

Video Article

A Neuroscientific Approach to the Examination of Concussions in Student-Athletes

Caroline J. Ketcham¹, Eric Hall¹, Walter R. Bixby¹, Srikant Vallabhajosula², Stephen E. Folger², Matthew C. Kostek³, Paul C. Miller¹, Kenneth P. Barnes¹, Kirtida Patel⁴

¹Department of Exercise Science, Elon University

²Department of Physical Therapy Education, Elon University

³Department of Physical Therapy, Duquesne University

⁴Department of Sports Medicine, Elon University

Correspondence to: Caroline J. Ketcham at cketcham@elon.edu

URL: <https://www.jove.com/video/52046>

DOI: [doi:10.3791/52046](https://doi.org/10.3791/52046)

Keywords: Medicine, Issue 94, Concussions, Student-Athletes, Mild Traumatic Brain Injury, Genetics, Cognitive Function, Balance, Gait, Somatosensory

Date Published: 12/8/2014

Citation: Ketcham, C.J., Hall, E., Bixby, W.R., Vallabhajosula, S., Folger, S.E., Kostek, M.C., Miller, P.C., Barnes, K.P., Patel, K. A Neuroscientific Approach to the Examination of Concussions in Student-Athletes. *J. Vis. Exp.* (94), e52046, doi:10.3791/52046 (2014).

Abstract

Concussions are occurring at alarming rates in the United States and have become a serious public health concern. The CDC estimates that 1.6 to 3.8 million concussions occur in sports and recreational activities annually. Concussion as defined by the 2013 Concussion Consensus Statement “may be caused either by a direct blow to the head, face, neck or elsewhere on the body with an ‘impulsive’ force transmitted to the head.” Concussions leave the individual with both short- and long-term effects. The short-term effects of sport related concussions may include changes in playing ability, confusion, memory disturbance, the loss of consciousness, slowing of reaction time, loss of coordination, headaches, dizziness, vomiting, changes in sleep patterns and mood changes. These symptoms typically resolve in a matter of days. However, while some individuals recover from a single concussion rather quickly, many experience lingering effects that can last for weeks or months. The factors related to concussion susceptibility and the subsequent recovery times are not well known or understood at this time. Several factors have been suggested and they include the individual's concussion history, the severity of the initial injury, history of migraines, history of learning disabilities, history of psychiatric comorbidities, and possibly, genetic factors. Many studies have individually investigated certain factors both the short-term and long-term effects of concussions, recovery time course, susceptibility and recovery. What has not been clearly established is an effective multifaceted approach to concussion evaluation that would yield valuable information related to the etiology, functional changes, and recovery. The purpose of this manuscript is to show one such multifaceted approach which examines concussions using computerized neurocognitive testing, event related potentials, somatosensory perceptual responses, balance assessment, gait assessment and genetic testing.

Video Link

The video component of this article can be found at <https://www.jove.com/video/52046/>

Introduction

Concussions are occurring at alarming rates in the United States and have garnered quite a lot of attention as a public health concern.¹⁻³ US Centers for Disease Control and Prevention (CDC) estimates that 1.6 to 3.8 million concussions occur in sports and recreational activities annually.^{4,5} Concussion as defined by the 2013 Concussion Consensus Statement² “may be caused either by a direct blow to the head, face, neck or elsewhere on the body with an ‘impulsive’ force transmitted to the head.” Concussion may result in neuropathological and/or substructural changes that may result in functional disturbances.² These deficits may persist for several weeks. It is not uncommon for athletes to experience increased self-reported symptoms, decrements in postural control, and decreased neurocognitive function even 14 days following the initial injury.⁶ The prolonged nature of symptoms, the inconsistent identification of concussions, and the variability in preinjury abilities often lead to complex and non standardized return-to-play decisions by physicians, uncertain recovery times, and possibly long-term sequelae.⁷⁻⁹

Following a concussion, an individual may experience both short-term and long-term effects. The short-term effects of sport related concussions may include changes in playing ability, confusion, memory disturbance, the loss of consciousness, slowing of reaction time, loss of coordination, headaches, dizziness, vomiting, changes in sleep patterns and mood changes. These symptoms typically resolve in a matter of days.^{2,10} However, while some individuals recover from a single concussion rather quickly, many experience lingering effects that can last for weeks or months following the injury.^{10,11,12} These symptomatic disturbances to daily function can be quantified using cognitive and performance related tests. While no one single test should determine diagnosis of a concussion, a battery of tests and known relationships between tests can aid the medical staff in making diagnoses, return to classroom, and return to play decisions.²

There is great variability in an individual's risk for concussion and their corresponding recovery.¹¹ The factors related to concussion susceptibility and recovery time course are not well known or understood. Several factors have been suggested that may impact an individual's concussion

susceptibility and recovery. These factors include the individual's concussion history, the severity of the initial injury, history of migraines, history of learning disabilities, history of psychiatric comorbidities, and possibly genetic factors.^{7, 9, 13, 14}

Many studies have individually investigated specific factors for both the short-term and long-term effects of concussions, recovery time course, and genetics as a factor of concussions.^{4, 8, 15-17} What has not been clearly established is an effective multifaceted approach to concussion evaluation that would yield valuable information related to the etiology, functional changes, and recovery from concussion. Due to the variety of symptoms and the uncertain time course of recovery, a multifaceted approach to concussion evaluation is warranted and this should include baseline testing of all athletes prior to participation in practice and competition as well as timely evaluation post injury. A recent review suggests that neurocognitive assessments may be more sensitive to recovery from a concussion than monitoring symptoms alone.¹⁸ It may be that there are other objective measures that may be better indicators of recovery from concussion.

For this protocol, we use several tasks to assess various components of the system to see how they are impacted by a concussion. A computerized neurocognitive test can assess memory, processing speed, problem solving skills, cognitive efficiency and impulse control.⁶ EEG with auditory and visual processing tasks can be used to assess neuroefficiency through the examination of event related potentials.¹⁹ A somatosensory discrimination task can be used to assess peripheral and central sensory processing capabilities.²⁰ Balance and gait measures can be used to assess functional performance capabilities.^{6, 21} In addition, we assess various genotypes that may have relations to concussion history, concussion recovery and cognitive function.²² We baseline test our varsity student-athletes on this battery of tests and repeat tests if they incur a concussion when asymptomatic.

The purpose of this project is to assess potential short-term and long-term decrements in performance as a result of concussions using genetic, neurocognitive, electrophysiological, behavioral, somatosensory, balance and gait measures. Understanding the potential mechanisms that may be related to various symptoms and impairments that occur with a concussion are important in furthering our knowledge about concussion. Greater knowledge about these changes may in the future aid in concussion diagnosis as well as concussion management as it relates to return to play and return to academics.

All measures described below are taken at baseline (before student-athlete participation in sport). Our current protocol is to complete the computerized neurocognitive testing at 48 hr along with the balance protocol because we believe that these provide useful information regarding recovery and possible return-to-play and return-to-academics. When the student-athlete reports asymptomatic they again return to the laboratory where all baseline measures are again conducted, except for genetic testing. The full protocol, baseline and asymptomatic, takes approximately 90 min to complete in one testing period.

Protocol

All the procedures described below have been approved by the Elon's Institutional Review Board.

1. Computerized Neurocognitive Testing

1. Ask the participants to be seated in front of the computer. Log participants on to system and instruct them to complete the computerized neuropsychological test which consists of a demographic and background information section, self-reported symptom checklist, and 6 modules (word discrimination, design memory, X's and O's, symbol matching, color match, and three letters).
2. Download summary report and enter four composite scores for verbal memory, visual memory, reaction time and motor processing speed.

2. Event Related Potentials

1. Measure head circumference using a measuring tape to determine size of EEG net to be used. Determine placement of the EEG net by measuring anatomical landmarks.
2. Soak the EEG net in solution of sodium chloride and baby shampoo for 5 min.
3. Place the EEG net on the head of the participant. The system that we use includes 32 channels.
4. Check impedance levels of the sites on the computer. For our system, an impedance below 100 kohm is deemed acceptable.
5. Explain the cognitive tasks and let the participant practice each of the tasks.
 1. Auditory Oddball Task: Instruct the participant to put on headphones and sit comfortably at a table. Inform them that they will hear a series of low and high tones and to respond as quickly and accurately as possible by clicking a button to a high frequency auditory tone.
 2. Flanker Task: Instruct participant to sit in front of a computer screen where they will be given a series of arrows projected onto a screen. Instruct participants to respond to the direction of the middle arrow by clicking the left mouse button if it was pointing left or clicking the right mouse button if it was pointing right as quickly and accurately as possible.
6. Instruct participant to complete two trials of both the auditory oddball task and the flanker task.
7. Remove the EEG net from the participant and clean the EEG net by soaking in germicide disinfectant for 10 min.

3. Somatosensory Perceptual Responses

1. Seat the participant comfortably with their left hand in a prone position resting on the sensory stimulus device and their fingers positioned along the contour of the device with the padded tips of digits 2 and 3 placed in contact with the stimulus probes.²³
2. Ask the participant to view task related instructions and cues on a computer monitor and enter responses using a two button computer mouse. Project 5 different tests: 2 simple single site reaction time tasks, a dual site amplitude discrimination,²⁴ a dual site amplitude task with a single site adapting stimulus,²⁴ and a temporal order judgment task.²⁵

3. Prior to the start of each test run, the cues on the computer will instruct the participant to complete practice trials to familiarize themselves with the task. The computer will give the participants performance feedback after each test (e.g. correct; incorrect).

4. Balance Protocol

1. Instruct participants to put on slip-resistant socks and then stand on the balance system to become acquainted with instrument.
2. Instruct participants to stand in a comfortable position, matching the center of pressure dot with the center dot on the screen. Researchers record this comfortable starting position such that all tests take place with the same foot position while standing on the device.
3. Ask the participant to stand for 30 sec for each of the four conditions (eyes open/firm surface, eyes closed/firm surface, eyes open/foam surface, eyes closed/foam surface). Provide the participants a 10 sec rest between each condition and a 3 sec countdown before beginning of each recording.
4. Repeat each of the conditions while completing a secondary task. Instruct them to count backwards by 7 starting from a random 3 digit number given to them (e.g., 843).
5. Record a sway index score, a measure of the standard deviation of the amount of sway for each condition and center of pressure data to use later for further analysis.

5. Gait Assessment

1. Assess participants' gait using a portable 15' long carpet instrumented gait analysis system with pressure sensors present throughout the length of the carpet to detect the participant's footfalls.
2. Ask the participants to walk across mat barefoot at a comfortable speed five times starting from a distance of 3' before the start of the mat and 3' after leaving the mat.
3. Instruct the participants to complete five additional walking trials while counting backwards by seven from a random 3 digit number as a concurrent cognitive dual task.
4. The dependent variables obtained as output from gait analysis include absolute and variability measures of several spatiotemporal parameters like velocity, cadence and step length.

6. Genetics

1. Ask the participant to carefully remove the swab stick from its sterile container (being careful to only touch the stick end of the swab stick), move the swab into their mouth, and vigorously rub the swab inside of both cheeks for a total of 20 sec.
2. Hand the swab stick to the technician who is wearing latex or nitrile gloves. Only hold the stick end and then place the swab tip into a sterile 1.7 ml tube (labeled with an identification number only), which is immediately placed on ice.
3. Within 24 hr transfer the samples are to a -20 °C freezer.
4. Extract DNA using a standard DNA Purification Kit according to the manufacturer's protocol. To obtain a more concentrated sample, after extraction, perform an isopropanol precipitation step and rehydrate DNA in 20 µl of EDTA buffer (pH 8.0).
5. Store the extracted DNA at -80 °C until genotyping analysis using standard polymerase chain reaction (PCR) assays with fluorescent tags.
6. "Call" the genotypes by PCR software and then verify manually by viewing PCR amplification plots.

Representative Results

Computerized Neurocognitive Testing

An example of results for the computerized neurocognitive test can be seen in **Figure 1**. The computer program elicits composite scores on Verbal Memory, Visual Memory, Visual Motor Speed and Reaction Time which are often used to make return-to-play and return-to-learn concussion management protocols. The verbal and visual memory composites evaluate attentional processes, learning and memory. Visual motor speed measures visual processing, learning and memory and visual motor response speed (ImpACT Clinical Interpretation Manual). It also lists a Total Symptom Score at time of the test, an Impulse Control Score and a Cognitive Efficiency Index. The Impulse Control Score is related to the number of errors made in testing and may be useful in interpreting results. The Cognitive Efficiency Index attempts to measure the tradeoff between speed and accuracy. If the student-athlete experiences a concussion they are asked to come back in at 48 hr following concussion and when asymptomatic. Depending on the length of recovery the student-athlete may be asked to complete the assessment to examine recovery. It is assumed that following a concussion there will be significant decrements on performance on one or more of the composite scores and will recover to baseline when asymptomatic since this is often used as one indicator to return-to-play and return-to-academics.

Event Related Potentials

For the Flanker task participants are asked to respond to a middle arrow pointing to the left or right. This middle arrow may be going the same direction as the two flanking arrows (congruent) or opposite of the flanking arrows (incongruent). From the responses it is possible to determine response accuracy as well as response time to the arrows for congruent and incongruent. Additionally, from the brain activity being measured it is possible to derive an event-related potential (ERP). **Figure 2** depicts the individual data for one subject on the Flanker Task. This data is derived from averaging across all the correct responses for the congruent and incongruent trials of the Flanker task. In examining the different ERP components one is typically interested in the amplitude and latency of the ERP component. Currently we are examining the P3, but we could also examine the N1, N2 and P2 components as well. The P3 typically occurs between 300–600 msec after stimulus presentation and is thought to represent context updating. The P3 can be quantified in amplitude, how high the peak is from baseline, and latency, how long the peak occurs from stimulus presentation. For the Auditory Oddball task it is also possible to determine response accuracy (number of correct

responses) as well as response time to the high pitch tones (not the low pitch tones). Similar to the Flanker Task, ERP components and their amplitude and latency can be determined.

Figures 3 and 4 present preliminary data for the amplitude and latency of the P3 in the Flanker and Auditory Oddball tasks. One may expect that those who have suffered a concussion may have a larger amplitude and longer latency compared to their baseline or non concussed counterparts.

Somatosensory Perceptual Responses

Figure 5 illustrates a subject's performance (difference limen) on an amplitude discrimination task with and without single site adaptation. Similar graphs could also be determined for simple single site reaction time task, dual site amplitude discrimination, a dual site amplitude task with a single site adapting stimulus and a temporal order judgment task. Individuals who suffer a concussion are expected to perform better on an amplitude discrimination task with a confounding single site adapting stimulus compared to non-concussed control subjects. An important point of emphasis is that a compromised neurological system (*i.e.* concussion) leads to better performance on some somatosensory testing tasks (including duration discrimination with an amplitude confound) which is a valuable contrast to the expected decrease in performance noted for other sensory and motor tests. Testing the somatosensory system can be performed quickly and may provide a sensitive measure to identify a concussion and track progress during the recovery phase to inform the return to play decision.

Balance

Figure 6 is a representative example of the results from the Balance protocol. The sway index and center of pressure data is used for further analysis. **Table 1** shows the kinematic variables that are calculated from the center of pressure data and tells us more about balance control vs. just balance stability. Following a concussion balance and stability are often changed to either less stable (higher sway) or more stable (lower sway). Recovery would be when measures come back to baseline. Both changes can have implications on the ability to recover from or prepare for a loss of stability thus potentially putting a student-athlete at increased risk for injury.

Gait

Figure 7 illustrates the data output of a single subject. Data is compiled from the multiple trials and analyzed as one large walking pass. **Table 2** includes the means and variability for gait measures across concussion history. One could expect that following a concussion the velocity and walking kinematics of a student-athlete will change. The implications of this in a dynamic task are far reaching. Gait parameters can help us understand how control of the system has changed and how it recovers.

Genetics

Table 3 is a sample output that is received after PCR analysis. Once this output is received genotypes can be determined for different participants and then equated with other variables such as concussion history, recovery from concussion and cognitive function. The current genotypes that are being determined include Apolipoprotein E (APOE), the polymorphic promoter region of APOE, Catechol-O-Methyltransferase (COMT) and Dopamine Receptor (DRD2).



ImPACT® Clinical Report

Exam Type	Baseline	Post-Injury 1	Post-Injury 2	Post-Injury 4	
Date Tested	09/12/2013	09/27/2013	09/30/2013	11/20/2013	
Last Concussion	06/14/2008	09/25/2013	09/25/2013	09/18/2013	
Exam Language	English	English	English	English	
Test Version	2.1	2.1	2.1	2.1	

Composite Scores	Percentile scores if available are listed in small type.						
Memory composite (verbal)	78	22%	55	<1%	68	4%	81 32%
Memory composite (visual)	91	93%	47	4%	53	12%	63 21%
Visual motor speed composite	36.23	31%	29.73	2%	30.88	7%	41.13 55%
Reaction time composite	0.48	92%	0.72	5%	0.65	12%	0.51 80%
Impulse control composite	13		23		13		13
Total Symptom Score	1		49		52		0

Cognitive Efficiency Index: 0.43 0.26 0.32 0.3

The Cognitive efficiency Index measures the interaction between accuracy (percentage correct) and speed (reaction time) in seconds on the Symbol Match test. This score was not developed to make return to play decisions but can be helpful in determining the extent to which the athlete tried to work very fast on symbol match (decreasing accuracy) or attempted to improve their accuracy by taking a more deliberate and slow approach (jeopardizing speed). The range of scores is from approximately zero to approximately .70 with a mean of .34. A higher score indicates that the athlete did well in both the speed and memory domains on the symbol match test. A low score (below .20) means that they performed poorly on both the speed and accuracy component. If this score

Scores in **bold RED** type exceed the Reliable Change Index (RCI) when compared to the baseline score. However, scores that do not exceed to RCI index may still be clinically significant. Percentile scores if available are listed in small type.

Figure 1: Example of computerized neuropsychological test report.

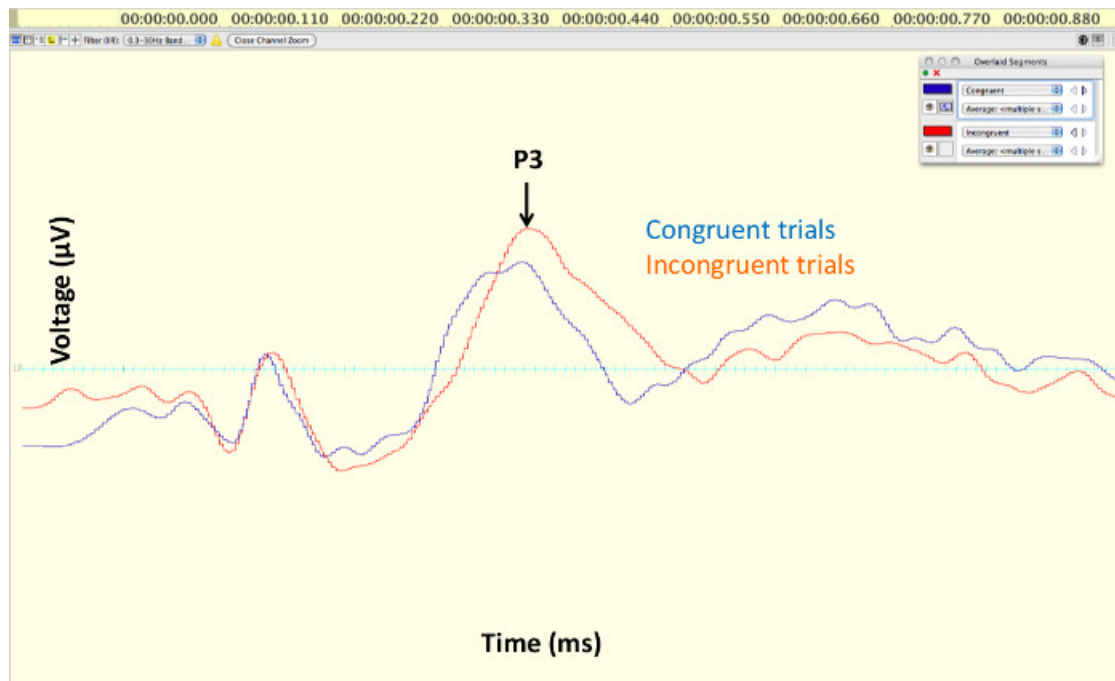


Figure 2: An example of a typical event related potential (ERP). The component of interest for the purpose of this investigation is the P3.

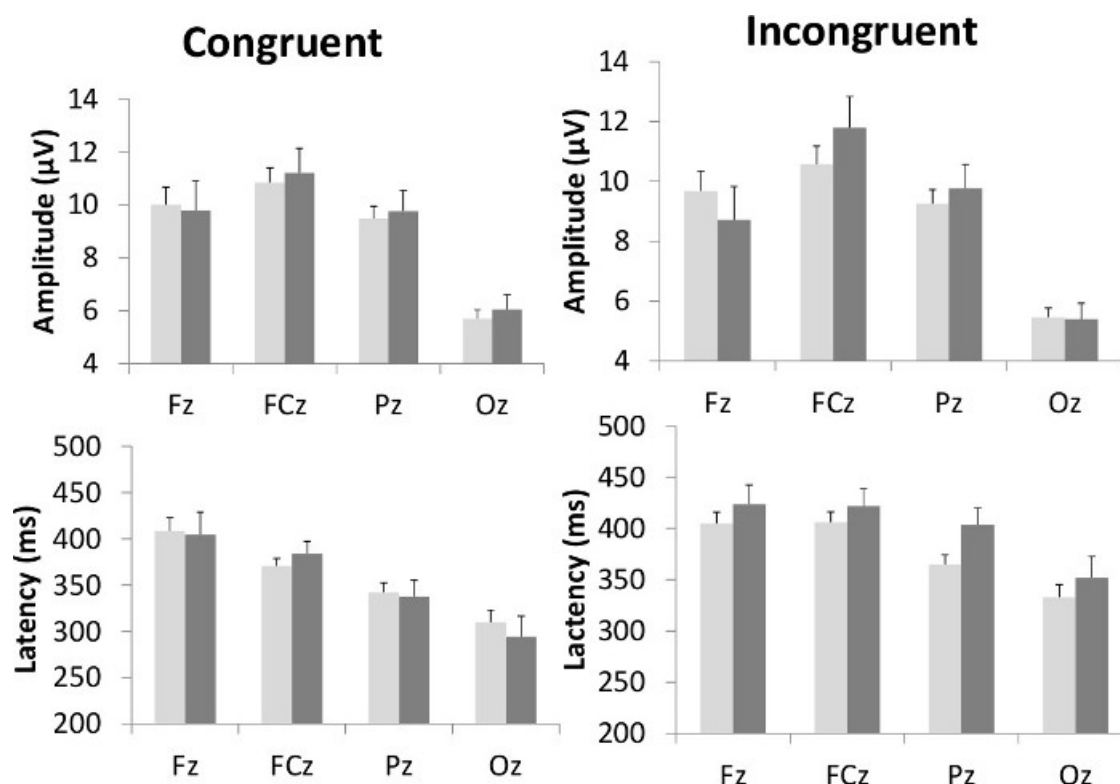


Figure 3: Preliminary results showing differences in amplitude and latency for P3 associated with the Flankers task. Results are presented from the midline electrodes associated with the frontal (Fz), frontocentral (FCz), parietal (Pz) and occipital (Oz) regions of the brain. Previously concussed subjects are indicated in dark grey while non concussed subjects are indicated in light gray.

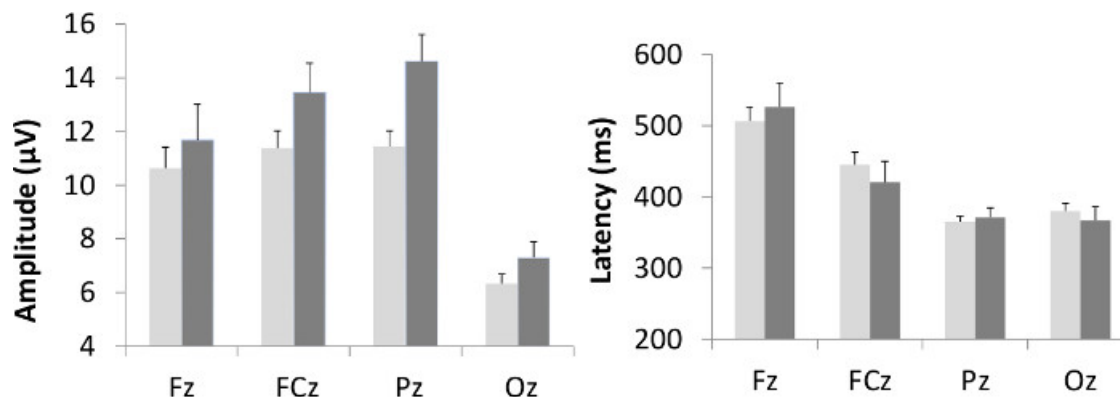


Figure 4: Preliminary results showing differences in amplitude and latency for P3 associated with the Auditory Oddball task. Results are presented from the midline electrodes associated with the frontal (Fz), frontocentral (FCz), parietal (Pz) and occipital (Oz) regions of the brain. Previously concussed subjects are indicated in dark gray while non concussed subjects are indicated in light gray.

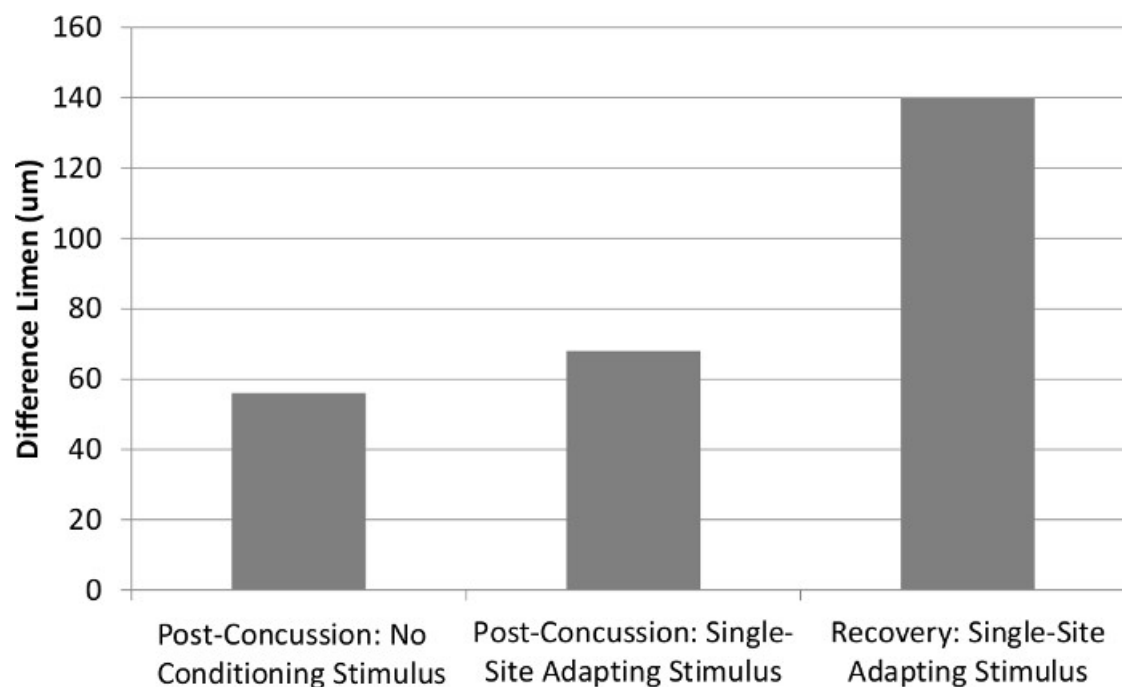
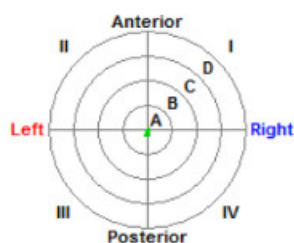
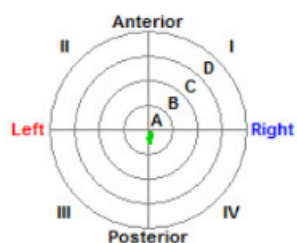


Figure 5: Comparison of difference limen for a single subject obtained with amplitude discrimination tasks with or without single site adaptation at post concussion and at recovery. The post concussion performance with a single site adapting stimulus is similar to the performance without a conditioning stimulus. However, in normal control subjects the presence of a single-site adapting stimulus leads to a decrease in performance (*i.e.*, the difference limen increases); similar to the recovery performance.

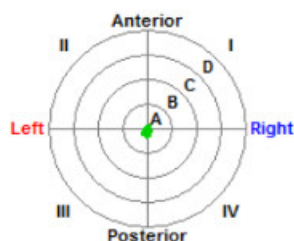
Condition	Sway Index	Mean
Eyes Open Firm Surface Baseline - Normals very stable	<u>0.33</u>	0.35
Eyes Closed Firm Surface Somatosensory predominant, Vestibular secondary Normals sway more with eyes closed	<u>0.52</u>	0.73
Eyes Open Foam Surface Vision predominant, Vestibular secondary Normals sway more on foam than firm	<u>0.55</u>	0.54
Eyes Closed Foam Surface Vestibular predominant Normals sway most with eyes closed on foam	<u>1.78</u>	1.65



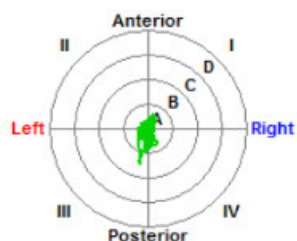
Eyes Open Firm Surface



Eyes Closed Firm Surface



Eyes Open Foam Surface



Eyes Closed Foam Surface

Figure 6: Example of balance test report. The top figure shows the sway scores as compared to normative data. The bottom shows the center of pressure data for each trial.



Figure 7: Example data produced by gait analysis system. The top is the foot pressure on the mat and the bottom has all the kinematic measures.

Kinematic Analysis Measures (cm; cm/s)	NONCONCUSED (n=60)				CONCUSED (n=28)			
	No Cognitive Load (Cognitive Load)				No Cognitive Load (Cognitive Load)			
	EO Firm	EC Firm	EO Foam	EC Foam	EO Firm	EC Firm	EO Foam	EC Foam
Medial-Lateral Range (cm)	0.6 (1.01)	0.87 (1.11)	1.62 (1.92)	4.52 (4.11)	0.79 (0.95)	0.93 (1.03)	1.44 (2.04)	4.37 (4.05)
Anterior-Posterior Range	1.01 (1.79)	1.86 (2.22)	2.11 (2.81)	6.23 (5.61)	1.11 (1.88)	1.73 (2.04)	2.05 (3.36)	5.91 (5.84)
Sway Area	0.66 (2.03)	1.78 (3.05)	4.4 (6.22)	29.72 (24.19)	0.79 (1.99)	1.68 (2.26)	3.09 (9.00)	27.29 (24.92)
Medial-Lateral Path Length	7.57 (11.87)	10.66 (13.28)	14.88 (17.61)	44.91 (39.59)	8.14 (12.08)	11.09 (12.35)	15.8 (19.82)	42.1 (39.8)
Anterior-Posterior Path Length	9.7 (15.47)	16.85 (22.92)	19.57 (24.53)	67.16 (63.20)	9.39 (15.80)	16.22 (20.58)	20.48 (29.82)	59.03 (60.79)
Total Path Length	15.27 (23.64)	23.81 (31.00)	29.2 (35.32)	90.4 (83.59)	15.62 (24.00)	23.71 (28.36)	30.62 (41.28)	81.56 (81.39)
Medial-Lateral Mean Velocity	0.38 (0.59)	0.53 (0.66)	0.74 (0.88)	2.25 (1.98)	0.41 (0.60)	0.55 (0.62)	0.79 (0.99)	2.1 (1.99)
Anterior-Posterior Mean Velocity	0.49 (0.77)	0.84 (1.15)	0.98 (1.23)	3.36 (3.16)	0.47 (0.79)	0.81 (1.02)	1.02 (1.49)	2.95 (3.04)

Table 1: Center of Pressure Kinematic Measures across conditions for a group of student athletes with and without a previous history of concussion.

	No concussion history		With concussion history	
	(n = 17)		(n = 3; # of concussions = 1)	
Measure	Mean (SD)	Coefficient of Variability (%)	Mean (SD)	Coefficient of Variability (%)
Number of steps	52.17 (7.05)	13.52	49 (6.24)	12.74
Stride length (m)	1.28 (0.12)	9.38	1.31 (0.12)	8.92
Step length (m)	0.64 (0.06)	9.32	0.65 (0.06)	9.14
Step width (m)	0.11 (0.03)	25.87	0.12 (0.03)	23.69
Stride velocity (m/s)	1.14 (0.14)	12.2	1.19 (0.17)	14.47
Stance time (s)	0.71 (0.05)	6.99	0.69 (0.05)	6.9
Step time (s)	0.57 (0.03)	5.99	0.56 (0.03)	6.23
Single support time (s)	0.43 (0.03)	6.03	0.42 (0.02)	5.46
Gait speed (m/s)	1.14 (0.14)	12.45	1.19 (0.17)	14.47
Cadence (steps/min)	106.34 (6.46)	6.07	108.36 (6.76)	6.24
Double support time (s)	0.28 (0.04)	14.68	0.26 (0.02)	8.52

Table 2. Spatiotemporal parameters from gait evaluations of high school football players collected as part of the Elon BrainCARE protocol using gait analysis instrument

Subject	rs7412 (APOE)	rs429358 (APOE)	rs1800497 (DOP)	rs405509 (APOE)	rs925946 (BDNF)
A	1/1	2/2	1/2	2/2	1/1
B	1/1	2/2	2/2	1/2	1/1
C	1/1	2/2	2/2	1/1	1/1
D	1/1	2/2	2/2	2/2	1/2
E	1/1	1/2	2/2	1/2	2/2
F	1/1	2/2	1/2	1/2	1/1
G	1/1	1/2	2/2	1/2	1/2
H	1/1	2/2	1/2	1/2	1/1
I	1/1	2/2	2/2	2/2	1/1
J	1/1	2/2	2/2	1/2	1/2
K	1/1	2/2	2/2	2/2	1/1
L	1/1	2/2	1/2	1/1	1/2
M	1/1	2/2	1/2	1/2	2/2

Table 3. Genetic results following PCR analysis.

Discussion

The goal of this multidimensional approach to baseline concussion testing is twofold: 1) to better understand the impact of a concussion (acute and long term) on the neuromuscular system; 2) to help the sports medicine staff make return to play decisions (they primarily use neurocognitive testing as has been suggested by McCrory).²⁶ This multifaceted approach to concussion evaluation provides valuable information related to the etiology, functional changes, and recovery from concussion. Little is understood about the comprehensive impact of concussions on the system as a whole and this protocol allows scientists from multiple disciplines to not only look at impact related to their expertise, but collaborate on how small changes affect multiple systems or aspects of behavior.

The significance of this multidisciplinary approach is to get a better understanding of which systems may be compromised and the timeline of recovery following injury. This protocol is currently used to help make return-to-play and return-to-academics decisions and build a body of data to determine which components are helpful in determining injury and recovery. This multidisciplinary approach allows researchers to understand deficits in any one area and how it might impact some very functional tasks like walking or maintaining stability and control of balance.

The approach used in this study provides objective systematic testing of athletes at the beginning of their collegiate career so that if an injury occurs there is a good baseline to measure recovery. The components of this protocol that are most useful to the medical staff are baseline and post injury computerized neurocognitive and balance assessments. Balance assessments are often done on the sideline, and utilizing an objective test will likely be helpful. If an athlete does not return to baseline, the sports medicine staff and the academic advising staff can work with athletes to determine and individualized plan for short and long term accommodations if needed. Most athletes return to baseline scores within 7-10 days.^{6,10} This data allows the medical staff to have informed and objective measures to support difficult conversations with athletes especially if recovery times are longer.

Some of the limitations of this protocol include testing time, gaining buy in from appropriate constituents, and training research assistants. It takes about 90 min to test each student-athlete. The EEG cap may take extra time to get impedances to desired threshold and in some cases researchers have to drop it from the testing session. We have spent time educating and establishing trust to get full buy in by the sports medicine staff, coaches, administrators and student-athletes at our university which is essential to being able to test every athlete. This takes enormous researcher time to test all varsity student-athletes at a Division I University. We are committed to our overarching goal; to provide for the well-being of student-athletes both on campus and for years to come. Therefore the time it takes to test, educate, train and analyze pales in comparison to the value it could provide.

Once this protocol or subset of tests has been established, the research team can provide outreach testing to local high school and youth sports teams. In addition, long-term follow-up testing can be completed to look at end of career comparisons. This is the future of concussion assessment, research and education.

Disclosures

The authors declare that they have no competing financial interests.

Acknowledgements

This study was supported by grants from the American Medical Society for Sports Medicine. The authors would like to acknowledge and show our appreciation for our undergraduate research students including David Lawton, Drew Gardner, Mark Sundman, Kelsey Evans, Graham Cochrane, Jordan Cottle and Jack Halligan for their assistance in data collection over the past four years.

References

1. Kristman, V., *et al.* Does the Apolipoprotein E4 allele predispose varsity athletes to concussion? A prospective cohort study. *Clin J Sports Med.* **18**: 322-328, doi: 10.1097/JSM.0b013e31817e6f3e, (2008).
2. McCrory, P. *et al.* Consensus statement on concussion in sports- the 4th International Conference on Concussion held in Zurich, November 2012. *Br J Sports Med.* **47**(5):250-258, doi: 10.1136/bjsports-2013-092313, (2013).
3. Giza, C.C. *et al.* Summary of evidence-based guideline update: Evaluation and management of concussion in sports: Report of the Guideline Development Subcommittee of the American Academy of Neurology. *Neurology.* **80**(24):2250-2257, doi: 10.1212/WNL.0b013e31828d57dd, (2013).
4. Langlois, J.A., Rutland-Brown, W., Waid, M.M. The epidemiology and impact of traumatic brain injury: a brief overview. *J Head Trauma Rehabil.* **21**, 375-378, (2006).
5. Faul, M., Xu, L., Wald, M.M., Coronado, V.G. Traumatic brain injury in the United States: emergency department visits, hospitalizations, and deaths. *Atlanta (GA): Centers for Disease Control and Prevention, National Center for Injury Prevention and Control.* (2010).
6. Broglio, S.P., Puetz, T.W. The effect of sport concussion on neurocognitive function, self-report symptoms and postural control: a meta-analysis. *J Sports Med.* **38**: 53-67, (2008).
7. Cancelliere, C., *et al.* Protocol for a systematic review of prognosis after mild traumatic brain injury: an update of the WHO Collaborating Centre Task Force findings. *Systematic Reviews.* **1**, 17, doi: 10.1186/2046-4053-1-17, (2012).
8. Guskiewicz, K., *et al.* Cumulative effects associated with recurrent concussion in collegiate football players. *JAMA.* **290**, 2549-2555, (2003).
9. Makdissi, M., Darby, D., Maruff, P., Ugoni, A., Brukner, P., McCrory, P.R. Natural history of concussions in sport: markers of severity and implications for management. *Am J Sports Med.* **38**, 464-471, doi: 10.1177/0363546509349491, (2010).
10. Kirkwood, M.W., Yeates, K.O., Wilson, P.E. Pediatric sport-related concussion: a review of the clinical management of an oft-neglected population. *Pediatrics.* **117**: 1359-1371, (2006).

11. McCrea, M., *et al.* Acute effects and recovery time following concussion in collegiate football players: the NCAA Concussion Study. *JAMA*. **290**, 2556-2563, (2003).
12. Henry, L.C., Tremblay, S., Boulanger, Y., Ellemberg, D., Lassonde, M. Neurometabolic changes in acute phase concussions correlate with symptom severity. *J Neurotrauma*. **27**: 65-76, doi: 10.1089/neu.2009.0962, (2010).
13. Terrell, T.R., *et al.* APOE, APOE promotor, and Tau genotypes and risk for concussion in college athletes. *Clin J Sports Med*. **18**, 10-17, doi: 10.1097/JSM.0b013e31815c1d4c, (2008).
14. Tierney, R.T., *et al.* Apolipoprotein E genotype and concussion in college athletes. *Clin J Sports Med*. **20**, 464-468, doi: 10.1097/JSM.0b013e3181fc0a81, (2010).
15. Iverson, G., Brooks, B., Collins, M., Lovell, M.R. Tracking neuropsychological recovery following concussion in sport. *Brain Inj*. **20**, 245-252, (2006).
16. McClincy, M.P., Lovell, M.R., Pardini, J., Collins, M.W., Spore, M.K. Recovery from sports concussion in high school and collegiate athletes. *Brain Inj*. **20**, 33-39, (2006).
17. Hootman, J., Dick, R., Agel, J. Epidemiology of collegiate injuries for 15 sports: summary and recommendations for injury prevention initiatives. *J Athl Train*. **43**, 311-319, (2007).
18. Johnson, E.W., Kegel, N.E., Collins, M.W.. Neuropsychological assessment of sport-related concussion. *Clin Sports Med*. **30**(1):73-88, viii-ix, doi: 10.1016/j.csm.2010.08.007, (2011).
19. Broglio, S.P., Pontifex, M.B., O'Connor, P., Hillman, C.H. The persistent effects of concussion on neuroelectric indices of attention. *J Neurotrauma*. **26**(9):1463-70, doi: 10.1089/neu.2008-0766, (2009).
20. Holden, J.K., Nguyen, R.H., Francisco, E.M., Zhang, Z., Dennis, R.G., Tommerdahl, M. A novel device for the study of somatosensory information processing. *J Neurosci Methods*. **204** (2):215-220, doi: 10.1016/j.jneumeth.2011.11.007, (2011).
21. Martini, D.N. *et al.* The chronic effects of concussion on gait. *Arch Phys Med Rehabil*. **92**: 585-589, doi: 10.1016/j.apmr.2010.11.029, (2011).
22. Jordan, B.D. Genetic influences on outcome following traumatic brain injury. *Neurochem Res*. **32**: 905-915, (2007).
23. Holden, J.K., Nguyen, R.H., Francisco, E.M., Zhang, Z., Dennis, R.G., Tommerdahl, M. A novel device for the study of somatosensory information processing. *J Neurosci Methods*. **204**, 215-220, doi: 10.1016/j.jneumeth.2011.11.007, (2012).
24. Tannan, V., Holden, J.K., Zhang, Z., Baranek, G.T., Tommerdahl M.A. Perceptual metrics of individuals with autism provide evidence for disinhibition. *Autism Res*. **1**, 223-30, doi: 10.1002/aur.34, (2008).
25. Nelson, A.J., Permij, A., Rai, N., Hogue, T., Tommerdahl, M., Chen, R. Dopamine alters tactile perception in Parkinson's disease. *Can J Neurol Sci*. **39**, 52-57, (2012).
26. McCrory, P. Future advances and areas of future focus in the treatment of sport-related concussion. *Clin Sports Med*. **30**, 201-208, doi: 10.1016/j.csm.2010.08.002, (2011).