

Original article

Evidence of a conservative gait strategy in athletes with a history of concussions

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Abstract

Background: A history of 3 or more concussions is frequently associated with numerous short- and long-term neuropathologies. Impairments in postural control are a known acute consequence of concussion; however, limited evidence exists on the effects of multiple concussions on gait. The purpose of this study was to assess gait stepping characteristics in collegiate aged student-athletes based on concussion history.

Methods: There were 63 participants divided into 3 even groups based on concussion history: ≥ 3 concussions, 1–2 concussions, and 0 concussion. All participants completed 10 trials of gait on a 4.9 m instrumented walkway. The dependent variables of interest included both gait stepping characteristics (step velocity, length, and width, double support time, and the percentage of the gait cycle in stance) and coefficient of variability (CoV) measures (step length, time, and width). The gait stepping characteristics were compared first with a MANOVA with follow-up 1-way ANOVAs and Tukey *post hoc* tests as appropriate. The CoV measures were compared with 1-way ANOVAs and Tukey *post hoc* tests.

Results: There were main effects for group for step velocity, length, width, and double support time. Overall, the 0 concussion group displayed typical healthy young gait parameters and performed significantly better than either concussion group. The 0 concussion group had a significantly greater step length CoV, but there were no differences in the step time or width CoV.

Conclusion: This finding provides evidence of subtle impairments in postural control during gait among individuals with prior history of concussion which could be an early indicator of future neurological deficiencies. The limited difference in the variability measures is consistent with prior static stance studies and could suggest the individuals constrain their motor systems to reduce variability. Taken together, these findings suggest a conservative gait strategy which is adopted by individuals with a history of concussions.

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1. Introduction

A specific causative relationship between concussion history and later life neuropathology has not been definitively identified.¹ Long-term population-based studies have found inconsistent results; however, these studies are generally limited to small populations, chart reviews, or self-reported patient information. Among retired National Football League (NFL) players, there was a self-reported increased risk of clinically

diagnosed depression and mild cognitive impairment in individuals with a lifetime history of 3 or more concussions.^{2,3} NFL players also had a higher neurodegenerative related mortality rate than the general public.⁴ Further, while the specific neuropathology and epidemiology remain debated, multiple case reports have identified the presence of chronic traumatic encephalopathy in deceased collision sport athletes.^{5–7} In military settings, there was a positive relationship between increased number of mild traumatic brain injuries and increased risk of depression, post-traumatic stress disorder, and suicide risk; however, this may not be independent of other confounding variables.^{8,9} Conversely, others have reported limited evidence of neurological impairment in either a population-based study or a patient-based neurological examination.^{10–12}

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Similar to the later life issues, there have been inconsistent results when assessing short-term potential impairments in younger individuals with a history of multiple concussions. Multiple studies suggest that prior concussion history is associated with increased likelihood of future concussion, a worse initial post-concussion presentation, and prolonged recovery of recurrent concussion.^{13–15} A history of concussions does not adversely affect performance on computerized neuropsychological testing in high school or collegiate aged individuals.^{16–20} The effect of previous concussions on self-reported symptoms has been split with findings of both increased symptoms and no differences.^{17,21} Prior concussion history has been associated with altered electrophysiological responses months to even years following the last concussion.^{22–24} Finally, a history of at least 3 concussions has been associated with lower quality of life; specifically bodily pain, vitality, social functioning, and headache.²⁵

Impairments in both static and dynamic postural control are a known acute consequence of concussion.^{26,27} Standard clinical testing, utilizing non-instrumented static challenges, suggests recovery within 1 week of injury.^{26,27} However, laboratory based investigations, assessing transitional and dynamic postural control, suggest these impairments may persist far longer.^{28–33} Altered gait stepping kinematics have been identified to persist for up to 1 month following a concussion.^{29,30,34–39} In individuals with a history of at least 1 concussion, both a conservative gait strategy, defined as reduced gait velocity and increased time in double support, and altered postural control dynamics have been identified.^{40,41} The underlying pathophysiological mechanism for this strategy in individuals has not elucidated, but Martini et al.⁴⁰ speculated a strategy to reduce their time in less stable positions. This is consistent with acute and sub-acute concussive gait studies which have identified conservative gait strategies marked by reduced step and center of mass (COM) velocity, shorter steps, increased time in double support, and reduced separation of the center of pressure (COP) and COM which is suggestive of incomplete physiological recovery.^{29,30,34–38,42–44}

There is no agreed upon number of concussions which result in neurological impairment; however, a history of at least 3 concussions appears to be frequently associated with numerous deficits.^{2,3,22,25} Previous gait studies have either utilized acute post-concussion participants or non-athletes with a history of at least 1 concussion.^{28–30,34–40,42–44} However, the relationship between concussion history and performance on gait tasks has received limited attention and could be an important marker of neurological consequences of concussion. Therefore, the purpose of this study was to assess gait stepping characteristics in student-athletes with differing concussion history; specifically, 1) 3 or more concussions (≥ 3), 2) 1 or 2 concussions (1–2), and 3) 0 concussion (0). We hypothesized the participants with a history of at least 3 concussions would present with impaired gait characteristics and exhibit a conservative gait strategy compared to the 0 concussion group and the 1–2 concussions group would fall along a range between the 0 and ≥ 3 groups.

2. Methods

2.1. Participants

Sixty-three National Collegiate Athletic Association (NCAA) Division I student-athletes were recruited at 2 separate universities by members of the research team for the study. The participants were divided into 3 groups based on their concussion history (≥ 3 , 1–2, 0). The 0 concussion group was selected from a larger database of potential participants by tightly matching the gender, sport, and demographics of the ≥ 3 concussion group. The 1–2 concussions group was then matched upon the same criteria and there were no differences between groups for any demographic variable except concussion history (Table 1). Participants were excluded if they had prior or current orthopedic injury which would impair postural control, or any self-reported balance, psychiatric, visual, or vestibular deficits. All participants in the concussion groups were at least 3 months

Table 1
Participants' demographics (mean \pm SD) and sports by group.

	≥ 3 concussions ($n = 21$)	1–2 concussions ($n = 21$)	0 concussion ($n = 21$)
Demographic			
Gender (male/female)	12/9	12/9	12/9
Age (year)	19.7 \pm 1.3	18.9 \pm 1.2	19.7 \pm 1.3
Height (cm)	176.1 \pm 14.9	176.9 \pm 9.7	176.7 \pm 12.1
Weight (kg)	84.1 \pm 23.7	77.0 \pm 15.5	83.7 \pm 19.5
Concussion history (range)	3.7 \pm 1.3 (3–8)	1.5 \pm 0.5 (1–2)	0 \pm 0
Sport			
Football	10	7	8
Women's soccer	3	3	3
Baseball	1	4	4
Cheerleading	2	1	1
Softball	2	0	2
Men's basketball	2	1	0
Rifle	0	0	2
Women's volleyball	0	2	0
Track and field	1	0	0
Swim and dive	0	1	0
Women's basketball	0	1	1
Women's tennis	0	1	0

post-concussion, denied lingering concussion related symptoms, and were fully engaged in their activities of daily living. All participants provided written informed consent as approved by Georgia Southern University and Elon University Institutions' Review Board. There were no significant differences for age ($p = 0.08$), height ($p = 0.986$), or weight ($p = 0.342$) and exploratory *post hoc* analysis identified no differences between groups. As expected based on inclusion criterion, there was a main effect for concussion history ($F = 105.78$; $p < 0.001$) and *post hoc* testing identified differences at each level ($p < 0.001$). There were no differences for group participation in concussion high risk (football, soccer, basketball, and cheerleading) and low risk (softball, baseball, track and field, swim and dive, and rifle) sports ($F = 1.159$, $p = 0.321$). Exploratory *post hoc* testing failed to identify any between-group differences.

2.2. Instrumentation

The gait characteristics were assessed using identical 4.9 m GAITRite instrumented walkways (CIR Systems, Sparta, NJ, USA). The GAITRite is a reliable (intraclass correlation coefficient (ICC): 0.80–0.98) and valid (ICC: 0.92–0.99, compared to motion capture and a clinical stride analyzer) portable walkway gait analysis system with 18,432 sensors over a 0.6 m (W) \times 4.9 m (L) grid that detect footfalls as the participant progresses its length.^{45,46} The walkway was connected to a computer through a USB cable and program software calculated common spatiotemporal parameters of gait. The GAITRite mat was positioned such that participants had 2–2.5 m of space to walk at both ends of the walkway.

2.3. Procedures

Each potential participant completed a health history questionnaire and personal interview with a member of the research team in order to ensure that inclusion and exclusion criteria were achieved. Data collection was completed in a single testing session in each institution's respective gait laboratory.

The participants were dressed in comfortable athletic clothing and were barefoot for all trials. The participants initiated each trial at least 1 m prior to the walkway and the third step, at the earliest, was the first step to be captured by the GAITRite. Thus, steady state gait would have been achieved prior to contacting the GAITRite walkway.⁴⁷ Participants were instructed to walk at a self-selected pace to a mark located 2.5 m past the end of the walkway. All participants completed 10 trials and were instructed not to talk during the trials in order to avoid dual-tasking effects on gait.

2.4. Data analysis

This was a cross sectional study comparing the gait stepping characteristics and variability measures including step velocity, step length, step width, double support time, and the percentage of the gait cycle in stance averaged from both limbs. Step velocity was defined as the ratio of the distance covered to time taken to cover the distance. Step length was defined as the antero-posterior distance between heel position of ipsilateral foot and the heel position of the contralateral foot at the heel

strike of the ipsilateral foot. Step width was defined as the medio-lateral distance between heel position of ipsilateral foot and the heel position of the contralateral foot at the heel strike of the ipsilateral foot. Double support time was defined as the time both the legs were contact with the ground during the gait cycle. The percentage of gait cycle in stance was defined as the percentage of time spent on a single leg (stance phase) during gait cycle. The mean of the 10 trials was used for computing the gait stepping characteristics measures.⁴⁸ For variability measures (step length, time, and width) coefficient of variation (CoV = $SD/mean \times 100$) was used. The CoV provides a meaningful method of comparing the variability among different dependent measures as it is both dimensionless as well as normalized around the mean and has been frequently utilized in the gait literature.^{49,50}

2.5. Statistical analysis

As gait stepping characteristics are interrelated, all stepping data were first compared with a multiple analysis of variance (MANOVA).⁵¹ Once significance was identified overall, 1-way analysis of variance (ANOVA) was performed to compare each of the stepping dependent variables between groups. If main effects for group were identified, a Tukey *post hoc* test was performed to identify the between-group differences. The CoV dependent variables of interest are independent of each other and therefore were compared with 1-way ANOVAs and, when a significant main effect was identified, followed with Tukey *post hoc*. The *a priori* α level was set at 0.05.

3. Results

The overall MANOVA was significant for gait stepping characteristics ($F(10, 112) = 5.09$, $p < 0.001$, $\eta^2 = 0.31$). There was a significant main effect in the gait stepping characteristics for step velocity ($F = 9.07$, $p < 0.001$, $\eta^2 = 0.23$), step length ($F = 4.861$, $p = 0.011$, $\eta^2 = 0.14$), step width ($F = 9.544$, $p < 0.001$, $\eta^2 = 0.24$), and double support time ($F = 4.407$, $p = 0.016$, $\eta^2 = 0.13$) (Table 2). There was no main effect for the stance percentage of the gait cycle ($F = 1.212$, $p = 0.305$). Step velocity *post hoc* testing identified differences between the 0 concussion group and both the 1–2 concussions group ($p < 0.001$) and the ≥ 3 concussions group ($p = 0.028$), but no difference between the 1–2 and ≥ 3 concussions groups ($p = 0.263$). Step length *post hoc* testing identified differences between the 0 concussion group and both the 1–2 concussions group ($p = 0.016$) and the ≥ 3 concussions group ($p = 0.038$), but no difference between the 1–2 and ≥ 3 concussions groups ($p = 0.940$). Step width *post hoc* testing identified significant differences between ≥ 3 concussions and both 0 concussions ($p = 0.025$) and 1–2 concussions ($p < 0.001$), but no difference between 0 concussions and 1–2 concussions ($p = 0.238$). Double support time *post hoc* testing identified significant differences between 0 concussion and both 1–2 concussions ($p = 0.049$) and ≥ 3 concussions ($p = 0.024$), but no difference between 1–2 concussions and ≥ 3 concussions ($p = 0.952$) (Table 2).

For CoV measures, there was a significant main effect for step length CoV ($F = 18.144$, $p < 0.001$, $\eta^2 = 0.38$), but no

Table 2
Gait stepping characteristics results (mean \pm SD).

	0 concussions	1–2 concussions	≥ 3 concussions	Main effect (<i>p</i> value)
Step length (m)	0.73 \pm 0.04	0.68 \pm 0.05 [†]	0.69 \pm 0.06 [†]	0.011
Step velocity (m/s)	1.43 \pm 0.13	1.25 \pm 0.15 [†]	1.32 \pm 0.13 [†]	<0.001
Step width (cm)	12.0 \pm 3.2*	10.3 \pm 3.2*	14.7 \pm 3.5	<0.001
Double support time (s)	0.21 \pm 0.03	0.25 \pm 0.04 [†]	0.25 \pm 0.03 [†]	0.016
Stance %	60.6 \pm 1.3	61.1 \pm 1.4	61.2 \pm 1.3	0.305

* Significantly different from ≥ 3 concussions group.

[†] Significantly different from 0 concussion group.

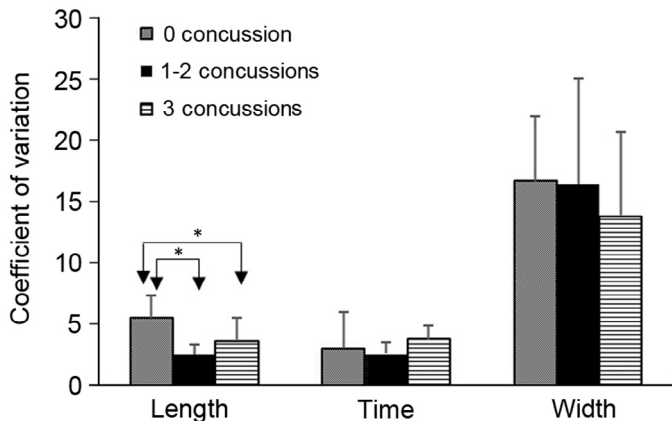


Fig. 1. Gait coefficient of variation. *Significant group differences on *post hoc* testing.

differences for step time CoV ($F = 1.973$, $p = 0.148$) or step width CoV ($F = 1.074$, $p = 0.348$). Step length *post hoc* analysis identified a significantly higher CoV for the 0 concussion group compared to both the 1–2 concussions group (5.51 \pm 1.87 vs. 2.55 \pm 0.76, respectively, $p < 0.001$) and the ≥ 3 concussions group (5.51 \pm 1.87 vs. 3.59 \pm 1.93, $p = 0.001$) (Fig. 1).

4. Discussion

The effect of multiple concussions on neurological function in student-athletes is an emerging research area with inconsistent findings to date. While the majority of studies have investigated neuropsychological or general neurological functioning, there has been limited investigation of postural control among collegiate student-athletes with varying concussion histories. The primary finding of this study was the presence of a conservative gait strategy among student-athletes with a concussion history. Interestingly, while both concussion groups performed worse than the 0 concussion group on the majority of gait stepping characteristics, there was only a significant difference in 1 dependent variable, step width, between the ≥ 3 and 1–2 concussions groups. These differences, albeit subtle as indicated by the small effect sizes, could be early indicators of potential later life neuropathological concussion related sequella.

A conservative gait strategy, characterized by reduced step velocity, increased step width, reduced step length and longer durations in double support phase, has been identified in acute,

subacute, and chronic post-concussion individuals.^{30,31,34,35,40} Both concussion history groups herein demonstrated varying degrees of conservative gait strategies whereas the 0 concussion group had typical healthy gait performance (e.g., step velocity = 1.43 m/s, step length = 0.73 m, stance percentage = 60.6%). Indeed, the multiple concussions group's step velocity (1.25–1.32 m/s) was closer to acute (1.23 m/s) and subacute (1.30 m/s) populations than chronic post-concussion participants (1.46 m/s).^{35,40} Interestingly, the chronic (6-year post-concussion) participants' step velocity on single task unobstructed gait exceeded the 0 concussion group in this study (1.46 m/s and 1.43 m/s, respectively); however, Martini et al.⁴⁰ utilized non-athletes and some evidence exists to suggest that, on average, athletes have slower gait velocities than non-athletes.²⁹ While step velocity may have driven many of the additional findings, the multiple concussions groups herein also had a 4–5 cm reduction in step length and the ≥ 3 concussions group had an increased step width which were both similar to findings of acute and subacute post-concussion individuals.^{29,42–44} The percentage of time spent in double support for the multiple concussions participants was also similar with non-athletes with a concussion history.⁴⁰ These findings suggest the concussion groups' conservative gait strategy was likely in an effort to maximize stable (e.g., more time in double support) gait patterns.⁴⁰

The specific neurological rationale underlying the conservative gait strategy has not been fully elucidated. One proposed explanation suggests concussions result in long-term neuronal and axonal damage with reduced synaptic plasticity.⁵² Supporting this hypothesis, De Beaumont et al.^{24,53,54} have reported abnormalities in the primary motor cortex resulting in alteration of motor planning and control in individuals with a history of concussions. More acutely, altered motor control strategies, independent of step velocity, have been noted during gait termination despite apparent recovery on clinical concussion measures.²⁸ Alternatively, routine participation in collision athletics (e.g., football, ice hockey, and soccer) results in numerous head impacts that do not elicit concussion symptoms and are thus referred to as “subconcussive blows”. These subconcussive impacts may cause acute neurophysiological deficits and have been speculated, but not proven, to result in long-term neurodegeneration including chronic traumatic encephalopathy.^{55–57}

Physiological variability was previously considered as an unwanted “noise” in biological systems; however, recent studies

have shown that variability is inherent in our system.^{58,59} Indeed, a certain amount of variability present in physiological signals like heart rate often indicates a healthy system.^{60,61} However, in gait analysis, excessive variability is indicative of increased fall risk in the elderly and is a marker of multiple neurological disorders including Parkinson's disease, Huntington's disease, and multiple sclerosis.⁶²⁻⁶⁶ Following a concussion, increased swing time variability has been identified both acutely and nearly 1 month post-injury which was suggestive of incomplete recovery.³⁹ Conversely, Cavanaugh et al.^{67,68} repeatedly identified reduced variability in approximate entropy during static stance post-concussion and suggested that decreased brain region coupling could increase the regularity of the cortical oscillations. Finally, Sosnoff et al.⁴¹ suggested variability could be specific to the difficulty of the task. Herein, and contrary to the study hypothesis, the participants with 0 concussion had increased step length variability, but still below the 7% CoV postulated threshold, compared to either concussion history group and there were no differences noted in step time or width variability.⁶⁹ This finding, in agreement with Cavanaugh et al.,^{67,68} suggests a post-concussion strategy to constrain their motor systems to reduce variability. This reduced gait variability along with slower step velocity and shorter step lengths together suggest a conservative gait strategy employed by the multiple concussions groups, particularly the ≥ 3 concussions group; however, the physiological rationale for this strategy was beyond the scope of this study and requires further investigation.

The number of steps required to calculate valid and reliable variability measures is inconsistent in the literature with recommendations up to 400 steps.⁷⁰ However, gait variability measures have been calculated from as few as 3–5 steps; nonetheless, the 4.9 m length of the instrumented walkway, allowing approximately 7 steps per trial, utilized in this study may have been a limitation.^{49,50} The participants were tightly matched based on demographic characteristics and there were no group differences; however, leg length was not measured and thus absolute, not relative, stepping data are presented herein. Further, self-reporting of concussion history, while common in the literature, has only moderate reliability which could have resulted in participants being grouped incorrectly; however, the research team extensively interviewed participants in an effort to minimize this limitation.⁷¹ This study investigated college aged NCAA Division I student-athletes only so the results may not be extrapolated to other populations (e.g., high school). Future studies should address these limitations as well as expand the testing protocol to move beyond gait to incorporate additional motor and cognitive challenges (e.g., transitional movements, athletic related activities, and similar) to postural control. Finally, while logistically challenging, serial tracking of individuals with extensive concussion histories would substantially improve the scientific understanding of the sequella.

5. Conclusion

The primary finding of this study was an apparent conservative gait strategy (slower step velocity, shorter steps, wider

step width, and increased time in double support with decreased step length variability) adopted by individuals with a history of concussions. These findings are suggestive of an either persistent deficit in post-concussion postural control or as a canary in a coal mine early indicator of neurological consequences of multiple concussions. Previous concussion history is an established predictor of future concussion, and perhaps non-concussive sport related injury, and the impaired postural control identified herein could be a contributing factor to be considered in future studies.^{14,72}

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Authors' contributions

All authors were involved in the development of this manuscript. TAB was responsible for the conception, overall project design, assisted in data collection and analysis, was primarily responsible for data interpretation, and drafted the manuscript. SV, CJK, and EEH were responsible for data collection, analysis, and interpretation at the second site involved in the study and provided feedback on the manuscript. SV and EEH were also involved in the overall project design. JRO was involved in data collection, analysis, and interpretation and helped draft the manuscript. BAM, KME, and DAK were involved in the data collection, analysis, and interpretation from one of the project sites and provided feedback on the manuscript. BAM and DAK were also involved in the conception and design of the project. All authors have read and approved the final version of the manuscript, and agree with the order of presentation of the authors.

Competing interest

None of the authors declare competing financial interests.

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