Longitudinal Study on the Detection and Evaluation of Onset Mild Traumatic Brain Injury during Dual Motor and Cognitive Tasks

Hung Nguyen[1], Fouaz Ayachi[1], Etienne Goubault[1], Catherine Lavigne-Pelletier[1], Bradford J. McFadyen[2,3] and Christian Duval[1,4]

[1]*Département des Sciences des I'activité physique, Université du Québec à Montréal, Montréal, Canada*

[2]*Département de Réadaptation, Faculté de Médecine, Université laval, Québec, Canada*

[3]*Centre interdisciplinaire de recherche en réadaptation et intégration sociale, Québec, Canada*

[4]*Centre de Recherche Institut Universitaire de Gériatrie de Montréal, Montreal, Canada*

Keywords: Concussion, Youth, Athletes, Markerless, Football, Walking, Obstacle, Performance, Speed, Step Width, Preventive, Sensors, Head Injuries.

Abstract: Currently, concussions are detected by observing physical and cognitive symptoms such as dizziness, disorientation and loss of consciousness that are often associated with mild traumatic brain injury (mTBI). Evaluation methods such as neurocognitive tests and neuroimaging are often performed post-concussion. However, these methods can be expensive and cumbersome to use. In this study, we developed a new testing protocol using a markerless motion capture system to quickly monitor the cognitive and motor dysfunction of football players over the course of the season. This protocol utilized a dual-task paradigm to identify kinematic measures that could detect the subtle changes in the motor and cognitive function of players due to mTBI. Four high school football players (2 healthy and 2 with history of concussion) volunteered to participate in the study. Participants were asked to navigate a staged obstacle course with and without an N-Back (N-2) cognitive task. Positional data of 23 limb segment nodes were recorded using markerless motion tracking system. Data collection lasted less than 5 minutes, with minimal preparation time. The results showed that *walking speed*, *median frequency* of sacrum in the vertical direction and *step width variability* during straightway walking were strongly associated with the presence of mTBI.

1 INTRODUCTION

Among high school athletes in the U.S, football players have the highest rate of concussion at 15% per season (Rosenthal et al., 2014). However, the true incidence is estimated to be much higher due to the difficulty of detecting concussion as well as under reporting. Recently, concussion in sports has garnered tremendous media attention due to the catastrophic effects on the health of retired professional football players (Pilon and Belson, 2013) as they deal with consequences of repetitive impact on their body throughout their football career. While the attention to concussion has encouraged team and medical professionals to be more cautious when administering *post-concussion* protocols, there are still elements of subjective diagnoses involving concussion. Furthermore, the reactive diagnosis of concussion ignores the progressive aging of the brain due to repetitive impacts (Bowen, 2003, Bey and Ostick, 2009, Cantu and Gean, 2010). These repeated impacts often induced more long-term problems due to our inability to quantify the effect of concussion. In youth athletics, where resources are often unavailable to monitor the impact of these hits on their developing brain (Field et al., 2003, Grady, 2010), a quick and accurate testing mechanism is needed to arm healthcare professionals with quantifiable metrics to evaluate the cognitive and motor dysfunction of players who are at high risk of concussion. If we can longitudinally monitor the players and detect subtle changes in their behaviour that correlate to traumatic brain injury, it is possible to prescribe preventive care that could minimize the long-term effects of mild traumatic brain injury (mTBI).

Currently, concussion is diagnosed by visually

Nguyen, H., Ayachi, F., Goubault, E., Lavigne-Pelletier, C., McFadyen, B. and Duval, C..
Longitudinal Study on the Detection and Evaluation of Onset Mild Traumatic Brain Injury during Dual Motor and Cognitive Tasks.
In *Proceedings of the 3rd International Congress on Sport Sciences Research and Technology Support (icSPORTS 2015)*, pages 77-83
ISBN: 978-989-758-159-5

observing signs that often associate with mTBI such as headache, disorientation, dizziness and more severely, loss of consciousness. However, loss of consciousness only happens in less than 5% of reported concussion (Castile et al., 2012). These symptoms make concussion difficult to objectively quantify. The diagnostics and follow-up of clinical concussion are normally done by administering neurocognitive and balance tests such as the Sports Concussion Assessment Tool (SCAT3) that subjectively scores the cognitive and motor performance of an individual based on questionnaires and the results of simple motor and cognitive tasks. More advance methods of diagnosing concussion such as Functional Magnetic Resonance Imaging (fMRI) has also been used to evaluate cranial fracture, bleeding (Khurana and Kaye, 2012) and monitor of the alteration in the brain (Talavage et al., 2014). However, fMRI are expensive, time consuming and not widely available. Accordingly, it would be impossible to administer these tests chronically to monitor the state of the player during the season. The diagnostic value of such tests could also be challenged since most concussions do not show enough structural damage to be detected by neuroimaging.

Recently, more efforts are focused on embedding sensors, such as accelerometers, into helmets to longitudinally monitor the cranial movement during exposure to impacts. The aim is to use these sensors to develop performance metrics to determine if an impact experienced by a player could lead to clinical concussion. However, the issue is complex and it had been shown that acceleration alone could not predict concussion (Greenwald et al., 2008, Post and Hoshizaki, 2015). For example, Talavage (2014) used a combination of hit events (6 accelerometers in the helmet), neurocognitive test and neuroimaging to monitor the neurological and mental health of varsity and junior varsity football players from *pre* to *post-season*. The data showed that there was no correlation between the peak helmet acceleration and cognitive deficit. Auerbach (2015) used multiple cranial accelerometers attached to the player's helmet to measure the pulsation of the cerebral blood flow and its impact at different locations of the skull. The results showed that there was a shift in the high harmonic frequency of these sensors in the concussed group. However, using a system of sensors only monitor the physical impact to the head of the individual while the cognitive performance is ignored during process. Furthermore, the cause of this shift in harmonic frequency remains unexplained.

In this study, we proposed a quick and non-invasive testing protocol using a dual-task paradigm to extract relevant kinematics measurements that could be used to longitudinally monitor the cognitive and motor dysfunction of players who are at high risk of concussion. Dual tasks that involved both cognitive and motor tasks have demonstrated promising results in differentiating the kinematic behaviour between concussed and non-concussed group. Cossette (2014) showed that gait speed and dual-task cost during stepping over obstacle were sensitive to the executive dysfunction of people with mTBI. Parker (2005) showed gait and center of mass measurement were significantly different between the two groups during walking with a cognitive task. A systematic review of the dual-task paradigm in detecting concussion also concluded that gait velocity and the sway in the medial lateral direction could be used for long-term monitoring of sport-related concussion (Lee et al., 2013). These results in dual-task paradigm provide a viable platform to develop a novel testing protocol that could quickly and reliably monitor the cognitive and motor behaviour of these high-risk players. Interestingly, dual-tasking has a clear advantage compared to other diagnostic methods; it replicates situations encountered during play. Indeed, players are systematically required to move their body onto the playing field while making quick decisions. Their ability to maintain their concentration, which is normally associated with high cognitive load, is vital in order to play the game. In fact, a reduction in dual-tasking ability could put the player at risk of further unnecessary impacts due to loss of situational awareness on the field (Fait et al., 2013).

Contrary to previous studies where optical systems requiring complicated setup and lengthy testing protocol, the present study used a markerless motion tracking system that is simple to setup. The protocol was designed to minimize the disruption to the player's life while monitoring their cognitive and motor performance throughout the season. Such a system may eventually provide a platform to follow players during an entire season, so as to help athletic trainers and healthcare professionals detect and manage concussions.

2 METHODS

2.1 Participants

Four male football players volunteered from a local high school for the study (15.5 ± 0.6 years old, height =1.82 ± 0.07 m, weight = 79.3 ± 13.0 kg). Participants were excluded if they suffered physical injury during the season that compromised their normal gait pattern. Two participants had a history of concussion while two had never been diagnosed with concussion. During the course of the season, one participant was clinically diagnosed with a concussion. The institutional research ethics review board of the Centre de Recherche de l'Institut Universitaire de Gériatrie de Montreal (CRIUGM) approved this research and each participant and their guardians read and signed an informed consent form.

2.2 Data Acquisition

A markerless motion capturing system from Organic Motion (New York, NY) was used to monitor and measure the performance of the football players throughout the playing season. The system contains 16 cameras to capture the motion of the participants within the staged course. The system generates a full body skeletal model by tracking 23 nodes on the body. The (x,y,z) coordinates of these nodes are tracked by the system at 60 Hz. The data were filtered using a zero-phase fourth-order digital filter with a 6 Hz cut-off frequency. An external data acquisition system controlled by DasyLab (Norton, MA, USA) was also programed to randomly generate numbers between 1 and 9 for the cognitive tests (see below). The acquisition system also monitored sensors attached to the turn markers and the hanging obstacle on the testing stage to monitor errors during turning (contact). The sensors data were sampled at 100 Hz. All data were exported to Matlab® (Natick, MA, USA) for analysis.

2.3 Protocol

Participants were asked to navigate a staged obstacle course at higher than normal walking speed (without running) for 45 seconds (Figure 1). The obstacle course included tasks such as straightway walking, turning and stepping under and over obstacles.

The testing stage had two obstacles: a ground obstacle and a hanging obstacle. These obstacles allowed us to measure the motor function in stepping over and ducking under an obstacle. The testing stage also had three turns. At each turn, there was a strain gauge sensor attached to a string marking the centroid of the turn. These sensors recorded if the participants touched the string while turning. Similarly, the hanging obstacle was also equipped with a strain gauge to measure the disturbance if participants touched the bar.

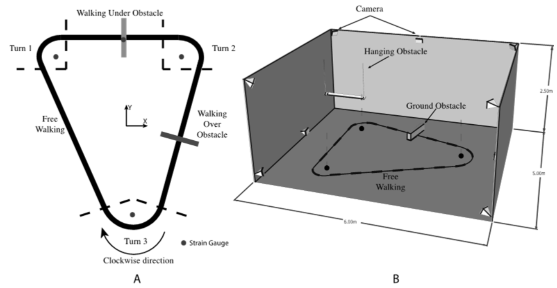

Figure 1: A) Top view schematic of the different challenging segments in the testing protocol. B) 3-D view of the testing stage.

An N-back (N-2) cognitive task (Kirchner, 1958) was used to challenge the cognitive and motor functions of the players. The test aims at evaluating the working memory, concentration and their impact on motor functions during the single and dual-task environments. The dual-task was optimized to challenge the players during the navigation of the obstacle course. Such dual-task is ideal since it replicates game situations where players are asked to move on the field (motor aspect) while make decisions according to their environment (cognitive aspect). Participants were monitored throughout the football season and tested at least once a week. Participants were asked to perform two trials of the cognitive task only, two trials of the motor task only, one in each direction (clockwise and counter clockwise) and, similarly, two trials of the motor and cognitive tasks combined. It is important to note that each testing session lasted on average less than 15 minutes from the time the participant entered the laboratory and the time the test was completed. The actual data collection was only 4.5 minutes.

2.4 Performance Analysis

2.4.1 Task Segmentation

The obstacle course was separated into different sections for analysis. The segmentation was done by specifying the x-y boundary on the stage to mark different regions. Each segment provided specific metrics for performance analysis corresponding to the activities within each segment. For instance, during the hanging obstacle segment, the distance between the participant and the obstacle (clearance) was used as a possible marker sensitive to change over the course of the season. Similarly walking speed and step width were only calculated during straightway walking segment.

2.4.2 Kinematics Analysis

While many kinematic performance parameters could be used to determine whether they were viable factors in discriminating the symptoms of mild traumatic brain injury, this paper focused on segment *task time* (of each segment was defined by tracking when the sacrum entered and exited the x-y boundary of each segment), *median frequency* (the spectral analysis of the oscillation of the sacrum in the vertical direction) and *step width variability* (calculated by tracking the (*x,y*) coordinates of the left and right foot) during the free walking segments. The perpendicular distance between the left and right foot along the walking path were used to estimate the step width. Cognitive scores were recorded separately for each condition. The average and standard deviation across all conditions were calculated. The scores were calculated based on the correct responses given by the participants divided by the total number of possible correct responses.

3 RESULTS

Four participants volunteered for the project. Participant 3 and 4 had no history of concussion while participant 1 had a mild concussion in the last year. Participant 2 had suffered three concussions and two within the last four years. The latest one, in 2012, occurred during a football game.

There were no significant differences in the cognitive scores of the participants when it was performed alone or when it was performed in conjunction with a motor task given that they are within one standard deviation of each other. The average cognitive scores for the participants for the N-2 cognitive task was 89.6% (std +/- 7.1%) accuracy. Furthermore, the player who suffered a concussion (participant 4) during the season did not register a significant decrease in cognitive task score. Similarly, there were no significant differences in the motor performance of each participant across the different segments of the obstacle course in the *motor-only* condition given that their trends where relatively constant and within one standard deviation of each other. However, when cognitive task and motor function were simultaneously active during the obstacle course, several kinematic performance variables emerge as markers of concussion. Specifically, one participant experienced a hard hit(s) during practice (Tuesday, Fig.2). We proceeded to test him on the following day. Subsequently, he played a regular season game on the following Friday where he reported being light headed, with headache, and felt nauseous. The player was pulled from the game and was diagnosed with a concussion by the athletic trainer. The concussed participant was evaluated using a SCAT3 test a day after the game. He exhibited 16 of 22 possible symptoms and his Standardized Assessment Concussion score dropped 9 points from his baseline (out of a possible 25). He underwent concussion protocol before returning to football activities two weeks later.

The players who were not diagnosed with a concussion showed a steady walking time during free walking (Figure 2). While there were differences between the non-concussed participants, their relative trends remained flat throughout the season. Furthermore, their values were close to the 99% confidence interval. However, the concussed participant showed more variable walking time throughout the season. For the test one day after impact during practice, there was an increase walking time during the free walking segment. While the concussed participant showed a return to baseline after the post-concussion protocol, he still showed a variable trend post-concussion.

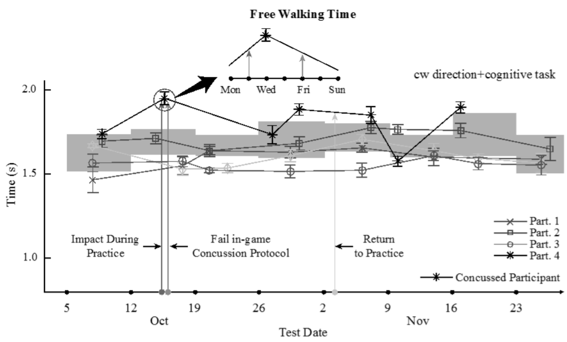

Figure 2: Walking time during free walking segment and the 99% confidence interval band for each testing week during cognitive + motor dual task.

Similar kinematic behaviours were also observed in the step width variability (Figure 3). The step width variability was normalized to height of each participant for comparison. The non-concussed group showed a relative steady trend over the course of the season while the concussed participant who showed an increasing trend in step width variability after the impact during practice and the subsequent concussion diagnosed during the game. However, this increase in the relative trend of step width variability was only observed when the participant walk in the counter clockwise direction.

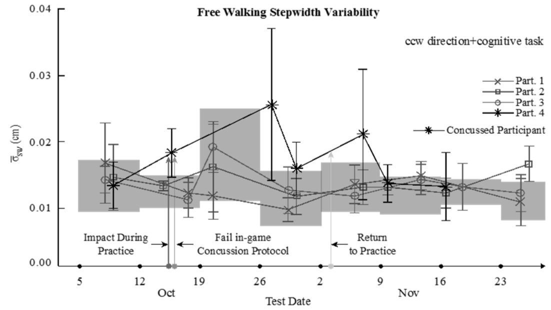

Figure 3: Step width variability during free walking segment normalized with the height of each participant and the 99% confidence interval band for each testing week during cognitive + motor dual task.

Spectral analysis of the sacrum during free walking also showed a shift in the median frequency of the concussed participants after a head impact during practice (Figure 4). Following the prescribed post-concussion protocol, the median frequency returned to baseline. However, the median frequency of participant 2 deviated from the baseline behaviour during the last week of testing while the other non-concussed participants remained relatively steady throughout the season.

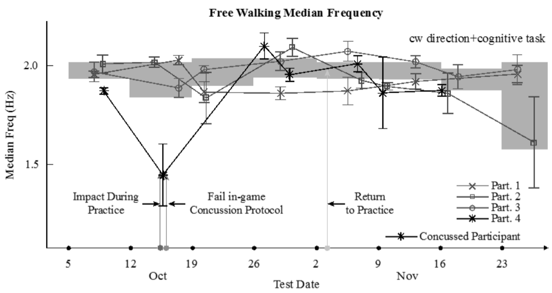

Figure 4: Median frequency of the sacrum in the z-direction during free walking segment and the 99% confidence interval band for each testing week.

4 DISCUSSION

Concussion is difficult to objectively quantify. Current testing mechanisms can be lengthy, cumbersome and expensive. Concussions are often not diagnosed until after gross cognitive and motor dysfunctions are visibly observed. We demonstrated here that our automated motor and cognitive test was able to detect changes in performance before the health staff of the football team detected the problem in one player. The majority of concussions do not exhibit any of these gross motor dysfunctions. This is why there is a need for long-term monitoring of youth athletes who are at risk of concussion. In this paper, we proposed a kinematic-based testing protocol using markerless motion capture system to monitor the cognitive and motor performance of football players throughout the playing season. This system would reduce the amount of time required to test each participant. Furthermore, it has the potential to reveal *cognitive* and *motor* deficits that are otherwise not visually observable.

Evidence suggests that youth athletes cognitively recover more slowly than a college-age group (Field et al., 2003, Covassin et al., 2012) and their symptoms tend to last longer (Castile et al., 2012). Furthermore, prolonged exposure to repetitive hits could expedite the aging of the brain that could result in more serious neurodegenerative diseases such as chronic traumatic encephalopathy (CTE) (Stern et al., 2011). Therefore, it is imperative that preventive care is provided at any sign of motor and cognitive deficiency to minimize the long-term effects of these impacts. Objectively quantifying these motor behaviours will remove the subjective nature of concussion detection and management. Castile (2012) found that 15.2% of youth athletes who suffered concussion returned to play while still symptomatic. This increases their exposure to recurrent concussion and catastrophic effects of second impact syndrome (Bowen, 2003, Bey and Ostick, 2009, Cantu and Gean, 2010, McCrory et al., 2012). Our approach will provide trainers with continuous monitoring of their behaviour to ensure that they are fully recovered from the effects of concussion before return to play.

Under reporting is a major problem in the detection and management of concussion. This could be attributed to many factors such as the effect of wanting more playing time and a perceived weakness when not playing through injury. Talavage (2014) longitudinal study of football player from *pre-* to *post*-season found a high number of players who were not diagnosed with concussion yet showed measurable cognitive impairments. This demonstrated that traditional cognitive testing might not be sufficient to detect athletes who exhibit signs of neurocognitive damage, yet never clinically diagnosed with concussion. For example, participant 2 was never diagnosed with concussion during the season; however, the median frequency was shifted toward a lower frequency with a larger variation. Relative to his baseline behaviour over the course of the season, this player *could be* experiencing an mTBI during the last week of the season. While more investigative work is needed to determine the reasons for the shift in the median frequency, the results should at least raise warning flags to medical professionals to implement preventive measures to ensure that the player is physically and cognitively healthy given his history of concussion. The aim of these preventive measures is to reduce the amount of undetected and unreported incidences of concussion. For youth athletes, these undetected injuries could have a detrimental impact on their cognitive development.

Long-term monitoring of these players is crucial in identifying players who might exhibit signs of cognitive and motor deficits without being clinically diagnosed with concussion. Coaches and medical professionals at the youth level often lack the resources and training to deal with the complexity of concussion detection since symptoms do not manifest themselves unless major injury occurs. Therefore, it is essential to provide these professionals with simple metrics to easily monitor the change in the motor and cognitive dysfunction of these players throughout the season. Multi-tasking is an essential element of sports; therefore, it is imperative to monitor players' performance when subjecting to these types of tasks. In this study, we aim to develop a testing protocol using a kinematic-based dual-task paradigm to *quickly* and *non-invasively* monitor high-risk players throughout the season to track their motor and cognitive functions. The ultimate goal would be to build a cognitive and biomechanical passport for each player using data collected longitudinally with a protocol such as the one presented here. Then, the performance of each athlete could be compared with that of his/her peers, but also with that of him/herself. Any abrupt changes could be considered as tell-tale signs that mTBI has occurred. Since the test is also performed without the cognitive tasks, the motor development or alterations could be taken into consideration in the detection of possible mTBI.

While the sample size is a limiting factor in this study, we hope to test and monitor more players *pre* and *in*-season to develop more comprehensive metrics to measure the motor and cognitive function of these at-risk athletes in future studies. This could include simple performance metrics, such as the ones presented here, but also full-body pattern recognitions using more sophisticated techniques such as machine learning, neural or Bayesian network. Furthermore, as we are developing the algorithms to detect mTBI, we are also exploring hardware alternatives that could capture full-body kinematics in a markerless fashion easily, and with lower costs, so that such a system could eventually become accessible to teams. Still, the present results are encouraging, and are in line with previous research using more conventional (yet more complicated and time consuming) approaches (Cossette et al., 2014). We hope to provide coaches and medical professionals with a more simple, fast and fully automated tool to objectively identify at-risk players, and provide preventive care so as to avoid the unhealthy consequences of multiple undetected concussions and their impact long-term health.

5 CONCLUSIONS

An automated kinematic-based dual-task paradigm provided a promising testing mechanism to detect the onset of concussion. This novel approach allows for the monitoring of players over the entire season and provides faster assessment of concussion effects than traditional neurocognitive tests.

REFERENCES

Auerbach, P. S., Baine, J. G., Schott, M. L., Greenhaw, A., Acharya, M. G. & Smith, W. S. (2015). Detection of concussion using cranial accelerometry. *Clin J Sport Med,* 25**,** 126-32.

Bey, T. & Ostick, B. (2009). Second impact syndrome. *West J Emerg Med,* 10**,** 6-10.

Bowen, A. P. (2003). Second impact syndrome: a rare, catastrophic, preventable complication of concussion in young athletes. *J Emerg Nurs,* 29**,** 287-9.

Cantu, R. C. & Gean, A. D. (2010). Second-impact syndrome and a small subdural hematoma: an uncommon catastrophic result of repetitive head injury with a characteristic imaging appearance. *J Neurotrauma,* 27**,** 1557-64.

Castile, L., Collins, C. L., McIlvain, N. M. & Comstock, R. D. (2012). The epidemiology of new versus recurrent sports concussions among high school athletes, 2005-2010. *Br J Sports Med,* 46**,** 603-10.

Cossette, I., Ouellet, M. C. & McFadyen, B. J. (2014). A preliminary study to identify locomotor-cognitive dual tasks that reveal persistent executive dysfunction after mild traumatic brain injury. *Arch Phys Med Rehabil,* 95**,** 1594-7.

Covassin, T., Elbin, R. J., Harris, W., Parker, T. & Kontos, A. (2012). The role of age and sex in symptoms, neurocognitive performance, and postural stability in athletes after concussion. *Am J Sports Med,* 40**,** 1303-12.

Fait, P., Swaine, B., Cantin, J. F., Leblond, J. & McFadyen, B. J. (2013). Altered integrated locomotor and cognitive function in elite athletes 30 days postconcussion: a preliminary study. *J Head Trauma Rehabil,* 28**,** 293-301.

Field, M., Collins, M. W., Lovell, M. R. & Maroon, J. (2003). Does age play a role in recovery from sports-related concussion? A comparison of high school and collegiate athletes. *J Pediatr,* 142**,** 546-53.

Grady, M. F. (2010). Concussion in the adolescent athlete. *Curr Probl Pediatr Adolesc Health Care,* 40**,** 154-69.

Greenwald, R. M., Gwin, J. T., Chu, J. J. & Crisco, J. J. (2008). Head impact severity measures for evaluating mild traumatic brain injury risk exposure. *Neurosurgery,* 62**,** 789-98; discussion 798.

Khurana, V. G. & Kaye, A. H. (2012). An overview of concussion in sport. *J Clin Neurosci,* 19**,** 1-11.

Kirchner, W. K. (1958). Age differences in short-term retention of rapidly changing information. *J Exp Psychol,* 55**,** 352-8.

Lee, H., Sullivan, S. J. & Schneiders, A. G. (2013). The use of the dual-task paradigm in detecting gait performance deficits following a sports-related concussion: a systematic review and meta-analysis. *J Sci Med Sport,* 16**,** 2-7.

McCrory, P., Davis, G. & Makdissi, M. (2012). Second impact syndrome or cerebral swelling after sporting head injury. *Curr Sports Med Rep,* 11**,** 21-3.

Parker, T. M., Osternig, L. R., Lee, H. J., Donkelaar, P. & Chou, L. S. (2005). The effect of divided attention on gait stability following concussion. *Clin Biomech (Bristol, Avon),* 20**,** 389-95.

Pilon, M. & Belson, K. 2013. Seau Had Brain Disease Found in Other Ex-Players. *New York Times*, January 11, 2013.

Post, A. & Blaine Hoshizaki, T. (2015). Rotational acceleration, brain tissue strain, and the relationship to concussion. *J Biomech Eng,* 137.

Rosenthal, J. A., Foraker, R. E., Collins, C. L. & Comstock, R. D. (2014). National High School Athlete Concussion Rates From 2005-2006 to 2011-2012. *Am J Sports Med,* 42**,** 1710-1715.

Stern, R. A., Riley, D. O., Daneshvar, D. H., Nowinski, C. J., Cantu, R. C. & McKee, A. C. (2011). Long-term consequences of repetitive brain trauma: chronic traumatic encephalopathy. *PM R,* 3**,** S460-7.

Talavage, T. M., Nauman, E. A., Breedlove, E. L., Yoruk, U., Dye, A. E., Morigaki, K. E., Feuer, H. & Leverenz, L. J. (2014). Functionally-detected cognitive impairment in high school football players without clinically-diagnosed concussion. *J Neurotrauma,* 31**,** 327-38.