

THE RELATIONSHIP BETWEEN CLINICAL CONCUSSION MEASURES AND
NATURALISTIC DRIVING BEHAVIOR IN COLLEGE STUDENTS

by

SARAH DHANJI

(Under the Direction of Julianne Schmidt)

ABSTRACT

The objective was to determine the association between concussion presentations and post-concussion naturalistic driving behaviors. Thirteen individuals with concussion and nine controls installed a GPS device for nine days post-concussion. Driving behaviors included driving duration, distance, average speed, and number of trips per day and risky driving events included hard braking and sudden acceleration. Clinical concussion assessments included neurocognition, balance, vestibulo-ocular function, and symptoms. Separate generalized linear mixed models were used to identify associations between acute clinical concussion presentations and acute driving behavior in the concussion group, relative to controls. Spearman's rank correlation was used to determine the correlation between daily symptom score and naturalistic driving in the concussion group. Relative to controls, concussed individuals with more symptoms and better balance drove at higher speeds, and difficulty with vestibulo-ocular function was associated with increased driving duration. Clinicians may focus on these to help guide post-concussion driving recommendations.

INDEX WORDS: Head injury, Mild traumatic brain injury, Naturalistic driving, Driving safety, Clinical concussion assessment

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CHAPTER 1

INTRODUCTION

A concussion is defined as a mild traumatic brain injury (mTBI) that causes a temporary neurometabolic imbalance within the brain as the result of biomechanical forces.¹⁻³ Concussions are prevalent, with an incidence rate of 132.4 concussions per 10,000 undergraduate students in the United States.² Dysfunction of the neural networks can affect an individual's ability to maintain balance, to pay attention, to recall information, and to perceive, which collectively appear as concussion signs and symptoms.³ These impairments often hinder participation in various activities, including school, sports, and driving.³

Driving, one of the essential activities of daily living for many individuals, is a complex task affected by concussion. Driving simulator studies have shown that individuals with concussion exhibit driving patterns associated with motor vehicle crash during the acute phase (~72 hours) of the injury.^{3,4} Some of these risky driving patterns observed in driving simulators include difficulty centering the car within the lane, more frequent lane excursions, and increased speed variability.⁴ Once asymptomatic, driving impairments were negligible, and by the time they were medically cleared, driving performance was no longer distinguishable from the control group.⁴ While driving simulator assessment and Hazard Perception Tests help understand how concussions affect driving performance,^{3,4} post-concussion naturalistic driving behavior is not well documented. Understanding driving behavior after concussion is important as it helps to identify potential risks and develop strategies to address them.

Survey studies provide insights into post-concussion naturalistic driving behavior.⁵⁻⁷ A study by Schmidt et al. reported that only 43.8% of concussion patients refrained from driving following concussion, and those who did so restricted their driving for only 24-48 hours post-concussion.⁵ Individuals with concussion (age: median 19 years, IQR: 16, 43.5) self-regulate their driving for up to 14 days post-concussion by avoiding nighttime driving (37%), avoiding busy traffic times (35%), driving less frequently (56%), and driving shorter distances (36%).⁶ Another study done specifically in young adults with concussion (age: 22.1±2.7) reported that most concussed drivers did not modify their driving behavior post-concussion.⁷ Young adults reported avoiding nighttime driving (7.8%) and limiting passengers in the car (12.1%).⁷ While the survey studies aid in understanding driving behaviors, the data are limited due to its self-reported nature. Thus, there is a need to describe driving behavior more objectively and extensively.

Naturalistic driving, which is defined as daily driving behavior in a nonexperimental environment where data collection methods do not interfere with the driver's behaviors,⁸ enables us to objectively and comprehensively study driving behavior in real-world settings. It provides precise driving behavioral data, such as distance driven, number of trips per day, average driving speed, and risky driving events. Using naturalistic driving data, researchers have revealed that individuals with pre-clinical Alzheimer's disease drove less frequently, visited fewer places, and had less aggressive driving behavior compared to those without pre-clinical Alzheimer's disease.⁹ Another study found that young drivers drove significantly faster and exhibited more aggressive driving behaviors during the COVID-19 lockdown compared to pre-and post-COVID-19.¹⁰ In terms of individuals with concussion, to date, only one study has investigated naturalistic driving behavior in individuals.¹¹ Individuals with concussion drove less frequently

and slower than non-concussed individuals during the initial 3 days of the injury and drove similarly after 3 days post-concussion.¹¹

Patients with concussion represent a wide range of impairments including balance, memory, concentration, and perception networks,³ and each patient presents with a unique set of deficits. Therefore, we must also assess driving behavior in the context of the type and magnitude of clinical deficit to determine whether post-concussion naturalistic driving behaviors are differentially affected by the injury. One study reported that individuals suffering from headache, dizziness, and “not feeling right” refrained from driving for 2 weeks following concussion.¹² However, little is known about how other concussion signs and symptoms affect driving behavior. Clinical concussion assessments commonly used to assess the effect of concussion on neurocognition, balance, dynamic postural control, vestibulo-ocular function, and symptoms include computerized neurocognitive test, balance error scoring system (BESS), tandem gait test, vestibular ocular motor screening (VOMS), and symptom checklists.¹

Study Objectives

Objective 1): To determine the association between clinical concussion assessments and naturalistic driving behaviors and risky driving events in college students with concussion relative to the control group during the acute phase of the injury (days 2-4). Post-concussion naturalistic driving behavioral outcomes included driving duration, driving distance, average speed, and number of trips per day. Risky driving events included hard braking and sudden acceleration. Clinical concussion assessment outcomes included neurocognition, static balance, dynamic balance, vestibulo-ocular function, and concussion symptoms.

Objective 2): To determine the association between daily symptom reporting and post-concussion naturalistic driving behaviors and risky driving events in the concussion group for up to nine days post-concussion.

Hypotheses

- 1) Worse neurocognitive function, balance function, vestibulo-ocular symptom provocation, and symptom reporting are associated with shorter driving durations, shorter driving distances, slower driving, less frequent trips, more risky driving events in the concussion group when compared to the control group during the acute time period (days 2-4).
- 2) A greater symptom score is associated with shorter driving durations, shorter driving distances, slower driving speeds, and more frequent risky driving events in the concussion group.

Clinical Implications

The objectives of this study allow us to find associations between concussion presentation and post-concussion driving behaviors. The findings will help in understanding how specific post-concussion deficits impact post-concussion driving behaviors and aid in the development of standardized post-concussion driving guidelines to better assist healthcare providers in giving informed recommendations to their patients. By identifying key clinical concussion presentations that are associated with naturalistic driving behavior and risky driving events, clinicians can make more informed decisions about which concussion assessments to use in guiding return-to-drive decisions following concussion.

CHAPTER 2

LITERATURE REVIEW

Concussion

A concussion is a pathophysiological disturbance of the brain resulting from a direct blow to the head, or elsewhere on the body, transmitting an impulsive force to the head.¹⁻³ Immediately after the impact, the neurometabolic cascade occurs, characterized by a disruption in ion balance including potassium efflux and calcium and sodium influx, causing depolarization and glutamate release.¹³ This process depletes ATP, leading to an energy crisis, which is often exacerbated by mitochondrial dysfunction.¹³ These changes affect neurotransmission, potentially disrupting cognitive processes and memory function.¹³ Additionally, there may be inflammation in the brain, theorized to be caused by immunoexcitotoxicity, characterized by glutamate release and immune receptor activation further complicating the recovery process.¹³

In addition to the neurometabolic and chemical disruptions, concussions can also present with physical damage.¹³ The concussion impact can harm dendritic arbors, axons, and astrocytic processes.¹³ Furthermore, the excess calcium can cause neurofilament sidearms to phosphorylate and collapse, which causes proteolytic damage to cytoskeletal components such as subaxolemmal spectrin.¹³ These physical damages interfere with axonal transport and disrupt normal neurotransmission.¹³

Concussion Assessment

Concussion diagnosis and monitoring rely on various clinical measures. The Sports Concussion Assessment Tool version 5 (SCAT-5) is a widely used clinical concussion

assessment tool.^{1,14} Recently, version 6 was introduced,¹⁵ but the majority of current studies utilize the SCAT-5 due to completion of study before the release of SCAT-6. The SCAT-5 consists of two main sections: an immediate or on-field assessment section and an office or off-field assessment section.^{16,17} The immediate or on-field assessment includes various components such as red flags, observable signs, Maddock Questions, Glasgow Coma Scale, and cervical spine assessment to rule out severe traumatic brain injury requiring immediate referral.^{16,17} The office or off-field assessment includes the athlete's history, symptom checklist, cognitive screening of memory and concentration, neurological screening, and balance screening with the modified BESS (mBESS) and tandem gait test.^{16,17}

Postural control is commonly assessed using BESS and the tandem gait test.¹⁴ The BESS, originally developed as a balance screening tool for orthopedic injuries, consists of maintaining static balance in 3 stances for 20 seconds with eyes closed and hands on hips: double-leg stance, single-leg stance, and tandem stance.^{18,19} These stances are performed on both firm and foam surfaces with balance errors recorded.^{18,19} The BESS has moderate to high criterion validity and content validity, but depending on the stance: the more complicated the stance is (i.e., single-leg on foam), the higher the validity.¹⁸ The BESS has moderate intertester reliability (ICC=0.57-0.85) and intratester reliability (ICC=0.60-0.92).¹⁸ Specifically for concussed patients, the BESS has high content validity with large effect sizes when determining balance deficits in the acute (~3-5 days) phase.¹⁸

The tandem gait test is a reliable tool for assessing dynamic postural control, coordination, and speed, which are common deficits post-concussion.²⁰ It consists of walking on a 3m long straight line with an alternating heel-to-toe gait, making a 180° turn at the end and returning to the start using the same gait pattern.²⁰ The tandem gait has 0.632 sensitivity and

0.605 specificity to identify post-concussion postural control deficits during the acute phase of the injury.²⁰ A study by Howell et al. reported that individuals with concussion took significantly longer to complete dual-task tandem gait up to 23 days post-concussion, relative to non-concussed controls.²¹

VOMS evaluates impairments in the vestibular and ocular systems.²² This screening tool assesses symptoms of headache, dizziness, nausea, and foggiess before and immediately after 7 subtests: smooth pursuits, horizontal/vertical saccades, near point of convergence, horizontal/vertical vestibulo-ocular reflex (VOR), and visual motion sensitivity.²² VOMS allows for more targeted assessments, rehabilitation, and referrals for impairments caused by the vestibular and ocular systems rather than the neurometabolic cascade.²² VOMS is a useful screening tool, with a sensitivity ranging from 0.58-0.96 and a specificity of 0.46-0.92 to detect vestibulo-ocular deficits post-concussion, and there is at least a medium effect size comparing controls to concussion groups for all the individual tests besides horizontal VOR.²³

The symptom assessment is helpful when predicting and tracking recovery.¹⁴ A higher number and severity of symptoms indicate a slower recovery.^{1,14} Daily symptoms assessment further assists in tailoring treatment plans and protocols for return-to-play by allowing healthcare providers to monitor changes in symptoms in response to various activities or allow for appropriate referrals for patients experiencing prolonged recovery.¹⁴

While neurocognitive tests alone may not be sufficient in diagnosing concussions, they play a crucial role in making decisions for returning to activity by testing for cognitive deficits, particularly in attention, memory, and reaction time.¹⁴ CNS Vital Signs have a moderately positive correlation with traditional neuropsychological tests.²⁴ When administered to individuals who have recovered from concussion, CNS Vital Signs indicated no statistically significant

differences compared to the control group, suggesting its ability to determine when a patient has recovered.²⁴ Additionally, CNS Vital Signs was able to identify approximately 70% of sandbagging, where the individual intentionally performs poorly on the baseline test to return from a concussion sooner, showing its effectiveness in detecting invalid results.²⁵ These concussion assessments help healthcare providers determine specific impairments experienced by patients and the impact on various aspects of daily life due to concussion. This includes the individual's ability to engage in activities such as attending school, participating in sports, or driving safely. Early identification of these impairments is crucial for implementing appropriate interventions and support systems to facilitate recovery.

Driving

Driving is a complex task that requires motor, cognitive, vestibular, and ocular functions that are often affected post-concussion.²⁶ Driving impairments have been reported acutely following concussion using hazard perception tests and driving simulators.^{3,4} Within 24 hours, individuals with concussion displayed poorer driving performance relative to non-concussed controls.³ These individuals were slower to respond to traffic conflicts on hazard perception tests, with an average delay of .45 seconds, potentially increasing their risk of collision.³ Within 72 hours of the injury, individuals with concussion had more frequent lane excursions, a greater standard deviation of speed when avoiding a child pedestrian on the road, drove closer to the centerline, and had a greater standard deviation of lane position when maneuvering around a car crash, relative to non-concussed controls.⁴ These driving performances are associated with an increased risk of motor vehicle crash.⁴ Although non-significant during the acute phase, the concussion group also exhibited slightly shorter total drive duration, a greater percentage of exceeding speed limits, and more speed exceedances, relative to controls.⁴

At the point of asymptomatic, individuals with concussion demonstrated conservative driving including fewer speed exceedances and lower standard deviation of lane position while navigating through a traffic light compared to individuals without concussion.⁴ At the return-to-play time point, the concussion and control groups performed similarly on the simulated driving task.⁴

Current Protocols

Approximately 40% of athletic trainers always advise patients to refrain from driving temporarily post-concussion while approximately 60% do so occasionally.²⁷ Their recommendations are primarily based on clinical exams and are verbally communicated to refrain until their symptoms resolve.²⁷ Another study indicated that some clinicians use clinical measures such as reaction time to determine the readiness for return to driving post-concussion.²⁸ The recommendation includes minimizing distractions, driving shorter distances, and avoiding driving at night.²⁷ Some athletic trainers who have never given driving restrictions attributed their decision to not giving much thought to the driving restriction and the lack of publications and directives on the matter.²⁷ While healthcare providers feel that it is appropriate to give their patients restrictions for driving, the metrics used to determine those restrictions are unclear.²⁹ These indicate that there is a need for a standardized protocol for return-to-driving to help practitioners use the same, consistent clinical measures to relay appropriate driving recommendations to concussed patients.

Driving Behavior

While there is a growing understanding of how concussion affects driving performance post-injury, it is crucial to explore post-concussion driving behavior between the acute and asymptomatic time points. Understanding driving behavior after concussion is important as it

helps to identify potential risks and develop strategies to address them. Survey studies have provided insights into patients' attitudes towards driving post-concussion.^{5,6,10,30} Most adults, except college athletes, refrained from driving after sustaining an mTBI, including a concussion.^{5,6,30} The time frame in which concussion patients returned to driving varied between one to fourteen days post-concussion.^{5,6} Additionally, their driving behaviors were changed to driving less frequently, avoiding driving at night, driving shorter distances, avoiding busy traffic, and showing more restraint when driving with friends in the vehicle.^{6,7} Amongst majority of the patients, a healthcare provider did not give them any instructions regarding driving.^{5,30} However, if instruction had been given, they were 66% less likely to drive within the first 24 hours.³⁰ While the survey studies aid in understanding driving behaviors, the data is limited due to its self-reported nature. There is a need to capture driving behavior more objectively and comprehensively.

Driving Behavior in College Students

The highest total rates of deaths resulting from motor vehicle crashes occur in the 20-29 year-old age range, particularly more in males than females.³¹ Younger drivers tend to commit more traffic violations and participate more in risky driving behaviors.^{32,33} Some of these driving behaviors include not wearing a seatbelt, speeding, driving while drowsy, and failing to check mirrors.^{32,33} However, these risky driving behaviors tend to decrease as people age.^{32,33}

Young adults also tend to be more distracted while driving compared to their older counterparts.^{32,33} Common distraction activities include talking with other passengers in the car, making a phone call, replying to text messages, smoking, eating, and drinking.^{32,33}

Due to their increased participation in risky driving behaviors and driving distractions, the young adult drivers are at a higher likelihood to be in a motor vehicle crash.³² During the

acute time period, driving impairments increase the likelihood for a motor vehicle crash in concussed individuals.⁴ In order to help reduce the likelihood of motor vehicle crashes and deaths from motor vehicle crashes, it is crucial to study the driving behavior in concussed participants within this age range, hence why the population is college students.

Naturalistic Driving

Within clinical research, wearable technologies are widely used to capture longitudinal data in natural environments.³⁴ Cardiologists have long used wearable devices such as ambulatory electrocardiography devices to monitor heart rhythm, chest-strap and wrist strap heart rate monitors to monitor heart rate, pedometers and accelerometers to measure daily activity, remote dielectric sensing to measure lung fluid concentration using electromagnetic waves, and bioimpedance monitors to measure transthoracic impedance in evaluation and treatment of chronic heart failure.³⁵ Sleep studies use wearable sleep-trackers in the form of wristbands, armbands, smartwatches, headbands, rings, or sensor clips to monitor time spent in specific stages of the sleep cycle, movement arousals, sleep latency, and snoring.³⁶ In terms of driving, continual monitoring can be achieved using devices placed in cars to capture naturalistic driving behavior. This naturalistic driving enables us to objectively and comprehensively study driving behavior in real-world settings.³⁷ It produces precise driving behavioral data, such as distance driven, time of day driven, number of trips per day, average driving speed, and risky driving behaviors.³⁷

There are many ways to capture naturalistic driving behavior: global positioning system (GPS), on-board logger, accelerometer, video camera, radar/LiDAR sensor, exhaust gas analyzer, mobile phone and eye-tracking devices.³⁸ A GPS or on-board logger device, which works by communicating with satellites to capture driving data, is the most common method.³⁸

This study will use a GPS tracker because of its minimal influence on driving behavior, its ability to capture multiple driving characteristics, and its widespread use which allows this study to be easily compared to existing and future studies.³⁸

Naturalistic driving data studies revealed that individuals with preclinical Alzheimer's disease drove less frequently, visited fewer places, and had fewer trips with aggressive behavior compared to those without preclinical Alzheimer's disease.⁹ Another study found that young drivers drove significantly faster and exhibited more aggressive driving behavior during the COVID-19 lockdown compared to pre-and post-COVID-19.¹⁰ To date, there is only one pilot study that investigated driving behavior in individuals with concussion using naturalistic driving.¹¹ Individuals with concussion drove less and slower than non-concussed individuals during the initial 3 days of the injury and drove similarly after day 3 post-concussion.¹¹ However, this study presents limitations of having a limited time frame, inconsistent data across days post-concussion, and a small sample size.¹¹ Additionally, the specific clinical presentations of concussion that correlate with such driving behavior in concussed individuals remain questionable. One study reported that individuals suffering from headache, dizziness, and “not feeling right” refrained from driving for 2 weeks following concussion.¹² However, little is known about how other concussion signs and symptoms affect driving behavior.

Rationale for the Study

There are many uncertainties when it comes to post-concussion driving. Several studies have shown having a concussion affects driving performance using a driving simulator.^{3,4} However, there is a lack of research using naturalistic driving to investigate driving behavior.^{3,4} Survey studies attempt to provide insight into naturalistic driving behaviors, demonstrating that many concussed individuals drive immediately after sustaining a concussion; some feel unsafe

driving, yet there is a lack of objective data due to the self-reporting nature of surveys.^{5-7,30} There are no currently established protocols for healthcare practitioners to follow regarding the return-to-driving after concussion. This lack of standardization leads to significant variability in how recommendations are provided to patients, influencing the patient's decision on driving.^{5,27-29} Therefore, there is a need for a better understanding of driving behavior in individuals with concussion, both to more objectively describe patterns and to correlate them with clinical measures. While it may take many years and multiple research findings to create a standardized protocol for return to driving post-concussion, this study aims to start the conversation by using GPS technology and standardized clinical concussion measures.³⁹ This study will help deepen understanding of driving behavior more accurately.

CHAPTER 3

METHODS

Design

To address our first objective, we used a longitudinal design to determine the association between clinical concussion assessments and naturalistic driving behaviors and risky driving events in college students with concussion relative to the control group during the acute phase of the injury (days 2-4).

To address our second objective, we used a cross-sectional design to determine the association between daily symptom severity score and driving behavior and risky driving behaviors in the concussion group through the whole time period as well as during the acute time period (days 2-4).

Participants

Thirteen college athletes with concussion and nine non-concussed college athlete controls were recruited as a part of a larger study that included simulated and naturalistic driving. For the concussion group, all individuals who met diagnostic criteria according to the Concussion in Sport Group criteria were invited to participate in the larger study, with the naturalistic driving portion being optional.⁴⁰ For the non-concussed control group, matched individuals were recruited based on age, sex, number of years driving, and sport (if applicable). For both groups, the inclusion criteria were as follows: holding valid Class C driver's licenses and normal or corrected-to-normal vision. Exclusion criteria for both groups included having 3+ previous self-reported concussions, major neurological disorders or injuries, use of prescription or over-the-

counter medications that elicit drowsiness, heavy use of alcohol, and any illegal drug use.

Informed consent was collected from all participants before data collection. The University of Georgia Institutional Review Board approved this study.

Instrumentation

GPS Unit

The participants were given the Azuga G2 Tracking DeviceTM (Figure 1, Model 850: Azuga Inc, San Jose, California) GPS at the initial post-injury evaluation within the first 48 hours, which was returned on day 9 post-concussion. Day 9 post-concussion was chosen to specifically capture the acute recovery while also monitoring the transition from symptomatic to asymptomatic status. During this timeframe, individuals with concussion often experience improvements in symptoms and function which may correspond to changes in driving behaviors.⁴ The GPS device was installed in the OBD-II port, where instructions were given to each participant based on their type of vehicle. The GPS device captured data every 30 seconds.⁴¹

From this device, the date, ignition start and stop time, start location, end location, total drive time, distance traveled (miles), stop time, idle time, idle percentage, maximum speed (mph), average speed (mph), number of speed exceedances, speeding duration, hard braking (speed decreases by 8-10mph per second or 3.5-4.5m/s), sudden accelerations (speed increases by 8-10mph per second or 3.5-4.5m/s), and detected collisions were collected for every drive taken.⁴² The device captured the number of speeding exceedances and speeding duration by detecting when the participant exceeded the posted speed limits on the road they drove.⁴² Participants completed a daily driving log which allowed the researcher to exclude drives where another person drove their vehicle.



Figure 1. Global positioning system to scale (Model 850: Azuga Inc, San Jose, California).

Symptoms

Daily symptom scores were assessed every day using the SCAT-6 symptom scale. The symptom checklist was a list of 22 symptoms that the participant rated from 0-6, with 0 being no symptoms and 6 being the most severe.¹⁵ The severities of each individual symptom score were summed to calculate the total daily symptom severity score, which was recorded every day for 9 days.¹⁵

Vestibular Ocular Motor Screening (VOMS)

The VOMS consists of five assessments of ocular and vestibular function: (1) smooth pursuit, (2) saccades, (3) near point convergence, (4) VOR, and (5) visual motion sensitivity.²¹ Before and after each VOMS assessment the patient rates headache, dizziness, nausea, and foginess on a scale from 0-10, with 0 being no symptoms and 10 being heavy symptoms.⁴³ A pre-test symptom score was calculated by adding four symptoms before the VOMS assessment.⁴³ The symptom provocation score for each assessment was calculated by subtracting pre-test symptom score from the post-assessment symptom score (post-pre). A positive value indicates a worsening of symptoms post-assessment, and a negative value indicates an improvement of symptoms post-assessment.^{22,23}

Smooth Pursuit: While the participant sat 3ft (91cm) away, the researcher held their finger at approximately eye level.⁴³ Then, the participant was directed to follow the researcher's

finger as they moved their finger 1.5ft (45cm) to the left and 1.5ft (45cm) to the right of the starting point over a total time of ~3s.⁴³ This motion was performed twice.⁴³ Then, beginning at the starting point, the researcher moved their finger up 1.5ft (45cm) and down 1.5ft (45cm), moving the total 3ft (91cm) over ~3s 2 times.⁴³

Saccades (Horizontal and Vertical): The participant sat 3ft (91cm) away from the researcher as they held two fingers up, each about 1.5ft (45cm) away from the participant's midline, for a total of 3ft (91cm) between the two fingers, at about eye level.⁴³ The participant was directed to move only their eyes from one finger to the other a total of 10 times.⁴³ Vertical saccades were performed similar to horizontal saccades except that the researcher's fingers were now 1.5ft (45cm) above and below the participant's eye level.⁴³

Near Point Convergence: The participant held a target straight up in the air at nose height about an arm's length away from their nose.⁴³ The participant was directed to focus on the target as they slowly moved the target closer to their nose.⁴³ The participant was directed to stop moving the target either when they saw two images or when the researcher saw an outward deviation of either eye.⁴³

Vestibular Ocular Reflex: For horizontal VOR, the researcher sat 3ft (91cm) away from the participant.⁴³ A metronome was set to 180 beats per minute (bpm).⁴³ The researcher held a target at about eye level 3ft (91cm) away from the participant.⁴³ The participant was instructed to focus on the target while moving their head from 20 degrees left to 20 degrees right with the beat of the metronome 10 times.⁴³ Vertical VOR was performed similar to horizontal VOR, except that the participant was now instructed to move their head from 20 degrees up to 20 degrees down.⁴³

Visual Motion Sensitivity: Visual motion sensitivity was performed by having the patient stand shoulder-width apart with their dominant thumb stretched out in front of them at shoulder-height.⁴³ A metronome was set to 50 bpm.⁴³ The participant was instructed to focus on their thumb while they rotated their trunk from 80 degrees left to 80 degrees right with the beat of the metronome 5 times.⁴³

Balance Error Scoring System (BESS)

During BESS, the participant performed six static balance tasks: (1) double leg stance, (2) single leg stance, and (3) tandem stance on a firm surface and then repeat the same three on a foam Airex pad (40×50×6.5 cm; Fitter International Inc., Calgary, Canada) for 20 seconds while having eyes closed and hands on the iliac crest.¹⁴ The time started when the participant first assumed the correct starting position with eyes closed. Trained examiners recorded the number of errors for each stance as outcome measures for a maximum of 10 errors per task.¹⁴ There were six possible errors: (1) hands coming off of the iliac crests, (2) opening eyes, (3) step, stumble, or fall, (4) moving hip into greater than 37 degrees abduction, (5) lifting forefoot or heel, and (6) remaining out of the test position for more than 5 seconds.¹⁴ If multiple errors were seen simultaneously, only one error was counted.¹⁴ The total error score was calculated by adding up the errors in each task and was calculated separately based on the surface.^{14,18}

Tandem Gait

The participant walked with an alternate heel-to-toe gait on the straight 3m line of athletic tape.¹⁴ At the end, the participant turned 180 degrees and used the same gait to return back to the starting point as quickly as possible.¹⁴ The completion time for successful trials was recorded in seconds, and the three trials were averaged (seconds).

The participant did the same tandem gait task with an added cognitive task of counting backward by 7s for dual-task tandem gait.¹⁴ The completion time was recorded in seconds, and three successful trials were averaged (seconds).

CNS Vital Signs

The participant took CNS Vital Signs, a computerized neurocognitive test, in a quiet, distraction-free environment.⁴⁴ There are ten subtests: verbal memory, visual memory, finger tapping, symbol digit coding, Stroop test, shifting attention, continuous performance, perception of emotions, non-verbal reasoning, and 4-part continuous performance.⁴⁴ The results of these subtests are expressed in domains.⁴⁴ For this research, visual memory, psychomotor speed, reaction time, complex attention, cognitive flexibility, processing speed, executive function, and motor speed were used as outcome measures.⁴⁴

Procedure

Participants came in for the initial appointment within 72 hours of the onset of the concussion. At the initial evaluation, participants completed a symptom checklist, VOMS, BESS, tandem gait, and CNS Vital Signs. This data collection took 45-60 minutes to complete. At the end of the evaluation, the participants were given the Azuga G2 Tracking DeviceTM and instructions on how to install the device specific to their vehicle. The participant was not given any driving guidelines and was asked to fill out the symptom checklist daily. They returned the device on day 9 post-concussion. Table 1 shows a timeline of the data collection for the clinical and driving measures.

Table 1. Data Collection Timeline for Clinical and Driving Measures.

	Day 2	Day 3	Day 4	Day 5	Day 6	Day 7	Day 8	Day 9
Clinical Concussion Assessment								
Symptoms	X	X	X	X	X	X	X	X
VOMS	X							
BESS	X							
Tandem gait	X							
CNS Vital Signs	X							
Driving Behavior								
Trip Duration	X	X	X	X	X	X	X	X
Trip Distance	X	X	X	X	X	X	X	X
Average Speed	X	X	X	X	X	X	X	X
Number of Trips	X	X	X	X	X	X	X	X
Risky Driving Events								
Hard Braking	X	X	X	X	X	X	X	X
Sudden Acceleration	X	X	X	X	X	X	X	X

Data Cleaning

The Azuga G2 Tracking DeviceTM transmitted data to a cloud portal where it was exported to Microsoft[®] Excel[®] (Microsoft Corporation, Version 2502). The raw data for each trip was then processed into appropriate units as outlined in Table 2. Trip duration and trip distance were summed across all drives each day. These values were summed to find the total trip duration and trip distance for the day. This approach better represents driving behavior rather than average duration and distance per day. Speed was averaged across all drives occurring within each day. The number of hard braking and sudden accelerations were expressed as events per hour to normalize across participants. A trip was defined as the distance traveled over 0.15 km as shorter distances are considered part of a stop or within the same visited location.^{45,46}

For the first and last days of data collection, they were considered full days of driving if the participant's first trip occurred before noon on the first day and last trip occurred after noon. This approach ensured that the driving behavior was representative of a full day's activity, allowing for consistent data comparison across participants. If trips on these days did not meet the criteria, they were excluded from the full-day analysis to prevent data from skewing the results.

Driving behaviors of total drive duration (s), total drive distance (km), average speed per trip (m/s), and number of trips per day (count) as well as risky driving events of hard brakings (events per hour) and sudden accelerations (events per hour) were averaged across days 2-4 to capture driving behavior and risky driving events during the acute phase (Table 2). Based on previous research in driving simulators, there are significant differences within the acute time period between driving behaviors in concussed and control individuals,^{3,4} so only acute driving behavior was used for the analysis of objective 1.

Table 2. Naturalistic Driving Data Outcomes.

	Driving Characteristic	Unit
Driving behavioral outcomes	Total Drive Duration	Seconds
	Total Drive Distance	Kilometers
	Average Speed	m/s
	Number of trips per day	Count
Risky driving behaviors	Hard Braking	Events per hour
	Sudden Acceleration	Events per hour

Statistical Analysis

Analyses were completed using Statistical Package for Social Science (SPSS) (IBM®, Chicago, IL) with a priori alpha level of 0.05. Demographic characteristics and clinical concussion assessments were compared between groups using a chi-square, Mann Whitney U, or an independent samples t-test based on distribution. Table 3 describes how the data were analyzed.

Objective 1): To determine the association between clinical concussion assessments and acute (days 2-4 post-concussion) driving behaviors and risky driving events in patients with concussion when compared to the control group. Separate generalized linear mixed models were

used to identify clinical concussion assessment outcomes associated with acute driving behavior in the concussion group, relative to controls. The models included the interaction effect (group x assessment) and fit either a Poisson distribution or normal distribution. A significant interaction indicates the relationship between clinical assessment outcomes and post-concussion driving behaviors differs across groups.

Objective 2): To determine the association between daily symptom score and driving behaviors and risky driving events in the concussion group for up to nine days post-concussion. Two analyses were conducted: one for the whole nine days and one for the acute period (days 2-4 post-concussion). Spearman's rank correlation was used based on having a non-normal distribution.

Table 3. Statistical Analysis.

Objective 1): Describe driving behavior characteristics			
Independent Variable		Dependent Variable	Statistics
Group - Concussion - Control	Clinical Concussion Assessment - CNS Vital Signs - BESS - Tandem gait - VOMS - Symptom checklists	Acute Driving Behavior (Days 2-4) - Total drive duration - Total drive distance - Average Speed - Number of trips per day Acute Risky Driving Events (Days 2-4) - Hard braking - Sudden acceleration	Generalized linear mixed model Interaction (group x assessment)
Objective 2): Association between symptoms and driving behaviors			
Independent Variable		Dependent Variable	Statistics
Total Symptom Score in Concussion group		Driving Behavior (Days 2-9) - Total drive duration - Total drive distance - Average Speed - Number of trips per day Risky Driving Events (Days 2-9) - Hard braking - Sudden acceleration	Spearman's rank correlation

CHAPTER 4

RESULTS

A total of twenty-two college students participated in the study including thirteen individuals with concussion and nine control participants. Table 4 describes the demographics of the sample. While the average age and driving experience were similar between groups ($p>0.05$), the concussion group reported a significantly higher number of previous concussions compared to the control group ($p=0.003$). Table 5 and Table 6 show descriptive outcomes of naturalistic driving and clinical concussion assessment in the concussion and control groups, respectively. Median and interquartile ranges were reported due to the non-normal distribution of the data.

Only 2 individuals with concussion committed hard braking events and sudden acceleration (Table 5). Additionally, in the control group, only 4 individuals committed hard braking events, and 3 individuals committed sudden acceleration events. Due to the lack of variability in the data, generalized linear mixed models were not conducted. Instead, descriptive statistics analyses were used (Figure 4).

Table 4. Demographics of Participants.

	Control	Concussion	p-value
Age (years)	20.22±1.37	21.15±1.52	0.124
Sex (Female)	8 (89%)	8 (62%)	0.353
Years with Driving License (years)	3.78±1.58	4.23±1.92	0.565
Number of Previous Concussions	0.11±0.32	1.69±1.18	0.003*
Sport			0.528
Baseball	0	1	
Basketball	1	4	
Cross Country/Track	1	0	
Equestrian	0	1	
Football	1	1	
Golf	1	1	
Gymnastics	0	1	
Soccer	2	1	
Softball	2	0	
Swimming	1	2	
Volleyball	0	1	

*Denotes significant differences ($p < 0.05$)

Table 5. Descriptive Statistics of Driving Behavior Characteristics and Risky Driving Events.

	Group	Min	Max	Median	Lower Quartile	Upper Quartile
Total Duration (s)	Concussion (N=13)	0	7331.3	2004.7	1566.0	5122.7
	Control (N=9)	2284	15128.3	4121.0	2998.0	5939.7
Total Distance (km)	Concussion (N=13)	0	50.4	9.3	6.2	30.8
	Control (N=9)	12.5	242.2	21.5	17.5	34.3
Average Speed (m/s)	Concussion (N=13)	0	12.6	5.6	4.0	8.4
	Control (N=9)	4.6	15.5	8.3	6.8	10.1
Trips per Day (count)	Concussion (N=13)	0	7.0	3.0	1.7	3.7
	Control (N=9)	2.3	7.3	5.3	4.0	6.3
Hard Braking (events per hour)	Concussion (N=13)	0	2.8	0.0	0.0	0.0
	Control (N=9)	0	1.5	0.0	0.0	0.5
Sudden Acceleration (events per hour)	Concussion (N=13)	0	1.1	0.0	0.0	0.0
	Control (N=9)	0	0.5	0.0	0.0	0.4

Table 6. Descriptive Statistics of Clinical Concussion Outcome Measures.

	Group	Min	Max	Median	Lower Quartile	Upper Quartile
Total Symptoms	Concussion (N=11)	0	61	27.0	16.5	44.5
	Control (N=9)	0	3	0.0	0.0	1.0
Complex Attention	Concussion (N=6)	1	21	9.5	6.3	16.5
	Control (N=5)	1	195	6.0	3.0	152.0
Cognitive Flexibility	Concussion (N=6)	35	53	44.0	38.0	47.0
	Control (N=5)	37	63	61.0	52.0	63.0
Executive Function	Concussion (N=6)	38	56	47.5	40.3	48.0
	Control (N=5)	39	64	63.0	52.0	63.0
Motor Speed	Concussion (N=7)	82	139	101.0	98.0	113.0
	Control (N=5)	102	143	128.0	109.0	132.0
Processing Speed	Concussion (N=7)	36	70	57.0	56.0	62.0
	Control (N=5)	60	79	75.0	64.0	76.0
Psychomotor Speed	Concussion (N=7)	120	204	164.0	158.5	174.0
	Control (N=5)	170	222	196.0	177.0	207.0
Reaction Time	Concussion (N=7)	504	812	626.0	572.0	701.0
	Control (N=5)	504	624	548.0	548.0	604.0
Visual Memory	Concussion (N=6)	37	55	43.0	39.5	48.8
	Control (N=5)	42	55	48.0	45.0	53.0
BESS Firm Total	Concussion (N=12)	0	13	3.0	1.8	6.3
	Control (N=9)	0	6	2.0	1.0	3.0
BESS Foam Total	Concussion (N=12)	0	16	9.5	6.5	12.0
	Control (N=9)	4	12	7.0	5.0	8.0
Single-Task Tandem Gait	Concussion (N=9)	4	27.8	15.3	14.1	22.1
	Control (N=9)	4	27.8	8.7	6.0	11.7
Dual-Task Tandem Gait	Concussion (N=9)	10.4	27.8	15.3	14.2	22.1
	Control (N=9)	12.7	27.8	17.4	13.7	21.2
Smooth Pursuits	Concussion (N=11)	-9	2	0.0	0.0	0.5
	Control (N=8)	0	0	0.0	0.0	0.0

	Group	Min	Max	Median	Lower Quartile	Upper Quartile
Horizontal Saccades	Concussion (N=11)	-7	3	1.0	0.0	1.0
	Control (N=8)	0	0	0.0	0.0	0.0
Vertical Saccades	Concussion (N=11)	-5	5	1.0	0.0	1.0
	Control (N=8)	0	0	0.0	0.0	0.0
Near Point Convergence	Concussion (N=10)	-9	3	0.5	0.0	1.8
	Control (N=8)	0	0	0.0	0.0	0.0
Horizontal VOR	Concussion (N=10)	-4	6	2.0	1.0	3.8
	Control (N=8)	0	0	0.0	0.0	0.0
Vertical VOR	Concussion (N=10)	-4	6	2.0	1.0	3.8
	Control (N=8)	0	0	0.0	0.0	0.0
Visual Motion Sensitivity	Concussion (N=10)	-3	9	2.0	0.5	6.3
	Control (N=8)	0	0	0.0	0.0	0.0

Note: A positive value for VOMS indicates a worsening of symptoms, and a negative value for VOMS indicates an improvement in symptoms compared to pre-VOMS assessment.

Objective 1

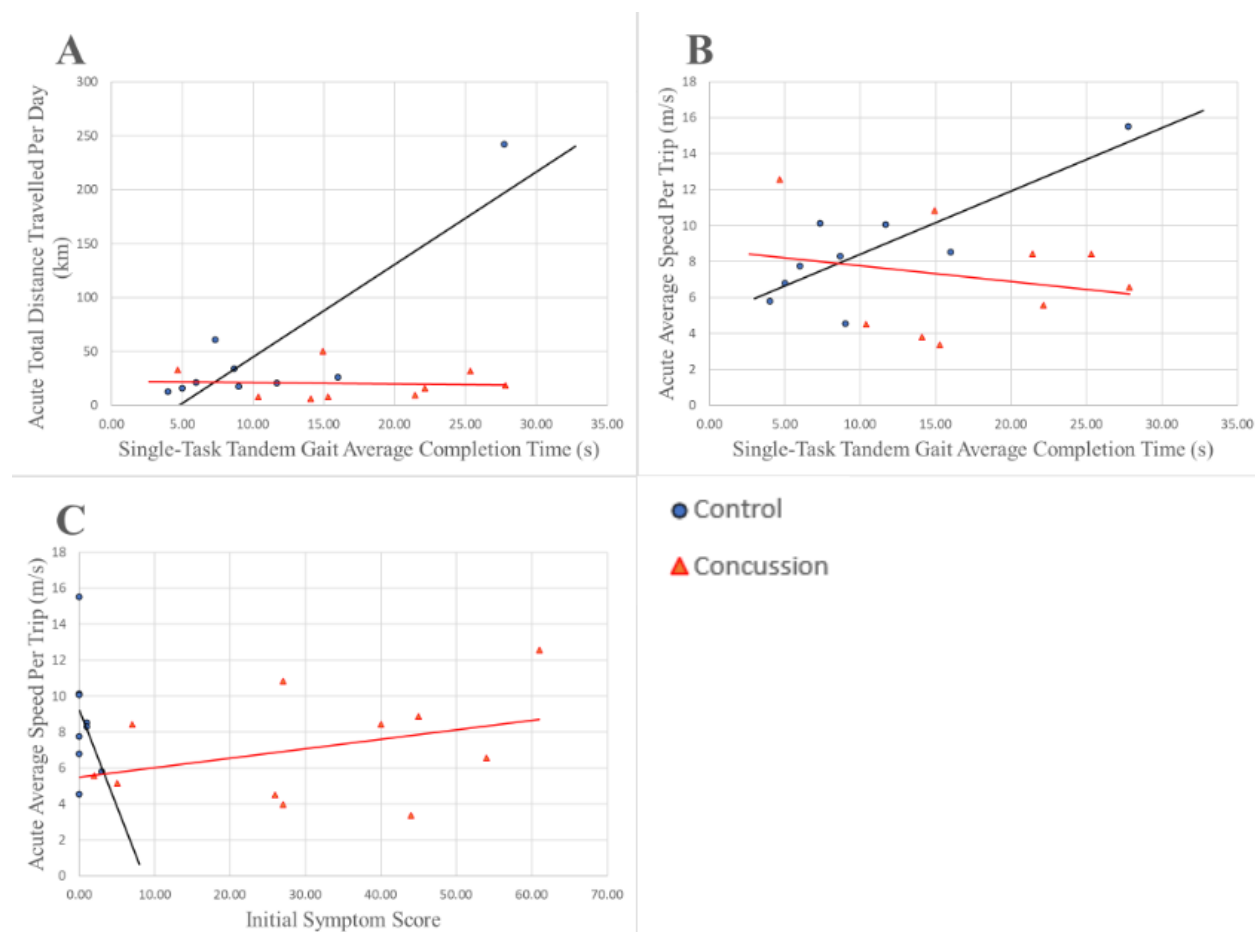


Figure 2. Interactions between acute total driving distance and A) single-task tandem gait completion time; acute average driving speed and B) single-task tandem gait completion time, C) initial symptom score.

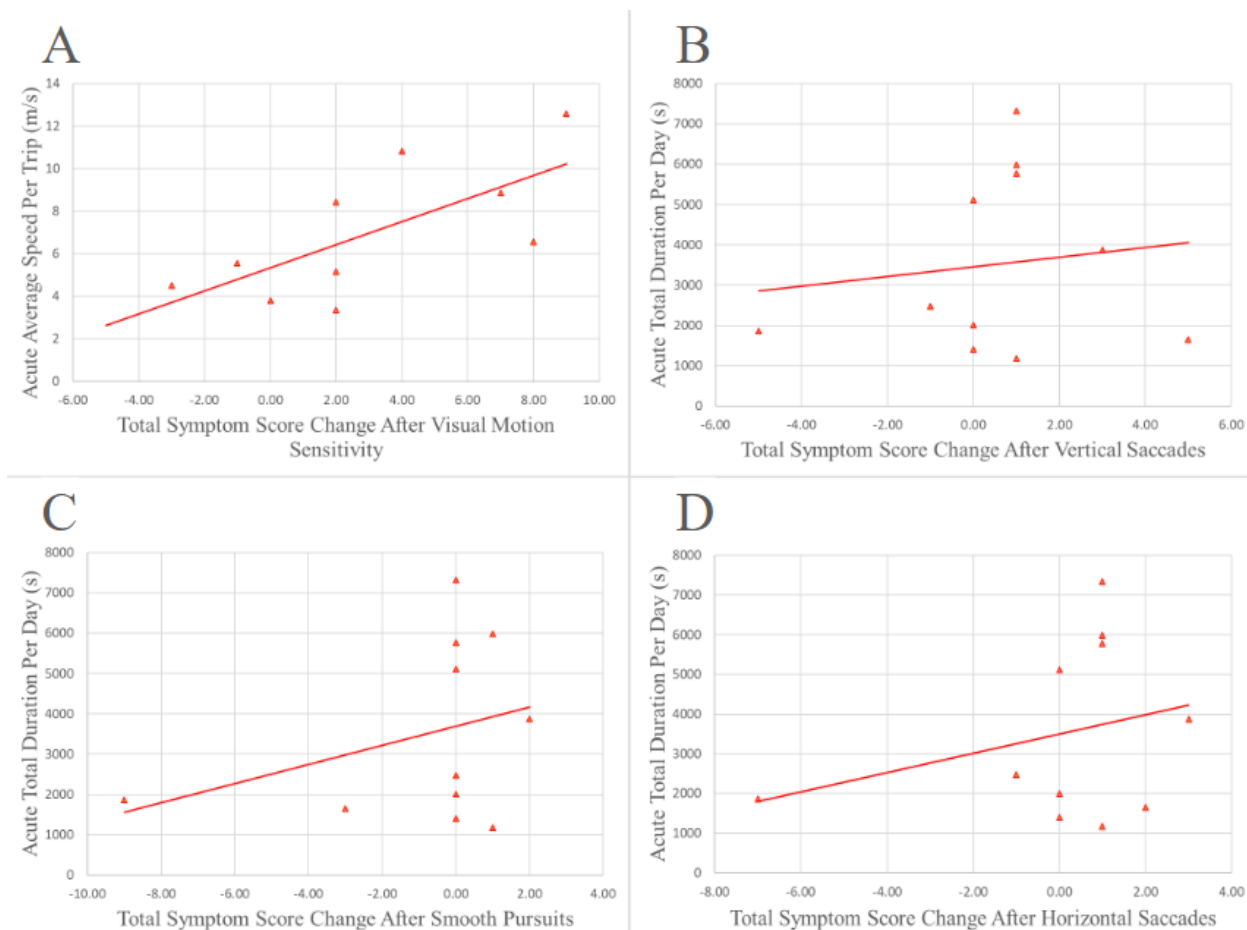


Figure 3. Correlations in the concussion group between acute average speed and A) symptom provocation score of visual motion sensitivity; and acute total driving duration and B) symptom provocation score of vertical saccades, C) symptom provocation score of smooth pursuits, D) symptom provocation score of horizontal saccades.

Driving behaviors

The interaction effects are reported in Supplemental Tables 1-4 in the appendix. Six significant interaction effects were found between clinical concussion assessment outcomes and driving behaviors as described below. For the interaction effects between the VOMS assessments, if a significant interaction effect was found, a subsequent analysis was done with Pearson's r correlation to determine the relationship in the concussion group only, and these values have been reported in Table 7. The Pearson's r values were used instead of the generalized linear mixed models for these outcomes because there was no symptom provocation during VOMS in control group, and the relationship between VOMS and naturalistic driving

behavior appeared as a vertical line. A false interpretation may happen due to interaction.

Therefore, Pearson's r correlation was used instead.

Total driving distance & single-task tandem gait (interaction effect: $p=0.006$): A slower completion time during the single-task tandem gait was associated with shorter driving distances ($B=-0.187$, Figure 2A) in the concussion group relative to controls.

Average driving & single-task tandem gait (interaction effect: $p<0.001$): A slower completion time during the single-task tandem gait was associated with slower average speed ($B=-1.024$, Figure 2B) in the concussion group relative to controls.

Average speed & initial symptom score (interaction effect: $p=0.022$): A higher initial symptom score was associated with greater average speed ($B=0.029$, Figure 2C) in the concussion group relative to controls.

Average speed & symptom provocation during visual motion sensitivity on VOMS (Pearson's $r=0.6930$): An increase in symptoms after the visual motion sensitivity portion of the VOMS was associated with a greater average speed ($\beta=0.5409$, Figure 3A) in concussed individuals relative to controls.

Driving duration & symptom provocation during vertical saccades on VOMS (Pearson's $r=0.1349$): An increase in symptoms after vertical saccades ($\beta=119.73$, Figure 3B) was associated with an increased driving duration in the concussed group relative to controls.

Driving duration & symptom provocation during smooth pursuits on VOMS (Pearson's $r=0.3253$): An increase in symptoms after smooth pursuits ($\beta=237.09$, Figure 3C) was associated with an increased driving duration in the concussed group relative to controls.

Driving duration & symptom provocation during horizontal saccades (Pearson's $r=0.2858$): An increase in symptoms after horizontal saccades ($\beta=241.95$, Figure 3D) was associated with an increased driving duration in the concussed group relative to controls.

Table 7. Correlation between VOMS Symptom Provocation and Average Speed or Drive Duration in the Concussion Group for Days 2-4.

VOMS outcomes	Driving Behavior	Pearson's r	R ²	Regression Coefficient	Intercept
Visual Motion Sensitivity	Average Speed	0.6903	0.4803	0.5409	5.3435
Vertical Saccades	Driving Duration	0.1349	0.0182	119.73	3451.1
Smooth Pursuits	Driving Duration	0.3253	0.1058	237.09	3688.8
Horizontal Saccades	Driving Duration	0.2858	0.0817	241.95	3494.4

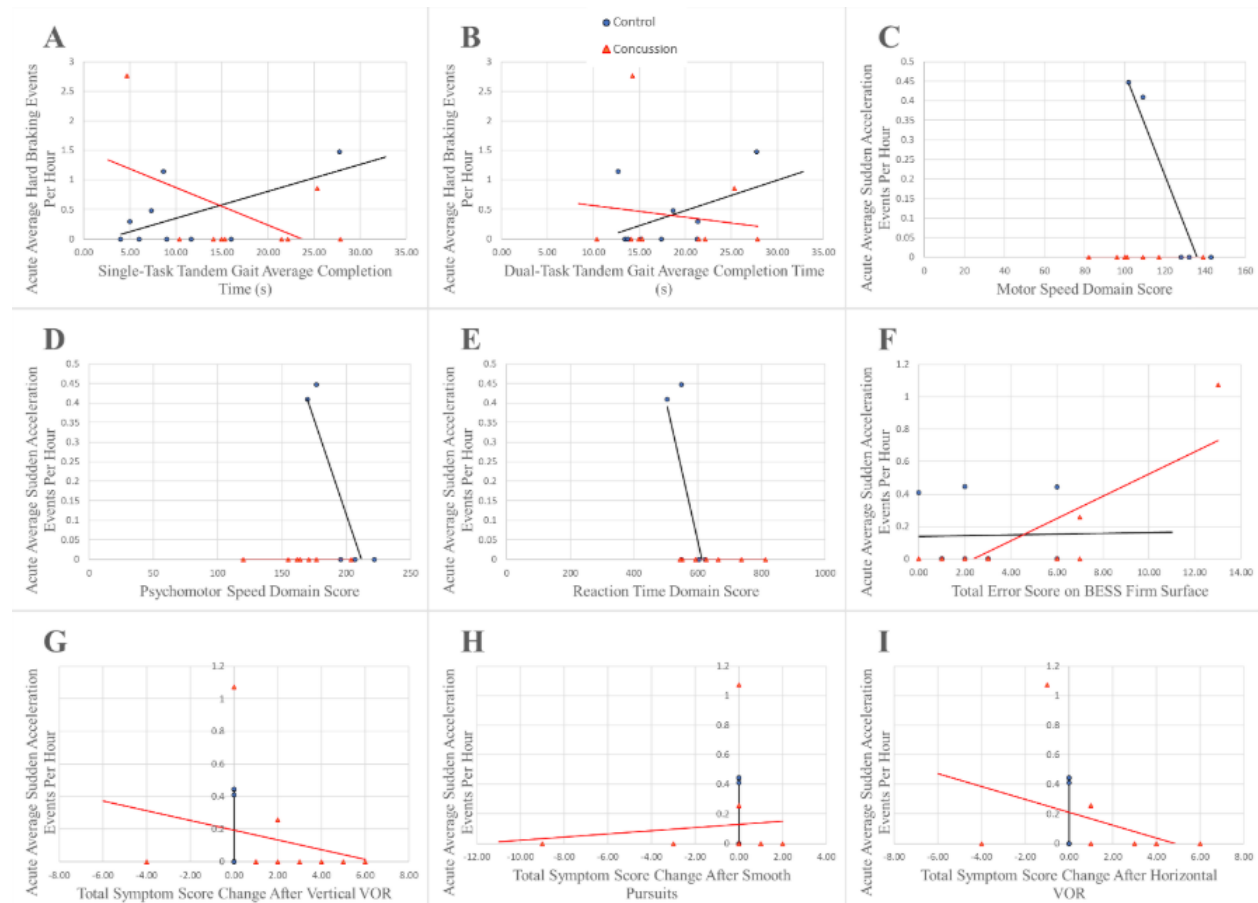


Figure 4. Interactions between hard braking events and A) single-task tandem gait completion time, B) dual-task tandem gait completion time; sudden acceleration events and C) motor speed domain score, D) psychomotor speed domain score, E) reaction time domain score, F) total errors on BESS Firm surface G) total symptom score change after vertical VOR, H) total

symptom score change after smooth pursuits, I) total symptom score change after horizontal VOR.

Objective 2

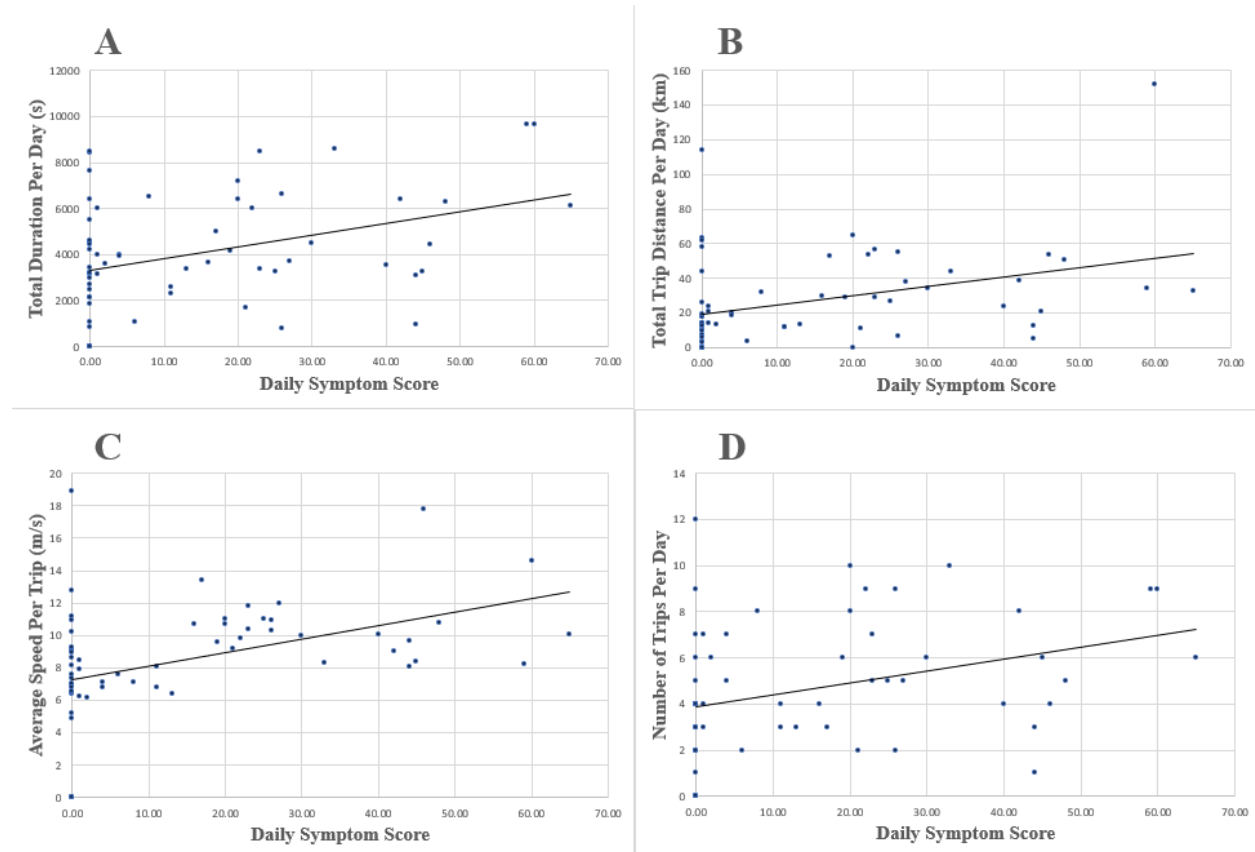


Figure 5. Interactions between total daily symptom score from days 2-9 and A) total trip duration per day, B) total trip distance per day, C) average speed per trip, and D) number of trips per day, for days 2-9 in the concussion group only.

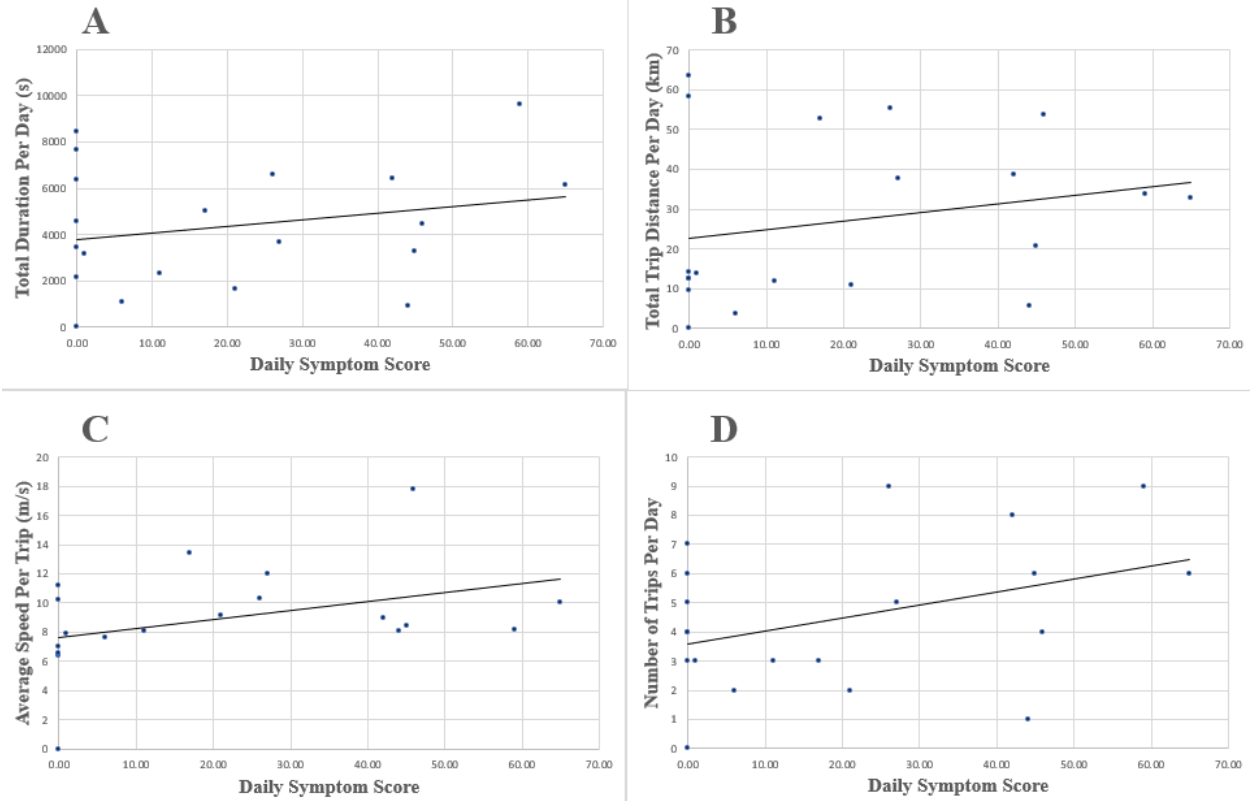


Figure 6. Interactions between total daily symptom score from days 2-4 and A) total trip duration per day, B) total trip distance per day, C) average speed per trip, and D) number of trips per day, for days 2-4 in the concussion group only.

For days 2-9, greater daily symptom severity score was associated with greater driving duration ($\rho=0.355$, $p=0.005$, Figure 5A), driving distance ($\rho=0.421$, $p<0.001$, Figure 5B), driving speed ($\rho=0.478$, $p<0.001$, Figure 5C), and number of trips per day ($\rho=0.464$, $p<0.001$, Figure 5D). For days 2-4, greater daily symptom severity score was associated only with greater driving speed ($\rho=0.516$, $p=0.020$, Figure 6C). Table 8 shows the correlation outcomes between daily symptom scores and naturalistic driving behaviors and risky driving events through the days 2-9 while Table 9 shows the correlation outcomes only in the acute time period (days 2-4).

Table 8. Correlation between Symptom scores and Naturalistic Driving Behaviors and Risky Driving Events in Concussion Group During Days 2-9.

Independent Variable	P-value	rho
Total Drive Duration	0.005	0.355
Total Drive Distance	<0.001	0.421
Average Speed	<0.001	0.478
Trips per Day	<0.001	0.464
Hard Braking	0.127	0.196
Sudden Acceleration	0.434	0.101

Table 9. Correlation between Symptom scores and Naturalistic Driving Behaviors and Risky Driving Events in Concussion Group During the Acute Time Period (Days 2-4).

Independent Variable	P-value	rho
Total Drive Duration	0.642	0.111
Total Drive Distance	0.362	0.215
Average Speed	0.020	0.516
Trips per Day	0.231	0.280
Hard Braking	0.507	0.158
Sudden Acceleration	0.260	-0.264

CHAPTER 5

DISCUSSION

Findings from our study provide novel preliminary insights into how post-concussion deficits may influence post-concussion naturalistic driving behaviors. Statistically, we observed static balance functions, symptom severity and vestibulo-ocular functions were associated with driving behaviors in the concussion group relative to controls.

Objective 1

Driving behaviors

The findings of this study highlight the key associations between balance function and naturalistic driving performance. In the concussion group, every additional 10 seconds taken to complete single-task tandem gait test was associated with 1.87km (1.16mi) decrease in total driving distance per day and a 10.24m/s (22.91mph) decline in average speed per trip compared to the control group. While the interaction between total drive distance and single-task tandem gait was statistically significant, the magnitude was small, and clinical meaningfulness may be limited. However, we have observed a quite large decrease in average speed when individuals with concussion took longer to complete single-task tandem gait. Prior research indicates that individuals with mTBIs, including concussions, may not accurately recognize and report cognitive and physical impairments post-injury.^{47,48} Especially if they are not having difficulties with simple balance tasks, they may perceive a higher motor function capability, potentially leading them to drive at higher speeds. Further research is needed to explore this finding and its implications for post-concussion driving safety.

Additionally, within the control group, there was one participant who had an extremely long single-task tandem gait completion time and also drove longer distances and higher speeds (Figure 2A-B). With this outlier removed, the relationship within the control group between variables looks very different (Figure 7A-B). However, it is important to note that this reflects the participant's natural driving behavior and given the small sample size of this study, it is unclear whether this outcome is a true outlier. Future studies with larger sample sizes and controlling weekday/weekend drives might account for variability in results.

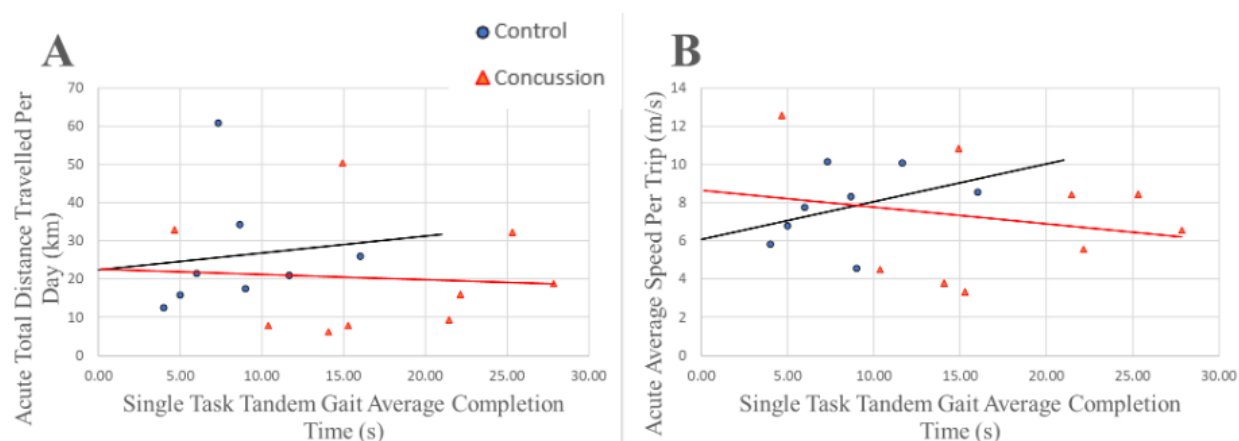


Figure 7. Interactions between acute total distance traveled and A) single task tandem gait; acute average speed and B) single task tandem gait where the outlier within the control group has been removed.

Every 10-point increase in total symptom severity in the concussion group was associated with a 2.9m/s (6.49mph) increase in average speed per trip. This number is quite large in magnitude and may reflect the change in safe driving abilities. Given this association, clinicians should consider integrating symptom monitoring into return-to-drive recommendations to enhance safety.

We found that an increase in symptoms after visual motion sensitivity on the VOMS led to a slight increase in average speed per trip. Specifically, every additional symptom provocation was correlated with a 0.5m/s (1.12mph) increase in average speed per trip. This magnitude is quite small, so the clinical significance of this finding may be limited. While the clinical

significance is limited, this finding is contrary to our hypothesis. A possible explanation for this could be a lack of disease insight with reduced symptom awareness.^{47,48} This may influence individuals to drive at a faster speed, which would be characteristic of normal driving behavior in this population,^{32,33} leading to the finding being contrary to our hypothesis. Further studies could focus on investigating this angle.

Additionally, symptom provocation after vertical saccades, smooth pursuits, and horizontal saccades in the VOMS test were all associated with an increase in drive duration. For every symptom provocation, drive duration increased 119.73s, 237.09s, and 241.95s respectively. In terms of the concussion group as a whole, this value is small in magnitude and may be limited in clinical significance. However, in terms of the concussed individuals within the lower quartile (1566.0s), this value is quite significant. A possible explanation could be that the motions of smooth pursuits as well as horizontal and vertical saccades are constantly happening while driving, when following objects on the road or looking between mirrors and the road in front. Doing these motions may lead to an increase in symptoms while driving, causing the concussed individuals to have a more difficult time while driving and, in turn, leading to longer driving durations. Though it is not recommended to drive in the acute time period, especially due to possible circumstances such as this, concussed individuals are still driving. Therefore, further studies are needed to confirm these findings to help with creating more comprehensive post-concussion driving education.

Risky driving events

Hard braking events and sudden acceleration events were rarer than originally expected and especially rare in our small sample, which limited our ability to explore these relationships statistically. One possible explanation is the location of the studies. Since the studies were done

in college towns, drivers may exhibit more conservative behavior due to the perception that urban areas are more hazardous to drive through compared to rural areas.⁴⁹ An additional explanation is the sample size combined with the rarity of these risky driving events, leading there to be too small of a number of events to be analyzed. Further studies may need to consider using a categorial approach of just counting how many events happened rather than normalizing them per hour and/or having a larger sample size where they have more events to analyze.

Objective 2

Contrary to our hypotheses, individuals with a greater total symptom severity after concussion had higher driving duration, distance, speed, and number of trips per day. Driving duration had a weak positive correlation with symptoms, and driving distance, average speed, and number of trips all had a moderate positive correlation. However, when looking only during the acute time period (days 2-4), only average speed has a moderate positive correlation with symptom severity. Since previous studies have shown that there is no difference between driving behaviors in concussion and control groups after the first 3 days,^{3,4,11} a possible explanation for the widespread correlation between driving behavior and symptom severity through the whole period may be driven by the driving behaviors from days 4-9. This explanation is strengthened with the results from the acute time period (days 2-4) that showed that trip duration, trip distance, and number of trips per day were not significantly correlated with symptom severity. However, average speed per trip correlating with symptom severity per day is similar to what was found in objective 1 where initial symptom score was also correlated with an increase in average speed. Further research is needed to confirm these results.

Limitations

We recruited college students only, which raises concerns about the generalizability of the results. The small sample size ($N=22$) and the short data capture period, especially when compared to other naturalistic driving studies, likely reduced the power of the analysis, limiting our ability to find significant differences if they did exist. Additionally, there were participants whose data was missing or incomplete in concussion assessments, particularly the daily symptom checklists. Another limitation is the location of the drives. The study was conducted in the college town; it itself is structured in a way that encourages shorter and slower drives. However, some participants drove outside the college town, and these drives were not controlled in the analysis. We also did not account for weekdays and weekend drives. There was a significant difference in the number of previous concussions between the control and concussed groups. There is some evidence that repeated concussions can have long-lasting effects, including increased recovery time and higher symptoms at baseline.⁵⁰ Future studies should consider the number of previous concussions and possibly to match this factor to minimize these differences and control for potentially confounding factors. As with any naturalistic driving study, there was a lack of control in driving environment and driving location. This led to widespread differences and variability in the data captured. With the small sample size ($N=22$) and short time period of data capture, the variability within the data could drive results, leading us to find differences that may not be significant or represent behavior that may not be accurate, like in the control group with the possible outlier for single-task tandem gait (Figure 2A-B, Figure 7A-B). Outliers have a greater impact on the results found in our study, and further research with more participants could help avoid this problem.

CONCLUSION

We found that post-concussion deficits in balance, symptoms, and vestibulo-ocular symptom provocation were associated with post-concussion naturalistic driving behavior in concussed individuals relative to controls. Concussed individuals with better balance may perceive higher motor function due to a lack of disease insight and struggle with speed regulation. Concussed individuals with higher symptom severity scores, both initially and daily, also drive at higher speeds. Additionally, concussed individuals with VOMS symptom provocation may indicate experiencing difficulties while performing tasks associated with driving, causing an increased trip duration. Considering these outcomes might help to ensure post-concussion driving safety, but further research is needed to confirm these findings due to the variability in the data, confounding factors, and methodological limitations that may be driving results.

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APPENDIX

Supplemental Table 1 Average Total Driving Duration Per Day in Days 2-4 with Initial Clinical Concussion Measures

Interaction Effect	B	Std. Error	95% CI (Lower)	95% CI (Upper)	p-value
Group * Total Symptoms	0.183	0.2048	-0.219	0.584	0.373
Group * Complex Attention	0.038	0.0380	-0.036	0.113	0.314
Group * Cognitive Flexibility	-0.066	0.0507	-0.165	0.034	0.195
Group * Executive Function	-0.051	0.0529	-0.155	0.052	0.330
Group * Motor Speed	0.012	0.0307	-0.048	0.072	0.693
Group * Processing Speed	0.002	0.0405	-0.077	0.081	0.963
Group * Psychomotor Speed	0.006	0.0189	-0.031	0.043	0.757
Group * Reaction Time	0.006	0.0068	-0.007	0.020	0.353
Group * Visual Memory	0.092	0.0724	-0.049	0.234	0.202
Group * BESS Firm	0.048	0.3151	-0.570	0.665	0.880
Group * BESS Foam	0.182	0.2267	-0.262	0.627	0.421
Group * Single-Task Tandem Gait	-0.080	0.0626	-0.202	0.043	0.204
Group * Double-Task Tandem Gait	0.003	0.0825	-0.159	0.165	0.973
Group * Smooth Pursuits	-0.946	0.4799	-1.886	-0.005	0.049^A
Group * Horizontal Saccades	4.176	1.6597	0.923	7.429	0.012^A
Group * Vertical Saccades	-3.229	1.5104	-6.189	-0.269	0.033^A
Group * Near Point Convergence	-0.340	0.2751	-0.879	0.199	0.216
Group * Horizontal VOR	0.119	0.3067	-0.482	0.720	0.698
Group * Vertical VOR	-0.338	0.3085	-0.943	0.266	0.273
Group * Visual Motion Sensitivity	0.099	0.1430	-0.181	0.379	0.489

Note: The control group was used as a reference. Main effects were included in the models, but this study focused solely on interaction effects.

A: A subsequent Pearson's R Correlation was used to analyze the relationship between these variables.

Supplemental Table 2 Average Total Driving Distance Per Day in Days 2-4 Correlated with Initial Clinical Concussion Measures

Interaction Effect	B	Std. Error	95% CI (Lower)	95% CI (Upper)	p-value
Group * Total Symptoms	0.319	0.2573	-0.185	0.824	0.215
Group * Complex Attention	0.042	0.0494	-0.055	0.138	0.400
Group * Cognitive Flexibility	-0.101	0.0631	-0.224	0.023	0.110
Group * Executive Function	-0.096	0.0643	-0.222	0.030	0.134
Group * Motor Speed	0.025	0.0402	-0.054	0.104	0.531
Group * Processing Speed	0.055	0.0553	-0.054	0.163	0.321
Group * Psychomotor Speed	0.022	0.0258	-0.029	0.072	0.403
Group * Reaction Time	0.016	0.0080	0.000	0.031	0.052
Group * Visual Memory	0.080	0.0941	-0.104	0.265	0.394
Group * BESS Firm	0.079	0.1760	-0.266	0.424	0.653
Group * BESS Foam	0.106	0.1267	-0.142	0.354	0.403
Group * Single-Task Tandem Gait	-0.187	0.0684	-0.321	-0.053	0.006
Group * Double-Task Tandem Gait	0.117	0.0902	-0.060	0.293	0.196
Group * Smooth Pursuits	-0.439	0.6964	-1.804	0.926	0.529
Group * Horizontal Saccades	3.381	2.4085	-1.340	8.102	0.160
Group * Vertical Saccades	-2.655	2.1918	-6.951	1.641	0.226
Group * Near Point Convergence	-0.511	0.3992	-1.294	0.271	0.200
Group * Horizontal VOR	0.103	0.4451	-0.769	0.976	0.816
Group * Vertical VOR	-0.461	0.4477	-1.338	0.417	0.303
Group * Visual Motion Sensitivity	0.243	0.2075	-0.163	0.650	0.241

Note: The control group was used as a reference. Main effects were included in the models, but this study focused solely on interaction effects.

Supplemental Table 3 Average Speed Per Trip in Days 2-4 Correlated with Initial Clinical Concussion Measures

Interaction Effect	B	Std. Error	95% CI (Lower)	95% CI (Upper)	p-value
Group * Total Symptoms	0.029	0.0128	0.004	0.054	0.022
Group * Complex Attention	0.012	0.2039	-0.388	0.411	0.954
Group * Cognitive Flexibility	-0.315	0.2426	-0.791	0.160	0.194
Group * Executive Function	-0.360	0.2394	-0.829	0.109	0.132
Group * Motor Speed	0.072	0.1557	-0.233	0.378	0.642
Group * Processing Speed	0.115	-2.217	-0.319	0.550	0.604
Group * Psychomotor Speed	0.039	0.1035	-0.164	0.242	0.706
Group * Reaction Time	0.055	0.0305	-0.005	0.115	0.070
Group * Visual Memory	0.358	0.2954	-0.221	0.937	0.225
Group * BESS Firm	-0.061	0.6209	-1.278	1.156	0.922
Group * BESS Foam	0.326	0.4468	-0.550	1.201	0.466
Group * Single-Task Tandem Gait	-1.024	0.2544	-1.522	-0.525	<0.001
Group * Double-Task Tandem Gait	-0.022	0.0291	-0.079	0.035	0.446
Group * Smooth Pursuits	-1.352	2.2300	-5.723	3.019	0.206
Group * Horizontal Saccades	9.760	7.7122	-5.355	24.876	0.294
Group * Vertical Saccades	-7.361	7.0182	-21.116	6.395	0.312
Group * Near Point Convergence	-1.292	1.2781	-3.797	1.213	0.915
Group * Horizontal VOR	0.152	1.4251	-2.642	2.945	0.109
Group * Vertical VOR	-2.298	1.4336	-5.107	0.512	0.109
Group * Visual Motion Sensitivity	1.473	0.6643	0.171	2.775	0.027^A

Note: The control group was used as a reference. Main effects were included in the models, but this study focused solely on interaction effects.

A: A subsequent Pearson's R Correlation was used to analyze the relationship between these variables.

Supplemental Table 4 Average Trips per Day in Days 2-4 Correlated with Clinical Concussion Measures

Interaction Effect	B	Std. Error	95% CI (Lower)	95% CI (Upper)	p-value
Group * Total Symptoms	0.073	0.5660	-1.036	1.182	0.897
Group * Complex Attention	0.079	0.1039	-0.124	0.283	0.446
Group * Cognitive Flexibility	-0.069	0.1372	-0.338	0.200	0.614
Group * Executive Function	-0.008	0.1411	-0.284	0.269	0.955
Group * Motor Speed	-0.040	0.0746	-0.186	0.106	0.594
Group * Processing Speed	-0.054	0.0926	-0.235	0.128	0.563
Group * Psychomotor Speed	-0.029	0.0429	-0.113	0.055	0.503
Group * Reaction Time	-0.002	0.0163	-0.034	0.030	0.883
Group * Visual Memory	0.263	0.1830	-0.096	0.621	0.151
Group * BESS Firm	0.257	0.3301	-0.390	0.904	0.436
Group * BESS Foam	-0.233	0.2375	-0.699	0.232	0.326
Group * Single-Task Tandem Gait	-0.231	0.1667	-0.557	0.096	0.167
Group * Double-Task Tandem Gait	0.078	0.2197	-0.353	0.509	0.722
Group * Smooth Pursuits	-2.266	1.4783	-5.164	0.631	0.125
Group * Horizontal Saccades	8.880	5.1124	-1.140	18.900	0.082
Group * Vertical Saccades	-7.794	4.6524	-16.912	1.325	0.094
Group * Near Point Convergence	0.234	0.8473	-1.427	1.894	0.783
Group * Horizontal VOR	-0.598	0.9447	-2.449	1.254	0.527
Group * Vertical VOR	-0.749	0.9504	-2.611	1.114	0.431
Group * Visual Motion Sensitivity	0.672	0.4404	-0.191	1.536	0.127

Note: The control group was used as a reference. Main effects were included in the models, but this study focused solely on interaction effects.