 (14.0)	0.14	0.153
Executive function[a]	51.5 (10.0)	50.5 (12.0)	0.60	0.054
Simple attention[a]	39.0 (3.0)	39.0 (3.0)	0.66	0.044
Motor speed[b]	117.6 (12.7)	117.7 (14.4)	0.97	0.006

[a] Median (interquartile range) and Cliff's Delta effect size reported.
[b] Mean (SD) reported, Hedge's *g* effect size reported.
[c] Lower numbers are better.

The time between concussion and testing did not significantly moderate the relationship between dual-task cost and complex attention ($F_{3,35} = 1.4$; $P = 0.27$; $R^2 = 0.105$), cognitive flexibility ($F_{3,35} = 1.0$; $P = 0.41$; $R^2 = 0.077$), executive function ($F_{3,35} = 1.0$; $P = 0.41$; $R^2 = 0.079$), or simple attention ($F_{3,35} = 0.6$; $P = 0.63$; $R^2 = 0.047$).

Cognitive Outcomes Group Comparisons

There were no significant differences for any of the cognitive outcomes between athletes with and without a concussion history (Table 4).

Single-Task, Dual-Task, and Dual-Task Cost Tandem Gait Outcomes

There was a significant interaction ($F_{1,166} = 4.504$; $P = 0.04$) for response rate, but there was no main effect of group ($F_{1,166} = 0.042$, $P = 0.84$) or condition ($F_{1,166} = 0.145$, $P = 0.70$). However, after decomposing the interaction, there were no significant differences with or without corrections for multiple comparisons (P range$_{\text{nonadjusted}}$ = 0.11-0.91; Table 5).

There was a significant main effect of condition ($F_{1,166} = 21.389$, $P < 0.01$) where single-task percent correct was significantly more accurate compared with dual-task percent correct (mean difference [95% CI] = 3.89% (1.69-6.09); $P < 0.01$, Cliff's Delta = 0.257). There was no main effect of group ($F_{1,166} = 0.073$; $P = 0.79$) or group by condition interaction ($F_{1,166} = 0.377$; $P = 0.54$; Table 5).

There was a significant main effect of condition ($F_{1,166} = 678.924$; $P < 0.01$) where single-task gait time was significantly faster compared with dual-task gait time (mean difference [95% CI] = 6.76 s (5.83-7.69); $P < 0.01$; Cliff's Delta = 0.765). There was no main effect of group ($F_{1,166} = 1.656$; $P = 0.20$) or group by condition interaction ($F_{1,166} = 1.999$; $P = 0.16$; Table 5).

Athletes with a concussion history had significantly better dual-task cost response rate compared with athletes without a concussion history ($U = 1953.0$; mean difference [95% CI] = 0.091 (0.017-0.166) responses per second, $P = 0.01$; Cliff's Delta = 0.262). There was no difference in dual-task cost percent correct ($U = 2555.5$, $P = 0.80$; Cliff's Delta = 0.026) or gait time ($U = 2465.0$; $P = 0.51$; Cliff's Delta = 0.068) between groups (Table 5).

DISCUSSION

There were similar correlations between athletes with and without a concussion history for single-task gait time. Athletes with a concussion history had slightly greater strength of correlations for dual-task gait time, and had more cognitive domains significantly correlated (4 vs 2), compared with athletes without a concussion history. In addition, athletes with a concussion history displayed a greater number of significant correlations between cognition and dual-task cost tandem gait time (9 vs 5). The time between concussion and testing did not moderate the relationship between gait outcomes and cognition.

Table 5. Gait outcomes

	Condition	Concussion History (n = 42)[a]	No History (n = 126)[a]
Gait time, s[b]	Single-task	13.69 (3.76)	14.08 (3.57)
	Dual-task	18.82 (7.00)	20.52 (6.93)
Percent correct, %[b]	Single-task	94.44 (10.45)	95.83 (11.11)
	Dual-task	91.31 (13.75)	90.65 (12.92)
Response rate, responses per second	Single-task	0.40 (0.16)	0.40 (0.15)
	Dual-task	0.41 (0.20)	0.42 (0.17)
Dual task cost[c]			
Gait time	-	-0.39 (0.26)	-0.42 (0.27)
Percent correct	-	-0.02 (0.12)	-0.03 (0.11)
Response rate[d]	-	0.06 (0.22)	-0.04 (0.22)

[a] Median (interquartile range).
[b] Main effect of condition ($P < 0.05$).
[c] Calculated as described in equation 1.
[d] Athletes with a concussion history had better dual-task cost response-rate compared with controls ($P = 0.01$).

Dual-task tandem gait time was significantly slower, and dual-task tandem gait percent correct was significantly worse compared with their respective single-task conditions, regardless of group.

The single-task gait time, for both groups, was significantly correlated with CNS Vital Signs motor and psychomotor speed domains. Although CNS Vital Signs assesses cognition, these tasks may be considered less cognitive and more motor-centric. For instance, the motor task requires tapping the space bar as quickly as possible. Athletes with a concussion history displayed unique correlations with complex attention, cognitive flexibility, and executive function, and dual-task tandem gait time. Both groups displayed reaction time correlations with dual-task tandem gait time. CNS Vital Signs generally defines complex attention, cognitive flexibility, and executive function as the ability to handle/manipulate multiple streams of information in various manners. Dual-task during gait is the process of handling both a cognitive and motor task, but the correlations were not significant for controls. Previous research associating cognition with static balance (Sensory Organization Test) speculated that their results indicate a shared neural process,[57] and the same may be true in our study. This shared neural process may not exist until the concussion occurs (although we do not have preconcussion data to confirm). For example, the prefrontal cortex displays higher activation during a squatting task and a cognitive task compared with matched controls.[14,56] The prefrontal cortex is responsible for various aspects of cognition and complex movement preparation but not the movement itself.[48] However, the greater activation may represent an increased need for cognitive input during movement postconcussion. Similar results are seen after an anterior cruciate ligament injury.[19]

There was no significant moderation of time between concussion testing for any of the significant correlations. Functional changes within the brain may persist well into adulthood after a concussion. For instance, greater cortical inhibition as measured with transcranial magnetic stimulation is displayed acutely and up to 30 years postconcussion.[13,54] Prolonged p300 latency (electroencephalography measure of attention) is similarly displayed years postconcussion.[29] Although symptoms, balance, and other common concussion ailments may resolve, certain underlying functional mechanisms, and in our study correlations, persist. Our results from this study agree with a previous study that showed unique correlations between cognition and landing biomechanics an average of 461 days postconcussion compared with controls.[2]

Our results demonstrate an association between cognition and movement (tandem gait) that also occurs in instances of neural deterioration such as the natural aging process. Specifically, cognition is related to both gait speed and fall risk in older adults,[23,45] whereas they are not related among young adults.[45] Concussions have been hypothesized to speed up the aging process,[5] and are associated with an increased risk of developing neurodegenerative diseases.[4,31] In addition, the unique correlations may represent shared neural resources.[57] This potentially indicates neither cognitive nor motor functions are easily accessible postconcussion leading to an increased risk for musculoskeletal injury.[38,50] The shared neural resources may also represent a break in the automaticity of a task postconcussion due to the task requiring greater cognitive input.[3,46] Training concepts have been hypothesized to improve the automaticity of tasks,[3] but none have been tested empirically postconcussion.

Several limitations are present. First, concussion history was self-reported. Although we followed a similar protocol to previous research,[6] self-reported concussion history may have influenced our findings. Second, we did not have any record of musculoskeletal injury history. Acute or chronic lingering impairments from a musculoskeletal injury may have influenced our results as they often display their own unique correlations.[19] Third, we did not have preconcussion data so we cannot define cause and effect. Lastly, we used clinically friendly measures of tandem gait and dual-task outcomes. More sensitive measures of gait may offer insight into more prolonged deficits postconcussion.[34]

In conclusion, athletes with a concussion history display unique correlations between tandem gait and cognition. These correlations were unaffected by the time since concussion and may represent shared neural resources between cognitive and motor function[57]; however, confounding factors such as a previous musculoskeletal injury, data on which was not collected in our study, may have influenced our results. Clinically, this may represent a break in the automaticity of movements; however, further research is needed to determine the underlying mechanisms.

CLINICAL RECOMMENDATION

Concussions moderate the relationship between cognition and tandem gait performance long term after the initial injury. Clinicians should ensure that dual-task performances have fully recovered. Future research should continue to evaluate the impact these unique correlations may have on various behavioral outcomes such as the increased risk of musculoskeletal injury and neurodegenerative pathologies.[4,31,38,50]

ACKNOWLEDGMENT

The authors would like to thank Emily Miller, Landon Lempke, Rachel Johnson, Rachel Le, and Melissa Anderson for their help in the data collection process.

ORCID IDS

Julianne D Schmidt https://orcid.org/0000-0002-9363-1391
Robert C Lynall https://orcid.org/0000-0002-0785-6640

REFERENCES

1. Ataullah AHM, Naqvi IA. Cerebellar dysfunction. In: *StatPearls*. StatPearls Publishing; 2022.
2. Avedesian JM, Covassin T, Baez S, Nash J, Nagelhout E, Dufek JS. Relationship between cognitive performance and lower extremity biomechanics: implications for sports-related concussion. *Orthop J Sports Med*. 2021;9(8):23259671211032250.
3. Avedesian JM, Singh H, Diekfuss JA, Myer GD, Grooms DR. Loss of motor stability after sports-related concussion: opportunities for motor learning strategies to reduce musculoskeletal injury risk. *Sports Med Auckl NZ*. 2021;51(11):2299-2309.
4. Brett BL, Kerr ZY, Aggarwal NT, et al. Cumulative concussion and odds of stroke in former National Football League players. *Stroke*. Published online November 29, 2021. doi:10.1161/STROKEAHA121035607.
5. Broglio SP, Eckner JT, Paulson HL, Kutcher JS. Cognitive decline and aging: the role of concussive and subconcussive impacts. *Exerc Sport Sci Rev*. 2012;40(3):138-144.
6. Broglio SP, Kontos AP, Levin H, et al. National Institute of Neurological Disorders and Stroke and Department of Defense sport-related concussion common data elements Version 1.0 recommendations. *J Neurotrauma*. 2018;35(23):2776-2783.
7. Burris K, Vittetoe K, Ramger B, et al. Sensorimotor abilities predict on-field performance in professional baseball. *Sci Rep*. 2018;8(1):116.
8. Büttner F, Howell DR, Ardern CL, et al. Concussed athletes walk slower than non-concussed athletes during cognitive-motor dual-task assessments but not during single-task assessments 2 months after sports concussion: a systematic review and meta-analysis using individual participant data. *Br J Sports Med*. 2020;54(2):94-101.
9. Cassidy JD, Carroll LJ, Peloso PM, et al. Incidence, risk factors and prevention of mild traumatic brain injury: results of the WHO Collaborating Centre Task Force on Mild Traumatic Brain Injury. *J Rehabil Med*. 2004;(43 Suppl):28-60.
10. CNS Vital Signs - FAQs. https://www.cnsvs.com/FAQs.html. Accessed March 16, 2022
11. Cohen J. *Statistical Power Analysis for the Behavioral Sciences*. 2nd ed. New York: L. Erlbaum Associates; 1988.
12. Dauty M, Collon S, Dubois C. Change in posture control after recent knee anterior cruciate ligament reconstruction? *Clin Physiol Funct Imaging*. 2010;30(3):187-191.
13. De Beaumont L, Théoret H, Mongeon D, et al. Brain function decline in healthy retired athletes who sustained their last sports concussion in early adulthood. *Brain*. 2009;132(3):695-708.
14. Dettwiler A, Murugavel M, Putukian M, Cubon V, Furtado J, Osherson D. Persistent differences in patterns of brain activation after sports-related concussion: a longitudinal functional magnetic resonance imaging study. *J Neurotrauma*. 2014;31(2):180-188.
15. Fine EJ, Ionita CC, Lohr L. The history of the development of the cerebellar examination. *Semin Neurol*. 2002;22(4):375-384.
16. Fino PC, Nussbaum MA, Brolinson PG. Locomotor deficits in recently concussed athletes and matched controls during single and dual-task turning gait: preliminary results. *J NeuroEngineering Rehabil*. 2016;13(1):65.
17. Fregni F, Boggio PS, Nitsche M, et al. Anodal transcranial direct current stimulation of prefrontal cortex enhances working memory. *Exp Brain Res*. 2005;166(1):23-30.
18. Goh H-T, Connolly K, Hardy J, McCain K, Walker-Batson D. Single session of repetitive transcranial magnetic stimulation to left dorsolateral prefrontal cortex increased dual-task gait speed in chronic stroke: a pilot study. *Gait Posture*. 2020;78:1-5.
19. Grooms DR, Diekfuss JA, Slutsky-Ganesh AB, et al. Preliminary report on the train the brain project: neuroplasticity of augmented neuromuscular training and improved injury risk biomechanics - part II. *J Athl Train*. 2022;57(9-10):911-920.
20. Gualtieri CT, Johnson LG. Reliability and validity of a computerized neurocognitive test battery, CNS Vital Signs. *Arch Clin Neuropsychol*. 2006;21(7):623-643.
21. Guse B, Falkai P, Wobrock T. Cognitive effects of high-frequency repetitive transcranial magnetic stimulation: a systematic review. *J Neural Transm (Vienna)*. 2010;117(1):105-122.
22. Herman DC, Barth JT. Drop-jump landing varies with baseline neurocognition: implications for anterior cruciate ligament injury risk and prevention. *Am J Sports Med*. 2016;44(9):2347-2353.
23. Holtzer R, Friedman R, Lipton RB, Katz M, Xue X, Verghese J. The relationship between specific cognitive functions and falls in aging. *Neuropsychology*. 2007;21(5):540-548.
24. Howell DR, Brilliant A, Berkstresser B, Wang F, Fraser J, Meehan WP. The association between dual-task gait after concussion and prolonged symptom duration. *J Neurotrauma*. 12;34(23):3288-3294.
25. Howell DR, Brilliant AN, Meehan WP. Tandem gait test-retest reliability among healthy child and adolescent athletes. *J Athl Train*. 2019;54(12):1254-1259.
26. Howell DR, Oldham JR, Meehan WPI, DiFabio MS, Buckley TA. Dual-task tandem gait and average walking speed in healthy collegiate athletes. *Clin J Sport Med*. 2019;29(3):238-244.
27. Hunt TN, Ferrara MS, Bornstein RA, Baumgartner TA. The reliability of the modified Balance Error Scoring System. *Clin J Sport Med*. 2009;19(6):471-475.

28. Ko JH, Monchi O, Ptito A, Petrides M, Strafella AP. Repetitive transcranial magnetic stimulation of dorsolateral prefrontal cortex affects performance of the Wisconsin card sorting task during provision of feedback. *Int J Biomed Imaging*. 2008;2008:143238.
29. Ledwidge PS, Molfese DL. Long-term effects of concussion on electrophysiological indices of attention in Varsity College Athletes: an event-related potential and standardized low-resolution brain electromagnetic tomography approach. *J Neurotrauma*. 2016;33(23):2081-2090.
30. Lempke LB, Howell DR, Eckner JT, Lynall RC. Examination of reaction time deficits following concussion: a systematic review and meta-analysis. *Sports Med*. 2020;50(7):1341-1359.
31. Li Y, Li Y, Li X, et al. Head injury as a risk factor for dementia and Alzheimer's disease: a systematic review and meta-analysis of 32 observational studies. *PLoS ONE*. 2017;12(1):e0169650.
32. Manor B, Zhou J, Harrison R, et al. Transcranial direct current stimulation may improve cognitive-motor function in functionally limited older adults. *Neurorehabil Neural Repair*. 2018;32(9):788-798.
33. Manor B, Zhou J, Jor'dan A, Zhang J, Fang J, Pascual-Leone A. Reduction of dual-task costs by noninvasive modulation of prefrontal activity in healthy elders. *J Cogn Neurosci*. 2016;28(2):275-281.
34. Martini DN, Sabin MJ, DePesa SA, et al. The chronic effects of concussion on gait. *Arch Phys Med Rehabil*. 2011;92(4):585-589.
35. McClincy MP, Lovell MR, Pardini J, Collins MW, Spore MK. Recovery from sports concussion in high school and collegiate athletes. *Brain Inj*. 2006;20(1):33-39.
36. McCrea M. Standardized mental status assessment of sports concussion. *Clin J Sport Med*. 2001;11(3):176-181.
37. McCrea M, Kelly JP, Randolph C, et al. Standardized assessment of concussion (SAC): on-site mental status evaluation of the athlete. *J Head Trauma Rehabil*. 1998;13(2):27-35.
38. McPherson AL, Nagai T, Webster KE, Hewett TE. Musculoskeletal injury risk after sport-related concussion: a systematic review and meta-analysis. *Am J Sports Med*. 2019;47(7):1754-1762.
39. Mishra RK, Thrasher AT. Transcranial direct current stimulation of dorsolateral prefrontal cortex improves dual-task gait performance in patients with Parkinson's disease: a double blind, sham-controlled study. *Gait Posture*. 2021;84:11-16.
40. Mishra RK, Thrasher AT. Effect of concurrent transcranial direct current stimulation on instrumented timed up and go task performance in people with Parkinson's disease: a double-blind and cross-over study. *J Clin Neurosci*. 2022;100:184-191.
41. Murray NG, Moran R, Islas A, et al. Sport-related concussion adopt a more conservative approach to straight path walking and turning during tandem gait. *J Clin Transl Res*. 2021;7(4):443-449.
42. Murray NG, Szekely B, Islas A, et al. Smooth pursuit and saccades after sport-related concussion. *J Neurotrauma*. 2020;37(2):340-346.
43. Okuda K, Abe N, Katayama Y, Senda M, Kuroda T, Inoue H. Effect of vision on postural sway in anterior cruciate ligament injured knees. *J Orthop Sci*. 2005;10(3):277-283.
44. Oldham JR, Howell DR, Knight CA, Crenshaw JR, Buckley TA. Single-task and dual-task tandem gait performance across clinical concussion milestones in collegiate student-athletes. *Clin J Sport Med*. 2021;31(6):e392-e397.
45. Oliveira AS, Reiche MS, Vinescu CI, et al. The cognitive complexity of concurrent cognitive-motor tasks reveals age-related deficits in motor performance. *Sci Rep*. 2018;8(1):6094.
46. Poldrack RA, Sabb FW, Foerde K, et al. The neural correlates of motor skill automaticity. *J Neurosci*. 2005;25(22):5356-5364.
47. Porter K, Quintana C, Hoch M. The relationship between neurocognitive function and biomechanics: a critically appraised topic. *J Sport Rehabil*. 2020;30(2):327-332.
48. Prefrontal Cortex - an overview | ScienceDirect Topics2. https://www.sciencedirect.com/topics/medicine-and-dentistry/prefrontal-cortex. Accessed September 6, 2022
49. Rahman-Filipiak AA, Woodard JL. Administration and environment considerations in computer-based sports-concussion assessment. *Neuropsychol Rev*. 2013;23(4):314-334.
50. Reneker JC, Babl R, Flowers MM. History of concussion and risk of subsequent injury in athletes and service members: a systematic review and meta-analysis. *Musculoskelet Sci Pract*. 2019;42:173-185.
51. Romano J, Kromrey J, Coraggio J, Skowronek J, Devine L. Exploring methods for evaluating group differences on the NSSE and other surveys: are the t-test and Cohen's d indices the most appropriate choices? *Annu Meet South Assoc Institutional Res*. 2006;13.
52. Schmahmann JD, Sherman JC. The cerebellar cognitive affective syndrome. *Brain J Neurol*. 1998;121(4):561-579.
53. Schober P, Boer C, Schwarte LA. Correlation coefficients: appropriate use and interpretation. *Anesth Analg*. 2018;126(5):1763.
54. Scott E, Kidgell DJ, Frazer AK, Pearce AJ. The neurophysiological responses of concussive impacts: a systematic review and meta-analysis of transcranial magnetic stimulation studies. *Front Hum Neurosci*. 2020;14:306.
55. Shibata S, Takemura M, Miyakawa S. The influence of differences in neurocognitive function on lower limb kinematics, kinetics, and muscle activity during an unanticipated cutting motion. *Phys Ther Res*. 2018;21(2):44-52.
56. Sirant LW, Singh J, Martin S, et al. Long-term effects of multiple concussions on prefrontal cortex oxygenation during repeated squat-stands in retired contact sport athletes. *Brain Inj*. 2022;36(8):931-938.
57. Sosnoff JJ, Broglio SP, Ferrara MS. Cognitive and motor function are associated following mild traumatic brain injury. *Exp Brain Res*. 2008;187(4):563-571.
58. Van Deventer KA, Seehusen CN, Walker GA, Wilson JC, Howell DR. The diagnostic and prognostic utility of the dual-task tandem gait test for pediatric concussion. *J Sport Health Sci*. 2021;10(2):131-137.
59. Vanderhasselt M-A, De Raedt R, Baeken C, Leyman L, D'haenen H. The influence of rTMS over the left dorsolateral prefrontal cortex on Stroop task performance. *Exp Brain Res*. 2006;169(2):279-282.
60. Wobbrock JO, Findlater L, Gergle D, Higgins JJ. The aligned rank transform for nonparametric factorial analyses using only ANOVA procedures. In: *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*. ACM; 2011:143-146.
61. Zuckerman SL, Kerr ZY, Yengo-Kahn A, Wasserman E, Covassin T, Solomon GS. Epidemiology of sports-related concussion in NCAA athletes from 2009-2010 to 2013-2014: incidence, recurrence, and mechanisms. *Am J Sports Med*. 2015;43(11):2654-2662.