ORIGINAL ARTICLE

TITLE: A preliminary study of longitudinal differences in local dynamic stability between recently concussed and healthy athletes during single and dual-task gait

KEYWORDS: Concussion, Brain Injury, Gait, Local Dynamic Stability, Lyapunov Exponents, mTBI

AUTHORS: Peter C. Fino, Department of Mechanical Engineering, Virginia Polytechnic Institute and State University

CORRESPONDING AUTHOR: Peter C. Fino, Ph.D. Department of Neurology, Oregon Health and Science University, 3181 SW Sam Jackson Park Road, L226, Portland, Oregon 97239-3098, fino@ohsu.edu

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Abstract

Concussed individuals commonly exhibit locomotor deficits during dual-task gait that can last substantially longer than clinical signs and symptoms. Previous studies have examined traditional stability measures, but nonlinear stability may offer further information about the health of the motor control system post-concussion. For up to one year post-concussion, this study longitudinally examined the local dynamic stability of five concussed athletes and four matched healthy controls during single- and dual-task gait. Local dynamic stability (LDS) was estimated using short-term, finite-time maximum Lyapunov exponents calculated from tri-axial accelerometers placed on the trunk and head. No main effects of group or task were found for LDS or stride time variability, but significant group*task interactions were apparent for trunk stability and stride time variability. Concussed individuals exhibited decreased trunk LDS and increased stride time variability during dual-task walking compared to matched controls despite similar single-task stability and variability. These preliminary results reinforce previous reports that concussions persistently affect dual-task processes even when single-tasks may be unaffected. Furthermore, the decreased local dynamic stability during dual-task gait indicates the concussed group attenuated local disturbances less than their healthy teammates. The decreased dynamic stability during dual-task activities was present after the athletes were cleared for competition and may be a contributing factor in the higher rates of musculoskeletal injuries in athletes post-concussion.

Introduction

Recent concussion literature suggests locomotor deficits persist beyond the typical 7-10 day resolution of other symptoms (Buckley et al., 2013; Catena et al., 2009; Fait et al., 2009; Fait et al., 2013; Howell et al., 2013; Lee et al., 2013; Martini et al., 2011; McCrory et al., 2013; Parker et al., 2006; Powers et al., 2014). While walking with a simultaneous attention-dividing task, recently concussed, yet asymptomatic athletes show increased mediolateral (ML) sway (Catena et al., 2009; Howell et al., 2013; Parker et al., 2006) and increased step and joint-coordination variability (Chiu et al., 2013; Niechwiej-Szwedo et al., 2007) lasting for up to two months (Howell et al., 2013) despite single-task (ST) gait similar to controls. However, these dual-task costs (DTCs) have not yet been translated to on-field performance or injury risk. It is possible that persistent gait modifications reflect an altered motor control system (Dingwell and Cusumano, 2000) that is less suited for high-demand situations such as competitive athletics, and may be a contributing factor in the high rate of musculoskeletal injuries following concussions (Brooks et al., 2016; Cross et al., 2015; Lynall et al., 2015; Nordström et al., 2014).

One technique to examine locomotor control is to assess an individual's response to local perturbations (Bruijn et al., 2013; Stergiou and Decker, 2011), such as neuromuscular noise or surface irregularities. Local dynamic stability (LDS) quantifies this neuromuscular response and attenuation of these perturbations (Dingwell and Cusumano, 2000; Lockhart and Liu, 2008) and reflects an individual's ability to respond to local disturbances (Stergiou and Decker, 2011; Stergiou et al., 2006). Decreased LDS has been associated with aging, recent fall-history, and mobility-impaired populations (Buzzi et al., 2003; Lockhart and Liu, 2008; Toebes et al., 2012), suggesting that LDS may also be an indicator of a system's response to global perturbations (e.g., slip, trip).

An athlete's ability to quickly respond to local and global perturbations is essential for performance and safety. Therefore, LDS may be an indicator of an athlete's underlying locomotor control and competitive readiness after a concussion. This study longitudinally examined the LDS of recently concussed and control athletes to examine the effect of concussion on the LDS of gait. We hypothesized that recently concussed athletes would exhibit persistent decreases in LDS compared to matched controls, and that such deficits would be exacerbated during cognitive dual-task (DT) gait.

Methods

Participants

Nine Virginia Tech varsity athletes (five concussed, four matched control) participated in this study (Table 1). All concussed athletes were clinically diagnosed by a Virginia Tech Sports Medicine physician and referred to this study by their athletic trainer. Controls were recruited from teammates of the concussed subject and individually matched based on sport position, skill level, and height. Skill level was determined using playing time, positional depth charts and / or performance times depending on the sport. In this regard, skill level roughly divided starters from non-starters to ensure both concussed and control participants experienced similar competitive demands throughout the study. Exclusion criteria for both groups included any unresolved acute lower extremity injury or any history of mental illness or diagnosed cognitive impairment. An additional exclusion criterion for controls was no concussion or brain injury within the previous year. No participant, concussed or control, had any concussion history prior to this study. All participants gave informed written consent. Recruitment procedures and experimental protocols were approved by the Virginia Tech IRB.

Table 1

Procedures

Recently concussed participants were tested weekly for six weeks, at means (SD) of 7 (0), 16 (1), 23 (2), 29 (1), 36 (2), and 45 (3) days post-concussion. Each control was also tested up to six times, and on the same days as their match to control for musculoskeletal afflictions from recent games or practices. A one-year follow-up testing session occurred at a mean (SD) of 363 (42) days post-concussion for three concussed and two control participants. Not all participants completed all sessions because of scheduling conflicts (Table 1).

At each testing session, the participants were fitted with two 6-axis inertial measurement units (IMUs) aggregated in the Technology Enabled Medical Precision Observation (TEMPO) platform (Barth et al., 2009; Soangra et al., 2013). The IMUs were located over the participant's xiphoid process and over the forehead. The IMU x , y , z directions approximately aligned with mediolateral, vertical, and anteroposterior directions, respectively. Data were sampled at 128 Hz.

All testing sessions occurred in a gymnasium with minimal distractions and clean, hardwood floors. Participants were asked to walk barefoot around a course containing an 18 m long straight section denoted with a pylon at the start and end of the section. Participants completed 14 laps, producing 14 bouts of straight ST gait. Participants were then given a random number between 900 and 999 and repeated the procedure while serially subtracting by sevens (Howell et al., 2014), producing 14 bouts of straight, dual-task (DT) gait.

Analysis

Steps were identified using the local minima of the trunk vertical accelerations, with strides identified as every two steps (van Schooten et al., 2014). Only the middle eight strides were analyzed for each bout to ensure steady-state straight gait. The standard deviation of stride times, assessed from the trunk IMU, defined the traditional stride time variability. Gait speed was determined from each participant's mean time per condition to walk the 18 m section.

Local dynamic stability was estimated using short-term, finite-time maximum Lyapunov exponents (λ_s), calculated for each bout of straight gait using the algorithm described by Rosenstein et al. (1993). To remove the effect of data series length on LDS (Bruijn et al., 2009b; England and Granata, 2007), strides were time-normalized to 130 samples per stride, corresponding approximately to the participants' mean stride time of 1.05 seconds (Sloot et al., 2011; van Schooten et al., 2014; van Schooten et al., 2013). A 9D fixed state space was reconstructed using the 3D accelerations and their twice time-delayed copies (van Schooten et al., 2014; van Schooten et al., 2013). The time delay of $\frac{1}{4}$ the average stride time was chosen to be consistent with previous methods that examined LDS over short bouts of gait (van Schooten et al., 2014; van Schooten et al., 2013). The LDS estimate, λ_s , was calculated from the slope of the log mean divergence curve between 0 and 0.5 strides (Bruijn et al., 2013), with a larger λ_s indicating *less* LDS and a smaller λ_s indicating *more* LDS (Rosenstein et al., 1993).

The LDS estimate was calculated for both the trunk ($\lambda_{s-Trunk}$) and head (λ_{s-Head}) IMUs for each bout of eight strides, and means obtained over the 13 walking episodes (Sloot et al., 2011; van Schooten et al., 2014) for both ST and DT gait. The first episode for each condition was excluded to ensure the participants were adjusted to the task. The λ_s values were normalized to individual gait speed for each condition to control for the effect of gait speed on LDS (Bruijn et al., 2009a; Dingwell and Marin, 2006; England and Granata, 2007).

Dual-task costs (DTCs) of the cognitive task on λ_s were calculated as

$$DTC \lambda_s = \frac{(DT \lambda_s - ST \lambda_s)}{ST \lambda_s} * 100\%$$

to represent the percent change in stability associated with the cognitive task. All analysis was performed in MATLAB (The Math-Works, Inc, Natick, Massachusetts, USA).

Statistical Analysis

Univariate descriptive statistics of gait speed, stride time variability, λ_{s-Head} and $\lambda_{s-Trunk}$ were calculated for each condition (ST/DT) and group (concussed/control). Linear mixed models were fit to describe each outcome over time. Models were adjusted for time, group, task, and two and three-way interaction effects. Higher order interactions with p values less than 0.10 were retained in the final model. Model assumptions were validated by examining the residuals. Stride time variability exhibited a non-normal distribution and was thus log-transformed. A two-sided significance level of 0.05 was used throughout, and all statistical analysis was performed in SAS 9.4 (SAS Institute, Cary, NC, USA).

Results

Univariate results at each week for gait speed, stride time variability, λ_{s-Head} and $\lambda_{s-Trunk}$ are depicted in Figures 1-4, respectively. Concussed athletes exhibited greater DTC than healthy athletes as indicated by significant group*task interactions for $\lambda_{s-Trunk}$ and stride time variability (Table 2). No differences in ST stability or variability were found between groups as no significant main effects of group, week, or task were found for stride time variability, $\lambda_{s-Trunk}$, or λ_{s-Head} . The group*task interaction is represented in Figures 5-6, which show the DTCs of the cognitive task on $\lambda_{s-Trunk}$ and λ_{s-Head} . Gait speed showed a significant group*day interaction and significant main effects of group and task. Concussed athletes walked slower than healthy

athletes. Yet, concussed athletes increased their speed over time, which was restored to healthy levels by the one-year follow up. Dual-task gait speed was slower than ST gait speed.

Table 2

Figures 1-6

Discussion

We examined the effect of a recent concussion on the LDS of gait through a prospective analysis of a small sample of concussed athletes and matched controls. No differences were found between groups for any variability measure, indicating rejection of our initial hypothesis that concussed athletes would exhibit decreased LDS during ST gait. However, a significant group*task interaction supported our second hypothesis and indicated that the addition of a cognitive dual-task influenced stability in the concussed group more than in the control group, despite similar ST stability. Recently concussed athletes also exhibited larger LDS DTCs post-concussion. This DT instability was present after the concussed athletes were medically cleared and had returned to full athletic participation. A prolonged decrease in gait speed was also found in concussed athletes, which eventually resolved to normal levels, consistent with previous evidence over similar post-concussion intervals (Buckley et al., In Press; Parker et al., 2006).

In agreement with previous studies, the present results did not show any differences, other than gait speed, between concussed and control groups during ST gait (Catena et al., 2007a; Catena et al., 2009; Howell et al., 2013; Parker et al., 2006). However, DT gait involving a simultaneous arithmetic task elicited a disproportionate destabilizing effect on the concussed individuals, a result which is consistent with recent literature (Catena et al., 2007b, 2011; Cossette et al., 2014; Fait et al., 2013; Howell et al., 2014; Howell et al., 2013; Register-Mihalik

et al., 2013). While previous studies assessed DTC using measures such as ML sway (Catena et al., 2007a; Howell et al., 2013; Parker et al., 2006), the present investigation provides new evidence using nonlinear LDS. The larger DT λ_s in concussed athletes reflects diminished responses by the neuromuscular control system to local perturbations. In contrast, previous results quantified the magnitude of such perturbations, such as step time variability (Niechwiej-Szwedo et al., 2007) and ML sway (Catena et al., 2007a; Howell et al., 2015; Howell et al., 2013; Parker et al., 2006), but did not reflect the neuromuscular response. Thus, these preliminary LDS results affirm earlier suspicions of motor control differences post-concussion.

The increased DTC in concussed individuals reported here and elsewhere may be associated with functional brain changes post-concussion. Decreased interhemispheric brain connectivity (Johnson et al., 2012) and altered cortical networks (Slobounov et al., 2010) post-concussion may alter the availability and/or organization of cortical resources. In concussed yet asymptomatic athletes, this reorganization produces a decline in cognitive efficiency and leads to difficulty allocating appropriate resources to match demands, particularly as task difficulty and demands increase (Sinopoli et al., 2014). In DT gait, where the cognitive and gait tasks compete for attentional resources (Yogev-Seligmann et al., 2008), this functional change in resource allocation may lead to the increased DTC in recently concussed athletes' LDS. Conversely, increased attentional demands in healthy individuals did not produce consistent or noticeable changes in the LDS, matching results from Dingwell et al. (2008). While both functional brain changes and DT gait abnormalities occur over the same sub-acute period post-concussion, combined functional brain imaging and gait studies are needed before any conclusions can be solidified.

A group*task interaction for stride time variability was found (Fig. 2), with a disproportionate increase in DT variability in the concussed group compared to controls. However, this temporal variability cannot account for differences seen in λ_s because strides were normalized to the same length. By normalizing stride time, temporal variations caused by kinematic disturbances were removed, leaving perturbations in the movement patterns without stride-duration variability and simplifying the relationship between walking velocity and λ_s (England and Granata, 2007). Therefore, recently concussed participants demonstrated greater temporal variability between strides, as indicated by stride-time variability, *and* attenuated those disturbances less effectively over the course of one step, as indicated by λ_s .

From a clinical perspective, the DT LDS deficit appears to last beyond the athletes' 1-2 week (Table 1, Figure 5) symptom directed return-to-play progression. The sample size limits our ability to make duration-based conclusions. Yet, the descriptive statistics indicate a persistent DT deficit that agrees with previous findings of prolonged DT gait recovery post-concussion (Buckley et al., 2013; De Beaumont et al., 2011; Fait et al., 2013; Howell et al., 2014; Howell et al., 2013). The DT LDS results also raise concern about a recently concussed athlete's well-being and risk of musculoskeletal injury after returning to competition. Similar trends with decreased LDS have been associated with an increased risk of falls (Bruijn et al., 2012; Lockhart and Liu, 2008) indicating that concussed athletes, while processing a cognitive load during practice or competition, may be at a greater risk of global destabilization. Given the high cognitive loads present during athletics (Tenenbaum and Bar-Eli, 1993), this decrease in DT LDS may contribute to the high rate of musculoskeletal injuries in recently concussed athletes (Brooks et al., 2016; Cross et al., 2015; Lynall et al., 2015; Nordström et al., 2014). It is also worth noting that these effects, though persistent, may be temporary; the LDS dysfunction may

resolve over the course of one year. While no effect of time was found in the mixed models, the DTC appeared to resolve to healthy control levels in 2 of the 3 athletes tested after one year. Interestingly, this period (<1 year) corresponds to the timeframe when increased musculoskeletal injuries have been reported post-concussion (Brooks et al., 2016; Cross et al., 2015; Lynall et al., 2015; Nordström et al., 2014) suggesting a connection between LDS and on-field risk.

This preliminary study was limited by a small sample size. Given the unpredictable nature of concussions and the longitudinal design, only five concussions and four controls were tested. Additionally, due to graduations and transfers of some participants, four participants were lost to follow-up at one year. However, the group*task interactions were acutely apparent and detected even with this small sample size. Secondly, this work focused on the initial six weeks post-injury given established timelines of neuropsychological (McCrory et al., 2013) and gait recovery (Howell et al., 2013). These preliminary results, though, suggest this timeline was too short to capture the recovery of gait stability. Future studies should examine a time period between six weeks and one year, in addition to the acute and sub-acute clinical phases. Given the post-concussion gait deficits and the implications for injury, DT gait (Lee et al., 2013; Register-Mihalik et al., 2013) should be considered an important paradigm in future concussion research and clinical assessments.

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Figure 1: Single (top) and dual-task (bottom) gait speeds for concussed and healthy groups over each week of testing.

Figure 2: Single (top) and dual-task (bottom) stride time variability, represented as the stride time standard deviation, of concussed and healthy groups over each week of testing.

Figure 3: Single (top) and dual-task (bottom) $\lambda_{s-{\text{Trunk}}}$ for concussed and healthy groups over each week of testing. Larger $\lambda_{s-{\text{Trunk}}}$ values indicate less stability. All $\lambda_{s-{\text{Trunk}}}$ values have been normalized to gait speed.

Figure 4: Single (top) and dual-task (bottom) $\lambda_{s-{\text{Head}}}$ for concussed and healthy groups over each week of testing. Larger $\lambda_{s-{\text{Head}}}$ values indicate less stability. All $\lambda_{s-{\text{Head}}}$ values have been normalized to gait speed.

Figure 5: Dual-task costs of $\lambda_{s-{\text{Trunk}}}$, as a percentage increase from single-task $\lambda_{s-{\text{Trunk}}}$, for concussed and healthy groups over each week of testing. Positive DTCs indicate increased in $\lambda_{s-{\text{Trunk}}}$ for DT gait compared to ST gait. Larger $\lambda_{s-{\text{Trunk}}}$ values indicate less stability. All $\lambda_{s-{\text{Trunk}}}$ values have been normalized to gait speed.

Figure 6: Dual-task costs of $\lambda_{s-{\text{Head}}}$, as a percentage increase from single-task $\lambda_{s-{\text{Head}}}$, for concussed and healthy groups over each week of testing. Positive DTCs indicate increased in $\lambda_{s-{\text{Head}}}$ for DT gait compared to ST gait. Larger $\lambda_{s-{\text{Head}}}$ values indicate less stability. All $\lambda_{s-{\text{Head}}}$ values have been normalized to gait speed.

Table 1: Age, height, and mass of concussed (C) and healthy matched control (H) athletes and the weeks each athlete were tested. The number of days before the concussed athletes were cleared for full return-to-play (RTP) is also provided. The one year follow-up session is indicated as 52 weeks post-concussion.

ID	Gender	Age (years)	Height (cm)	Mass (kg)	Days Before Full RTP	Weeks Tested Post-Concussion
C1	Female	18	170	63.3	7	(-, 2, 3, 4, 5, 6, 52)
H1		19	178	64.6	-	(-, 2, 3, 4, 5, 6, 52)
C2	Male	20	178	78.9	14	(1, 2, 3, 4, 5, 6, --)
H2		20	178	72.4	-	(-, -, 3, 4, 5, 6, --)
C3	Female	19	163	58.7	11	(-, -, 3, 4, 5, 6, 52)
H3		18	163	59.0	-	(-, -, 3, 4, 5, 6, 52)
C4	Female	19	163	59.4	16	(1, -, 3, 4, 5, 6, 52)
H4		21	170	66.6	-	(1, 2, 3, 4, -, 6, --)
C5*	Male	18	165	67.8	11	(1, 2, 3, -, 5 -, --)
* No eligible matched controls consented to participate						

395

396 **Table 2:** Results from the final linear mixed models. Beta coefficients show the mean
 397 differences between each effect with healthy, ST gait used as the reference state. The
 398 significance level was set at 0.05 and significant terms are shown in bold.

	λ_s -Trunk		λ_s -Head		Gait Speed		log Stride Time Variability	
	Beta (SE) *10 ³	<i>p</i> value	Beta (SE) *10 ³	<i>p</i> value	Beta (SE) *10 ³	<i>p</i> value	Beta (SE) *10 ³	<i>p</i> value
Group	-4.0 (31.6)	0.8994	21.4 (23.9)	0.3734	-154.3 (53.8)	0.0054	58.7 (169.2)	0.7298
Days	-0.02 (0.08)	0.7867	-0.06 (0.07)	0.4318	-0.04 (0.20)	0.8601	0.16 (0.43)	0.7151
Task	-15.2 (15.1)	0.3169	-17.2 (14.6)	0.2431	-66.7 (12.8)	< 0.0001	-53.6 (69.3)	0.4420
Group*Task	64.5 (19.9)	0.0018	34.8 (19.3)	0.0753	-	-	228.6 (91.5)	0.0146
Group*Days	-	-	-	-	0.67 (0.26)	0.0120	-	-

399

Figure 1

Figure 2

Figure 3

Figure 4

Figure 5

Figure 6