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Youth With Concussion Have Less Adaptable Gait Patterns Than Their Uninjured Peers: Implications for Concussion Management

Concussion,[32] a traumatic brain injury induced by biomechanical forces, affects different neurological functions.[12] Motor function evaluations are not commonly used to identify concussion-related impairments,[1] but may help to objectively evaluate health status,[44] adding value beyond traditional concussion assessments.[14,15] Gait dysfunction is common after concussion.[6,10,24] A dual-task paradigm (ie, completing 2 tasks simultaneously) is a way to assess gait coordination[8,34] and to identify motor control deficits, despite resolution by other clinical measures.[18-20] Within the first 48 hours of concussion, people also exhibit alterations in lower extremity interjoint coordination during gait.[8]

Previous concussion research has used measures that primarily quantify the magnitude of gait variability dysfunction (eg, linear measures, such as mean stride width or average gait speed).[14,15,35] Other approaches quantify the structure of gait variability[37]—the subtle changes in stride-to-stride fluctuations that are ever present in gait. Measures of magnitude

OBJECTIVE: To compare cross-recurrence quantification analysis measurements obtained during gait between adolescents who sustained a diagnosed concussion within 14 days of assessment and healthy adolescents.

DESIGN: Cross-sectional study.

METHODS: Youth athletes with concussion (n = 43; mean ± SD age, 14.4 ± 2.3 years; 56% female; tested median, 7 days post concussion) and healthy controls (n = 38; age, 14.9 ± 2.0 years; 55% female) completed a single-task and dual-task gait protocol while wearing a set of inertial sensors. We used cross-recurrence quantification analysis techniques to quantify the similarity between accelerations obtained from the sensor on the dorsum of each foot. Four outcome variables were compared between groups: percent determinism, average diagonal-line length, laminarity, and trapping time.

RESULTS: Athletes with concussion had significantly higher percent determinism, laminarity, and trapping time than the control group in single-task and dual-task conditions ($P<.05$). Gait patterns, when simultaneously completing a secondary cognitive task (dual task), were no different from gait patterns under a single-task condition.

CONCLUSION: Higher percent determinism, laminarity, and trapping time among athletes with concussion suggest that concussion may be associated with a more stuck and predictable gait pattern. These altered movement patterns may be one reason for underlying slower gait speeds that have been observed following concussion. *J Orthop Sports Phys Ther 2020;50(8):438-446. Epub 22 May 2020. doi:10.2519/jospt.2020.9133*

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are not sensitive to changes in the structure of gait variability.

Morse code provides an example illustrating the differences between magnitude and structure of gait variability. The pattern (ie, structure) within Morse code conveys the intended message based on the sequence and order of dots and dashes. The letter *a* is signaled by a dot followed by a dash (· –), whereas the letter *n* is signaled by a dash followed by a dot (– ·). Though the codes for these letters contain the same number of dots and dashes, the order of the dots and dashes affects interpretation. In contrast, magnitude is represented by the total number of dots and dashes present within a message. Both *a* and *n* have the same number of dots and dashes, but their location relative to other letters is the important factor for interpretation (structure). If the dots and dashes are randomly shuffled, the meaning is lost. However, the frequency of the dots and dashes does not change if the dots and dashes are shuffled. In this manner, structure analysis provides a method to interpret fluctuations throughout a gait trial, representing adaptability as opposed to a total or average value across multiple gait cycles.

Structural analysis can be used to quantify subtle changes in postural control variability that may not be apparent with magnitude analysis. For example, researchers have used center-of-pressure displacement patterns to identify alterations after concussion.[7,11,36] However, the physiological mechanisms driving postconcussion dual-task gait dysfunction are unclear.[10] Quantifying gait variability structure could help clinicians understand why dual-task gait deficits (eg, greater total body sway) exist following concussion. Cross-recurrence quantification analysis (CRQA)[26,43,45] assesses the structure of dynamic gait stability—measured by accelerometers—without the need for extended trials or step detection.[39] Thus, CRQA represents a viable method to understand gait variability structure with a clinically viable approach. Therefore, to better characterize concussion-related gait instability, the purpose of our investigation was to compare CRQA (ie, gait pattern) measurements during single- and dual-task gait between adolescents who sustained a diagnosed concussion and healthy adolescents.

METHODS

Study Design

We conducted a cross-sectional case-control study of youth athletes with and without concussion. The inclusion criteria were diagnosis of concussion by a sports medicine physician, evaluation within 14 days of injury (concussion group), and aged between 8 and 19 years. Concussion diagnoses were defined as a traumatic brain injury caused by a direct blow to the head, face, neck, or elsewhere on the body, resulting in the onset of neurological impairment.[32] All concussions occurred during sport or sport-like activities (eg, falling from ground level). Control participants were athletes who presented to an injury prevention center for an injury prevention evaluation. Exclusion criteria for all participants included a concussion in the past year, coexisting lower extremity injury, history of permanent memory loss, learning disability, Down syndrome, or developmental disability. Prior to study commencement, the Boston Children's Hospital Institutional Review Board reviewed and approved the study protocol (IRB-P00016317). All participants and parents/guardians provided written informed assent/consent to participate in the study prior to enrollment. Patients, athletes, and public partners were not involved in the design, conduct, interpretation, or translation of the research.

Gait Analysis Protocol

Participants completed trials in a hallway free from distractions under single-task and dual-task conditions. Participants walked toward a target (blank sheet of paper) 8 m in front of them at a self-selected speed, walked around it, and returned to the original position. The side they approached the target from was not specified. Dual-task trials were completed while walking and simultaneously completing a cognitive test (defined below). Prior to dual-task trials, the test administrator provided the auditory cue (verbal instruction).

The cognitive test consisted of (1) spelling a 5-letter word backwards, (2) subtracting by sixes or sevens from a 2-digit number, or (3) reciting the months in reverse order, starting from a randomly chosen month.[2,14,16] The test administrator recorded response accuracy. The test form completed was randomly selected for each trial to avoid learning effects, and no duplicate cues were used. Multiple dual-task trials (ie, 3-5) from each participant were averaged.

Data Processing and Analysis

Participants wore 3 inertial measurement sensors (Opal sensor; APDM, Inc, Portland, OR) attached to the lumbar spine at the lumbosacral junction and to the dorsum of each foot with an elastic belt.[13,21] Data were obtained at the sampling frequency of 128 Hz. For these devices, the industrial, scientific, and medical (ISM) radio frequency was 2.40 to 2.48 GHz, the calibrated frequency ranged from 150 kHz to 80 MHz, and the synchronization between devices was 1 millisecond or less. The accelerometers had a range of ±2 *g*, a bandwidth of 50 Hz, and a resolution of 14 bits. A raw time series (**FIGURE 1**) from each foot inertial measurement sensor was extracted using Mobility Lab 2.0 (APDM, Inc). The time series consisted of the acceleration in the *z*-axis (positive, superior; negative, inferior) from the sensors on the dorsum of each foot, as the vertical acceleration data provide the most salient motion to examine step characteristics using CRQA.

A custom algorithm was developed to objectively trim the gait time series, a necessary process due to the time when participants were not walking (ie, at the beginning and end of the trials).

The algorithm was written in MATLAB (The MathWorks, Inc, Natick, MA) and utilized the "findpeaks" function. Prior to analysis, the data were automatically trimmed: (1) using MATLAB's "findpeaks" function, the peaks—corresponding to individual strides—were automatically found using a minimum peak prominence of 20.0% of the maximum peak prominence (ie, the highest acceleration value); (2) the first and last peaks of eit were determined based on location in time (ie, the first and last peaks of the 2 time series); and (3) 2.5% of the total length of data prior to the first peak was retained (as indicated by the left-most red dashed line of **FIGURE 1**) and 2.5% of the total length of data after the last peak was retained (as indicated by the right-most red dashed line of **FIGURE 1**). We did not use filtering or downsampling methods. After preprocessing, further time-series analysis occurred to inves coordination dynamics (ie, CRQA).

Cross-recurrence Plots and Quantification Analysis

Cross-recurrence quantification analysis[31,46] is an extension of recurrence quantification analysis[45] and is used to index the dynamic characteristics of gait using inertial sensors.[3,26,39] Cross-recurrence plot construction depends on several parameters that influence plot organization and structure (**FIGURE 2**).[45] We used a variable radius value to ensure each recurrence plot maintained a fixed recurrence rate of 5.0%,[4,40] to prevent oversaturation of plots with recurrent points that may influence the dependent measures derived from the plot.[41]

We determined individualized delay and embedding dimension due to individual stride length and timing variations. A delay was chosen using the mutual information approach.[42] We created time-delayed copies of original signals to serve as surrogate dimensions for reconstructing the original system's state space in order to remove projection errors in the data. False nearest-neighbor analysis was used to select an embedding dimension.[23] On average, a delay of 19.03 and an embedding dimension of 5.50 were selected for the reconstructed state space. The distance matrix was rescaled using the maximum normalized distance, and the minimum line length for vertical and diagonal lines was set to 2 consecutive points. We used custom-written MATLAB (The MathWorks, Inc) scripts and open-source CRQA toolbox functions.[29,31] We calculated 4 cross-recurrence quantification dependent variables for use in further statistical analyses: percent determinism, average diagonal-line length, laminarity, and trapping time. Percent determinism and average diagonal-line length index diagonal-line structure. Laminarity and trapping time provide an index of the vertical-line structure (**TABLE 1**).

Diagonal-Line Measures

Percent determinism indicates the proportion of recurrent points on diagonal lines or sequences. The higher the percent of recurrent points that make up diagonal lines, the higher the predictability of coupling the 2 signals.[43] Average diagonal-line length is a measure of the average number of recurrent points that make up the diagonal lines of a recurrence plot. A longer average line length will indicate that the 2 signals spent more time in the same regions of reconstructed phase space, and may indicate stronger coupling between time series.[43]

Vertical-Line Measures

Laminarity is equivalent to percent determinism but applies to the percentage of recurrent points that make up vertical lines. Diagonal lines are related to the level of coordination (coupling) between 2 signals. Vertical lines indicate how often the signals exhibit laminar behavior—a type of behavior where the signals become "stuck."[4,30] Trapping time is equivalent to average diagonal-line length but applies to the average length of recurrent points that make up vertical

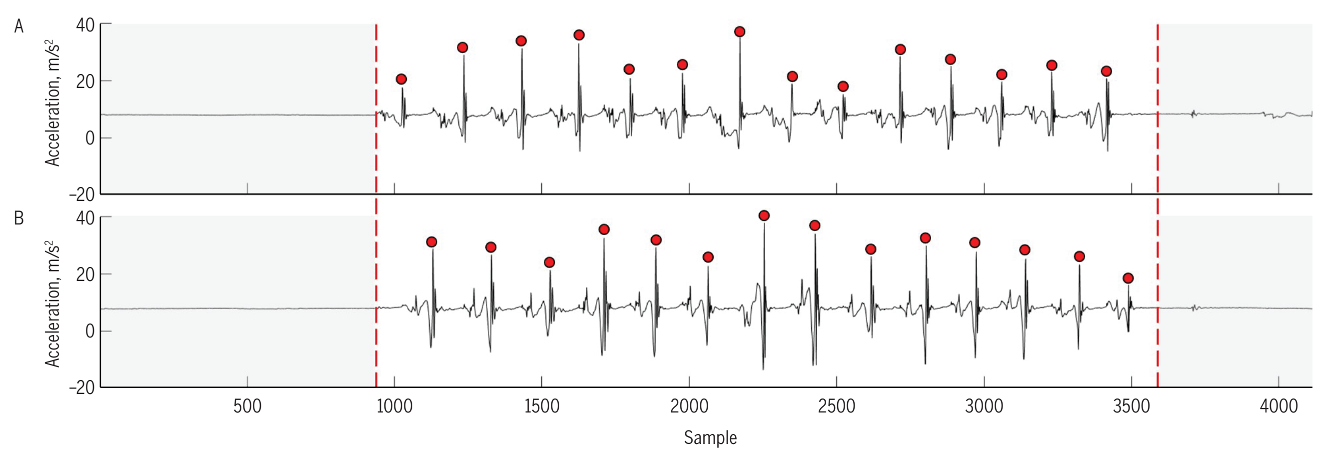

FIGURE 1. Example time series from a participant with concussion: (A) data from the right foot sensor and (B) data from the left foot sensor. The data within the light gray areas were not included in any analysis. Samples between approximately 2200 and 2400 mark the period during which the participant was turning around.

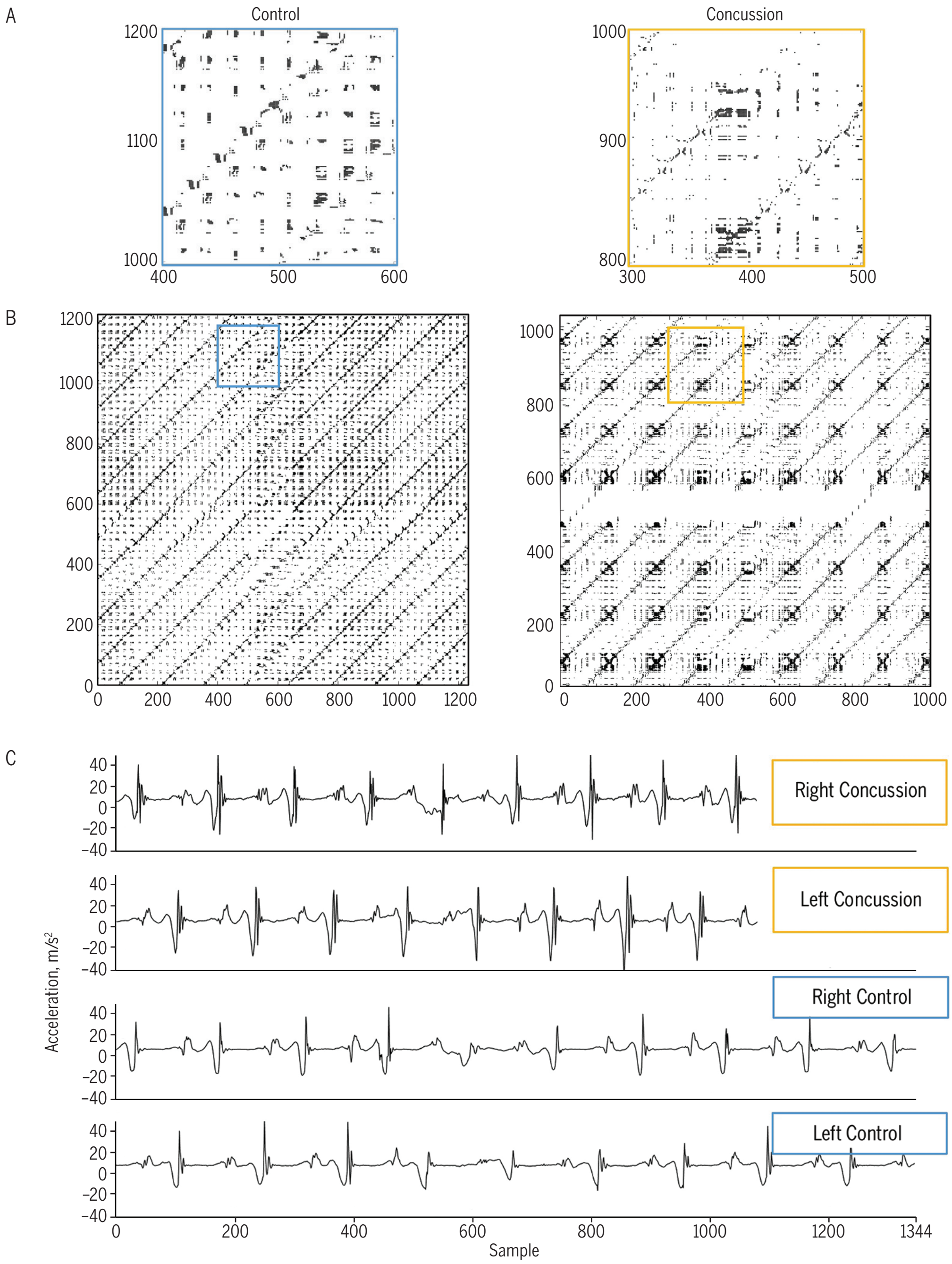

FIGURE 2. Data from randomly selected single-task gait trials from a control participant (blue) and a participant with concussion (orange). (A) Cross-recurrence quantification analysis plots (zoomed in from plots shown in panel B) for each pair of foot acceleration data for the control participant (left) and the participant with concussion (right). Recurrent points are spread out more for the control participant, and the participant with concussion has recurrent points grouped more closely together. (B) Entire corresponding cross-recurrence quantification analysis plots for each pair of foot acceleration data for the control participant (left) and the participant with concussion (right). The *x*-axis and *y*-axis of the plots correspond to the samples of the trajectory in the reconstructed state space of the left (*x*-axis) and right (*y*-axis) feet. The black data points in each plot indicate a recurrent trajectory within the state space (ie, the locations of the left and right foot trajectories are within the radius cutoff). It is the patterning of the recurrent points that each dependent measure quantifies. The plot from the control participant appears smoother, with less "blocking" of the recurrent points. The plot from the participant with concussion appears to have more periods of "blocking," where vertical and diagonal lines form. The most readily apparent difference between the participant with concussion and the control participant is the large period between 400 and 600 on the *y*-axis, where there were few recurrent points. This is the turn phase, where gait patterns from the participant with concussion did not repeat. (C) Acceleration time-series data acquired by inertial sensors on each foot (left or right), from the control participant (bottom 2 plots) and the participant with concussion (top 2 plots).

TABLE 1 A Summary of the Outcome Measures Obtained During Gait

Dependent Measure	Type	Description	Clinical Translation
Average gait speed	Traditional	The average speed (meters per second) at which a participant walked during a trial	Faster gait speed commonly indicates that a participant's gait is more efficient and/or healthy
Average diagonal-line length	Diagonal-line structure	The average length of recurrent points that form a diagonal line	A longer average diagonal-line length is usually an indication that a participant's gait cycle is more tightly coupled
Laminarity	Vertical-line structure	The proportion of recurrent points that contribute to vertical-line structures	A greater value of laminarity generally indicates that a greater proportion of recurrent points form periods of unchanging or "stuck" gait behavior
Percent determinism	Diagonal-line structure	The proportion of recurrent points that contribute to diagonal-line structures	Higher percent determinism indicates that gait is more coupled and predictable
Trapping time	Vertical-line structure	The average length of recurrent points that form a vertical line	Higher trapping time is an indication that the gait cycle exhibits, on average, greater periods of "stuck" or "frozen" gait behavior, regardless of the overall amount of vertical-line structures

lines. Trapping time indicates the average amount of time of laminar behavior (ie, "stuck" or unchanging gait).

Gait Speed

We calculated average walking speed, an established linear measure, using Mobility Lab 2.0 (APDM, Inc).[13,21] We included average walking speed as an independent outcome because CRQA quantifies the underlying organization of gait variability, regardless of average walking speed, and provides an index of gait-speed pattern around the mean, whereas the average gait speed gives a global walking behavior description. We did not use gait speed or trial length as covariates in our analysis, as our radius parameter value ensured that each cross-recurrence plot maintained a fixed recurrence value (ie, 5%), thus controlling for trial length by forcing each plot to contain a fixed number of recurrent points.

Clinical Evaluation

Participants completed the Post-Concussion Symptom Scale[25] by rating each concussion symptom from 0 (asymptomatic) to 6 (maximum severity). We calculated the sum of responses. We instructed participants to rate symptoms that began at the time of injury and that they had experienced within the prior 24 hours. All participants with concussion were symptomatic at the time of assessment.

TABLE 2 Characteristics of the Concussion and Control Groups[a]

Variable	Concussion Group (n = 43)	Control Group (n = 38)	*P* Value
Age, y	14.4 ± 2.3	14.9 ± 2.0	.28
Height, cm	162.4 ± 12.7	163.6 ± 10.1	.65
Weight, kg	56.5 ± 15.1	56.8 ± 12.4	.92
Sex (female), n (%)	24 (56)	21 (55)	>.99
History of prior concussion, n (%)[b]	23 (54)	8 (21)	<.01
Preinjury treatment for migraine, n (%)	4 (9)	4 (11)	.94
PCSS score at time of exam	33.5 ± 20.8	...	...
Symptom duration, d	37.9 ± 42.6	...	...

Abbreviation: PCSS, Post-Concussion Symptom Scale.
[a]*Values are mean ± SD unless otherwise indicated.*
[b]*Significant difference (P<.05).*

Statistical Analysis

Continuous variables were presented as mean ± SD or median (interquartile range). Categorical data were presented as the number in the group and the corresponding percentage. We compared group characteristics using independent-samples *t* tests and Fisher exact tests. We used 2-by-2 analyses of covariance (ANCOVAs) to evaluate linear and nonlinear gait differences between groups, between conditions, and for interactions. Outcome variables were average walking speed, percent determinism, average diagonal-line length, laminarity, and trapping time. Covariates were demographic variables (**TABLE 2**) that demonstrated potential significant differences between groups ($P<.20$).

Statistical significance was set at $P<.05$; tests were 2 sided. If an interaction reached statistical significance, pairwise follow-up comparisons were conducted, where statistical significance was defined as $P<.025$. For ANCOVAs, we also calculated partial eta-square values, where we interpreted a large effect as greater than 0.14, a medium effect as 0.06 to 0.14, and a small effect as less than 0.06. Statistical analyses were performed with SPSS Version 25.0 (IBM Corporation, Armonk, NY).

RESULTS

Eighty-one participants completed the study. Forty-three (53%) had sustained a concussion within 14 days of assessment (median, 7 days; interquartile range, 4-10). There were no significant between-group differences in age or sex (**TABLE 2**). A significantly higher proportion of the concussion group had a history of concussion (prior to the index injury) than the control group (**TABLE 2**). Concussion history was included as a covariate in ANCOVAs. The concussion group walked significantly slower than the control group in both single-task and dual-task conditions (**TABLE 3**). Both groups walked with a faster average gait speed during single-task gait compared to dual-task gait (**TABLE 3**).

Analyses of covariance for each nonlinear outcome variable indicated several main effects of group and time, but no significant group-by-time interactions. The concussion group had higher percent determinism than the control group (main effect of group, **FIGURE 3A**), and both groups had higher percent determinism during dual-task gait relative to single-task gait (main effect of condition, **FIGURE 3A**). Both groups had higher average diagonal-line length during dual-task gait than during single-task gait (main effect of condition, **FIGURE 3B**). The concussion group had higher laminarity (main effect of group, **FIGURE 3C**) and higher trapping time (main effect of group, **FIGURE 3D**) than the control group. When comparing between single-task and dual-task conditions, both participant groups had higher laminarity (main effect of condition, **FIGURE 3C**) and trapping time (main effect of condition, **FIGURE 3D**) during the dual-task condition relative to the single-task condition.

DISCUSSION

There were differences in nonlinear gait parameters between healthy adolescents and those suffering from a concussion, evidenced by higher percent determinism, laminarity, and trapping time for those with concussion relative to controls. Trapping time had the strongest effect between groups (medium effect). Our findings extend prior work observing gait alterations following concussion.[8,18,21] Future studies may consider quantification not only of spatiotemporal gait measures for postconcussion evaluations, but also nonlinear metrics that reveal the underlying pattern of observed alterations after concussion.

Stable gait is a product of coordinating movement of different body segments.[26] Cross-recurrence quantification analysis is capable of providing insights into the complexity and predictability of gait patterns beyond traditional spatiotemporal measures. Cross-recurrence quantification analysis methods were used previously to identify balance alterations among those with vestibular dysfunction.[26] Although we observed between-group differences, there was no effect of cognitive task condition. Researchers have previously observed dual-task gait impairments after concussion that outlast single-task gait impairments.[9,10,18] Due to the relative acuity of data collection after concussion, limb-control differences between groups were detected between the concussion and control groups during the single-task

TABLE 3 Single- and Dual-Task Gait Speeds for the Concussion and Control Groups[a]

Condition[b]	Concussion Group[c]	Control Group[c]
Single task	1.11 ± 0.17	1.16 ± 0.13
Dual task	0.85 ± 0.18	0.95 ± 0.14

[a]*Values are mean ± SD meters per second.*
[b]*Main effect of condition (F = 192.7, P<.001, η_p^2 = 0.715).*
[c]*Main effect of group (F = 4.07, P = .047, η_p^2 = 0.050).*

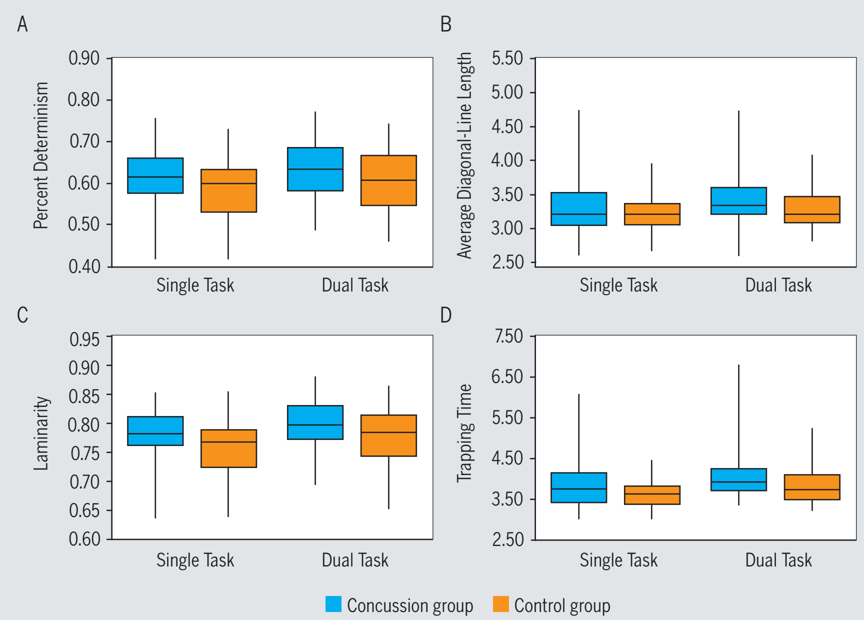

FIGURE 3. Single-task and dual-task nonlinear measures among concussion and control groups for (A) percent determinism, (B) average diagonal-line length, (C) laminarity, and (D) trapping time. The line within the box defines the median value. The range of the box defines the 25th and 75th percentiles, and whiskers extending from the box plots define the range of measurements obtained. There was a main effect of group for percent determinism (F = 4.05, *P* = .048, η_p^2 = 0.050), laminarity (F = 4.84, *P* = .031, η_p^2 = 0.059), and trapping time (F = 7.44, *P* = .008, η_p^2 = 0.088). There was a main effect of condition for percent determinism (F = 4.70, *P* = .033, η_p^2 = 0.058), average diagonal-line length (F = 4.97, *P* = .029, η_p^2 = 0.061), laminarity (F = 9.08, *P* = .004, η_p^2 = 0.105), and trapping time (F = 7.04, *P* = .01, η_p^2 = 0.084).

condition.[21] Adding a cognitive task changed gait behavior, but to a similar degree for both concussion and control groups. Thus, single-task approaches to identifying acute postconcussion changes in laminar behavior may be sufficient to implement in clinical practice, by simply asking a patient to walk from one point to another, rather than more complex dual-task approaches.

Due to the dual-task mental perturbation, the attentional resources available to devote to walking and mental tasks were challenged. Completing a dual task, particularly following a concussion, appears to be associated with a reduction in neuromuscular control.[15] This may be one mechanism by which slower gait is necessary during dual-task conditions, where the feet are placed without regard to an efficient behavioral pattern in order to continue ambulating and avoid falling. As healthy children walk more slowly during dual tasks compared to single tasks,[27] measuring the pattern of foot placement using CRQA techniques may allow for a better understanding of how gait is affected by a concussion. The 2 vertical-line measures, laminarity and trapping time, allow for the examination of the degree of behavior where the signals are stuck (eg, laminar behavior periods).[30] Longer laminar states may reflect "conservative" gait patterns previously documented.[2,5,18] Thus, clinicians with access to wearable sensor technology may assess laminar behavior as an outcome to determine progression during rehabilitation to baseline or normative levels of fluidity and ease of movement.

Changes in underlying movement patterns after concussion have been identified in quiet-stance paradigms: sway volume was greater following a concussion, but variability was lower.[36] Concussion may be associated with an increased risk of subsequent sport-related injury,[33] and persistent postconcussion gait impairments may be one method to identify those at risk.[14,15] Clinicians may consider incorporating auditory or visual feedback training during gait into rehabilitation. Feedback techniques, such as auditory-motor coupling,[22] visual metronomes,[38] and auditory metronomes,[28] can shift gait behavior (eg, sample entropy) toward a healthier state. Future intervention studies assessing feedback to shift gait patterns toward a healthy range following a concussion may yield insights into methods to reduce subsequent injury risk, using CRQA outcomes to determine rehabilitation efficacy.

Limitations

Our cross-sectional design limits the ability to examine recovery patterns. Additional balance measures such as the Balance Error Scoring System were not available; their inclusion would provide greater clinical context. Test-retest reliability measures have not yet been identified using CRQA for gait, although gait analysis among this age group has high consistency across time.[17] Future work to establish reliability characteristics among adolescents will help determine clinical applicability. Our findings may not be generalizable beyond adolescents. Participants with concussion required a longer time for symptom recovery (approximately 38 days) compared to the traditional 7- to 10-day trajectory, which might have biased our findings toward a more severe injury type. Future work exploring nonlinear measures after concussion may help to determine the restoration of biomotor abilities, such as walking patterns. Researchers should continue to investigate the recovery trajectories of nonlinear gait measures throughout clinical recovery.

CONCLUSION

Higher percent determinism, laminarity, and trapping time among athletes with a concussion suggest that concussion was associated with a more stuck and predictable gait pattern. These altered movement patterns may be one reason for underlying slower gait speeds that have been observed following concussion. ◉

KEY POINTS

FINDINGS: Adolescents assessed within 14 days of concussion had higher percent determinism, laminarity, and trapping time than their uninjured peers. Alterations in these metrics suggest that concussion may be associated with a less adaptable gait pattern.

IMPLICATIONS: The altered movement patterns, reflective of less adaptability for those with concussion, may be one reason why athletes had slower gait speeds following concussion.

CAUTION: The cross-sectional design does not allow for interpretation of what caused changes in gait patterns, and the single age group and testing site limit external validity to other age groups or geographic locations.

STUDY DETAILS

AUTHOR CONTRIBUTIONS: All authors contributed to the conception and design of the work. Drs Howell and Meehan contributed to the acquisition of data for the work. Drs Howell and Bonnette contributed to the analysis of data for the work. All authors contributed to the interpretation of data for the work, drafted the work or revised it critically for important intellectual content, gave final approval for publication, and agreed to be accountable for all aspects of the work to ensure that queries of accuracy or integrity of the work are appropriately investigated and resolved.

DATA SHARING: Deidentified individual patient data and other study-related documents can be shared upon request via the corresponding author. We do not plan to make the data publicly available.

PATIENT AND PUBLIC INVOLVEMENT: Patients, athletes, and public partners were not involved in the design, conduct, interpretation, or translation of the research.

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