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Are There Subconcussive Neuropsychological Effects in Youth Sports? An Exploratory Study of High- and Low-Contact Sports

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This exploratory study was designed to examine the neuropsychological effects of sports-related head trauma—specifically, repetitive subconcussive impacts or head blows that do not result in a diagnosable concussion. The researchers compared the Immediate Post-Concussion Assessment and Cognitive Testing (ImPACT) neurocognitive test scores of 2 groups of nonconcussed youth athletes ($n = 282$), grouped according to the frequency of concussions in their respective sports, with the assumption that more subconcussive impacts occur in sports in which there are more reported concussions. The results indicated that high-contact-sport (football) athletes had significantly poorer performance in processing speed and reaction time compared with athletes in low-contact sports (wrestling, soccer, baseball, judo, and basketball). This study into the effects of repetitive subconcussive head trauma tentatively raises concern that participation in high-contact sports, even without evidence of a diagnosable concussion, could result in lowered neuropsychological functioning among high school athletes. Limitations of this exploratory research effort are discussed.

Key words: *contact, subconcussive neuropsychological effects, youth sports*

INTRODUCTION

The panel at the Fourth International Conference on Concussion in Sport in 2012 defined concussion as "a complex pathophysiological process affecting the brain, induced by biomechanical forces" (McCrory et al., 2013, p. 250), associated with headaches, cognitive impairment, irritability, sleep disturbance, amnesia, and in a minority of individuals, loss of consciousness. While understandable concern is raised about brain injury caused by concussions, there is growing interest that head trauma that falls short of a diagnosis of concussion may also affect neurological functioning (Bailes, Petraglia, Omalu, Nauman, & Talavage, 2013; Baugh

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et al., 2012; Broglio, Eckner, Paulson, & Kutcher, 2012; Graham, Rivara, Ford, & Spicer, 2014). Evidence is mounting that these nonconcussive impacts can result in neuropathological changes, as observed early in classic studies of laboratory animals subjected to mild head trauma (Denny-Brown & Russell, 1941) and currently documented in advanced neuroimaging findings (Baugh et al., 2012; Lipton et al., 2013; McAllister et al., 2014). Subconcussive head injury has emerged as a serious concern in sports medicine as its repetitive occurrences may increase the risk for chronic traumatic encephalopathy (CTE) in athletes, especially participants in contact sports such as football (Baugh et al., 2012; Harmon et al., 2013). Repetitive head trauma in professional football was the target of a recent critical look at the alleged denial of concussive brain damage by the National Football League, with apprehensions about the implications for high school and college players (Fainaru-Wada & Fainaru, 2013).

Head injuries are observed in all youth sport activities, but the highest volume of concussion occurs in football (Datalys Center for Sports Injury Research and Prevention, 2013; Rosenthal, Foraker, Collins, & Comstock, 2014). In football, it may be impossible to avoid repetitive subconcussive injury that could occur in nearly every play (Gavett, Stern, & McKee, 2011). A high school or college football team may experience thousands of subconcussive impacts during the course of a single season (Duma et al., 2005; Greenwald, Gwin, Chu, & Crisco, 2008). A study employing in-helmet accelerometers with 449 high school football players revealed more than 7,000 nonconcussive impacts per team per season (Greenwald et al., 2008), while another study utilizing similar biomechanical measures showed that the average high school football player sustained 652 subconcussive impacts per season (Broglio et al., 2011).

Studies on the effects of repetitive subconcussive impacts have had mixed results, with some showing a relation between such impacts on neurological functioning and others not. A recent investigation employing head-impact telemetry placed in helmets of 46 collegiate football players showed no clinically meaningful effect of subconcussive impacts on neuropsychological test scores and other clinical measures of neurologic functions (Gysland et al., 2012). Additionally, a study of collegiate football players revealed that neurocognitive test scores were not altered by a season of repetitive contact in athletes who had not sustained a concussion (Miller, Adamson, Pink, & Sweet, 2007). In contrast, researchers who used head-impact telemetry placed in the helmets of 24 high school football players reported that a substantial proportion of the players who did not sustain a concussion showed significant functional magnetic resonance imaging (fMRI) changes; the researchers also observed significant relationships between the number of blows sustained by an athlete and subsequent neurophysiological impairment (Breedlove et al., 2012). Furthermore, an investigation on 11 high school football players, ages 15 to 19 years old, revealed that 4 players with no clinically observed symptoms associated with concussion demonstrated measurable neurocognitive and fMRI abnormalities (Talavage et al., 2013). The authors suspected that repeated subconcussive collisions in football produced subclinical impacts on the brain, and they were concerned that the players' continued participation in practice and games could result in an increased risk for CTE. Another recent investigation applying a wild bootstrap permutation test showed that 15 high school athletes (football and hockey) with multiple subconcussive head blows had significant changes in brain white matter that were more than 3 times more than those of controls (Bazarian, Zhu, Blyth, Borrino, & Zhong, 2012). Unfortunately, the small sample size employed in these studies seriously limited the significance of their results. The conflicting findings of these few studies raise concerns that high school football players compared with collegiate football players may be at greater risk for neurologic injury from repeated subconcussive hits, perhaps due to their stage of developmental maturation.

Efforts to investigate the neuropsychological performance of athletes participating in sports that vary in terms of head trauma occurrences have yielded inconsistent findings. Barr (2003) obtained the baseline scores of high school athletes on a brief battery of neuropsychological tests and found no differences in test scores among those playing football, soccer, or field hockey. While there is a higher incidence of concussion in rugby compared with football (Datalys Center for Sports Injury Research and Prevention, 2013; Gardner et al., 2014), South African rugby players and U.S. football players, ages 11 to 21 years old, obtained equivalent neurocognitive measures on the Immediate Post-Concussion Assessment and Cognitive Testing (ImPACT; Shuttleworth-Edwards, Whitefield-Alexander, Radloff, Taylor, & Lovell, 2009). In another study of repetitive head impacts, the hypothesis that soccer players' neuropsychological performance would be poorer than that of rugby and non-contact-sport players (e.g., basketball, tennis, swimming) due to the cumulative subconcussive trauma from regular soccer heading was not supported (Stephens, Rutherford, Potter, & Fernie, 2010). On the other hand, soccer players with the highest estimate of heading had poorer scores on tests measuring attention, concentration, cognitive flexibility, and general intellectual functioning (Witol & Webbe, 2003). Recently, McAllister et al. (2014) compared a cohort of collegiate contact-sport athletes (football and ice hockey) with a non-contact-sport cohort (track, crew, and skiing) employing diffusion tensor imaging and varied neuropsychological tests. Although the researchers found no difference between sport groups on the ImPACT, they noted that a higher percentage of contact-sport athletes performed more than 1.5 standard deviations below their predicted score on the California Verbal Learning Test-Second Edition, suggesting that repetitive head impacts affected the neuropsychological condition of contact-sport athletes.

With the increased popularity of sports among youths, a large number of young athletes are exposed to repetitive head trauma and are at risk for brain injury in a wide variety of contact sports, such as football, soccer, wrestling, ice hockey, rugby, skiing, and lacrosse (McKee et al., 2009). The present study was designed to explore the possible neuropsychological effects of subconcussive head trauma in varied sports among high school athletes with no prior history of concussion. In lieu of standard nomenclature, these undiagnosed head traumas have been referred to as subconcussive blows (Denny-Brown & Russell, 1941), multiple minor impacts (Boden, Kirkendall, & Garrett, 1998), repetitive low-impact forces (Green & Jordan, 1998), low-energy blows (Rabadi & Jordan, 2001), asymptomatic traumatic brain injury (Gavett et al., 2011), and subclinical concussions (Chamard et al., 2012). Webbe (2006, p. 64) defined a subconcussive impact as "an apparent brain insult with insufficient force to cause hallmark symptoms of concussion," but the term "subconcussion" remains ambiguous and without definite signs, symptoms, or criteria.

Although it remains difficult to track sports-related concussive events, the identifying of a subconcussive blow in sports is markedly more challenging. This investigation, utilizing a differential prevalence design, operationally defined subconcussion by focusing on six sports—football, wrestling, soccer, baseball, judo, and basketball—that vary in the frequency of concussions reported in each sport. According to the Datalys Center for Sports Injury Research and Prevention (2013), among the various high school sports, football had, by far, the highest rate of concussions, with 11.2 concussions per 10,000 athlete exposures, while wrestling had 6.2, soccer had 4.2, basketball had 2.8, and baseball had 1.2 concussions per 10,000 athlete exposures. Similar concussion rates for high school sports have been reported (Daneshvar, Nowinski, McKee, & Cantu, 2011; Lincoln et al., 2011; Rosenthal et al., 2014). The degree of subconcussive contact in this study was presumed to vary according to the known prevalence rates of concussion in the different sports. For the purpose of this research, based on the aforementioned epidemiologic reports, football was considered a high-contact sport, while wrestling, soccer, baseball, judo, and baseball, with relatively lower rates of concussions, were collectively considered low-contact sports. This research paradigm was similar to prior investigations of repetitive head impacts and subconcussive trauma that have compared athletes in contact sports (e.g., football, soccer) versus those in non-contact sports (e.g., tennis, track; McAllister et al., 2014; Stephens et al., 2010). With the lack of prior relevant research findings, the hypothesis was that the differences in the neuropsychological test performances of athletes in the high- and low-contact sports would be insignificant.

MATERIALS AND METHODS

This retrospective archival study was examined by the Hawaii Pacific Health Institutional Review Board and was deemed to be exempt from institutional review board review.

Participants

The research data were obtained from a pool of 282 non-concussed male high school athletes from four public high schools, Grades 8 through 12, in Honolulu, HI, who met the following study inclusion criteria: no history of concussion, primary language of English, and valid test results (i.e., Impulse Control Composite score <30). The study participants were composed of athletes in the following sports: 182 in football, 35 in wrestling, 25 in soccer, 22 in baseball, 10 in judo, and 8 in basketball.

Test Instrument

This study utilized the ImPACT battery, which has been employed in numerous studies of concussions among high school athletes (Lovell, 2006). The ImPACT is a 20-min to 30-min computerized neuropsychological test instrument that measures verbal and visual memory, processing speed, reaction time, impulse control, and postconcussion symptoms (Maroon et al., 2000). A large body of research in the past decade has established the ImPACT's usefulness in the neuropsychological assessment of mild traumatic brain injury in high school, collegiate, and professional athletes (Lovell et al., 2003; Schatz, Pardini, Lovell, Collins, & Podell, 2006). This study used data obtained from ImPACT Version 4.5.

The study examined five endpoints. The following ImPACT composite scores were used for this study: Verbal Memory, Visual Memory, Processing Speed, and Reaction Time. In addition, postconcussion symptoms were examined using ImPACT's Total Symptom score based on the Postconcussion Symptom Scale consisting of 22 commonly reported symptoms (e.g., headache, dizziness). The ImPACT database also provided biopsychosocial data, including age, years of education,

TABLE 1
Characteristics of the Two Contact Groups

	High-Contact-Sport Group n = *182* M *(SD)*	*Low-Contact-Sport Group* n = *100* M *(SD)*	t *(*df = *2)*	p	*Cohen's* d
Age (years)	15.65 (1.20)	16.40 (1.00)	4.21	< .001	−0.68
Years of sports experience	1.20 (1.24)	2.27 (2.81)	4.02	< .001	−0.49
Years of education	9.40 (1.32)	9.91 (1.11)	2.60	.01	−0.42

Note. The high-contact-sport group consisted of football players; the low-contact-sport group consisted of wrestling, soccer, baseball, judo, and baseball players.
p values are based on t tests (two-tailed).

primary spoken language, sport played, prior concussion, and history of learning disability, attention-deficit hyperactivity disorder, seizures, and psychiatric illness.

Procedure

In this study, two contact-sport groups were identified based on known rates of concussion among the various sports (Daneshvar et al., 2011; Datalys Center for Sports Injury Research and Prevention, 2013; Lincoln et al., 2011; Rosenthal et al., 2014). The high-contact-sport group, composed of football players, was formed based on the high rate of concussion in that sport. The low-contact-sport group consisted of athletes from wrestling, soccer, baseball, judo, and basketball. The two contact groups were compared in terms of their four ImPACT composite scores and Total Symptom scores.

Protocol

The research utilized the ImPACT baseline test scores obtained prior to the athletes' respective seasons. Testing was conducted in small groups of about 20, monitored by an athletic trainer who was trained in the standard administration of this computerized neuropsychological test battery. Although the baseline testing was conducted before season play, it was assumed that the athletes participated in their respective sports in the past, which involved varying degrees of contact and head trauma.

Data Analysis

Descriptive statistics (means, standard deviations) were computed for the two comparison groups for all variables of interest. Analyses using t tests were conducted to compare the two groups in terms of their ages, years of sports experience, years of education, and five ImPACT scores (Verbal Memory, Visual Memory, Processing Speed, Reaction Time, and Total Symptom). Cohen's d values were computed as measures of the effect size. Statistical tests reported were two-tailed, with an a-priori statistical significance set with Bonferroni correction at $p < .01$ for all analyses.

RESULTS

The data pertaining to age, education, and years of sport experience appear in Table 1. Group differences in age were statistically significant, $t(280) = 3.78$, $p < .001$, but were small (on average, 0.5 years) and clinically insignificant. The two contact-sport groups did not differ in terms of education and years of sport experience. The

TABLE 2
Comparison of ImPACT Scores for the Two Contact Groups

	High-Contact-Sport Group n = *182* M *(SD)*	*Low-Contact-Sport Group* n = *100* M *(SD)*	t *(*df = *280)*	p	*Cohen's* d
Verbal Memory	0.82 (0.10)	0.84 (0.09)	1.66	.10	−0.21
Visual Memory	0.84 (0.09)	0.75 (0.14)	2.30	.02	−0.29
Reaction Time	0.71 (0.14)	0.54 (0.05)	4.57	< .001	0.61
Processing Speed 34.04	0.75 (0.14)	39.41 (6.54)	5.66	< .001	−0.71
Total Symptom	8.23 (12.15)	6.88 (9.20)	0.40	.69	0.05

Note. The high-contact-sport group consisted of football players; the low-contact-sport group consisted of wrestling, soccer, baseball, judo, and baseball players.
p values are based on *t* tests (two-tailed).

means and standard deviations of the four ImPACT composite scores and the Total Symptom scores are presented in Table 2. Analyses using t tests comparing the two groups showed significant differences in Processing Speed, $t(280) = 5.66$, $p < .001$, and Reaction Time, $t(280) = 4.57$, $p < .001$, with large effect sizes. No group differences were seen in Verbal Memory, Visual Memory, or Total Symptom scores.

DISCUSSION

This exploratory research focused on the neurocognitive functioning of nonconcussed youth athletes exposed to two levels of contact sports, determined by the epidemiologic frequency of concussions (Daneshvar et al., 2011; Datalys Center for Sports Injury Research and Prevention, 2013; Lincoln et al., 2011; Rosenthal et al., 2014), with the assumption that more subconcussive head traumas occur in sports in which more concussions are reported. High-contact (football) athletes performed significantly more poorly than low-contact (wrestling, soccer, baseball, judo, and basketball) athletes in Processing Speed and Reaction Time, with large effect sizes, while no significant group differences were found between sport groups on Verbal Memory, Visual Memory, or Total Symptoms. The findings tentatively suggest that participation in a high-contact sport may affect neuropsychological functioning in young athletes due to repetitive subconcussive head trauma.

The presence of lower neuropsychological scores among the football players presumably due to subconcussive impacts was consistent with the findings of Talavage et al. (2013), who reported neuropsychological and neurophysiologic impairment in high school football players who had no apparent concussions. Neuroimaging findings have also shown the detrimental neurological effects of repetitive impacts without concussion among high school football players (Bazarian et al., 2012; Breedlove et al., 2012). The findings of this study were consistent with prior neuropsychological research, neuroradiological findings, laboratory evidence, and clinical examinations of head trauma that suggest that subconcussive-level impacts can result in significant neurological effects (Bailes et al., 2013; Baugh et al., 2012; Gavett et al., 2011). Because this study included only athletes who have had no history of concussion, the role of subconcussive head trauma was assessed more clearly than in previous studies that have attempted to examine subconcussive blows to the head but included athletes with prior concussions (Gysland et al., 2012; McAllister et al., 2014; Miller et al., 2007; Stephens et al., 2010). The present results are some of the first to compare the neuropsychological test data of nonconcussed high school athletes participating in sports that vary in terms of exposure to multiple subconcussive head trauma.

The neuropsychological effects of repetitive subconcussive impacts upon the young athletes in this study may be a function of their incomplete neurological development. Animal studies and clinical research have shown that the immature adolescent brain seems more susceptible to head injury (Field, Collins, Lovell, & Maroon, 2003; Giza & Hovda, 2004). High school athletes, thus, may sustain more diffuse axonal injury from subconcussive blows and significant impacts on their neurocognitive functioning compared with older athletes. There is also concern that the age at which the brain is subjected to repetitive trauma may be a factor in the later development of CTE (Broglio et al., 2011; Stern et al., 2011). Thus, even when obvious signs of concussion are not present, trauma to the adolescent head should be taken seriously and managed conservatively.

Alternative explanations for the present findings must be considered. The differences in ImPACT neurocognitive scores between the high-contact-sport group and the low-contact-sport group could be due to differences in general intellectual abilities, but data regarding the academic aptitude or achievement of the participants were not available. The two contact-sport groups may have differed in levels of effort, as studies have indicated that some athletes tend to "sandbag" their baseline test performance so as to make postconcussion return-to-play testing easier to pass (Schatz & Glatts, 2013). However, no effort tests were administered in this study that could have assessed test motivation in the participants.

Limitations

Discussion of the presence of subconcussive effects is somewhat speculative in that there is no consensus as to the definition or criteria for identifying a subconcussive impact. The differential prevalence design in this study provided, at best, an indirect estimate of subconcussive head trauma in different sports, but, as seen in prior research (McAllister et al., 2014; Stephens et al., 2010), it could be a useful method to examine this relatively unchartered area of sports medicine. Nonetheless, this indirect approach is problematic in that causal inferences between subconcussive hits and neurocognitive functioning cannot be drawn. The use of head-impact telemetry placed in football helmets represents a more objective and precise measure of subconcussive events (Breedlove et al., 2012; Gysland et al., 2012), although its ability to predict concussion sequelae has been questioned (Broglio et al., 2011; Eckner, Sabin, Kutcher, & Broglio, 2011).

The groupings in this research—high- and low-contact sports—were not fully mutually exclusive entities. Although participants in this study were classified as playing only one of the six sports, high school athletes often participate in multiple sport activities. Thus, a basketball player could have played football earlier in the school year, but for the purpose of this research was considered only as a basketball player. Future comparisons of sports should utilize those athletes who only play one particular sport.

Other drawbacks of this study included dependence on the self-report of concussion, which was an important study inclusion criterion; the involvement of only male athletes, which limits the generalizability of the results to female athletes; and the absence of external correlates of subconcussive impacts, such as academic performance and socioemotional functioning. Despite the varied limitations of this exploratory effort into the effects of repetitive subconcussive head trauma, the findings, nonetheless, raise concern that involvement in high-contact sports, even without evidence of a concussion, could lead to decline in neuropsychological abilities among youth athletes. A subconcussion is a yet-to-be-defined indistinct condition with vaguely understood pathophysiology and potentially serious consequences that deserves further research attention. Physicians, athletic trainers, coaches, players, and parents would benefit from updated information about the cumulative effects of multiple head impacts for the care and safety of high school athletes.

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REFERENCES

Bailes, J. E., Petraglia, A. L., Omalu, B. I., Nauman, E., & Talavage, T. (2013). Role of subconcussion in repetitive mild traumatic brain injury, *Journal of Neurosurgery*, *119*, 1235–1245. doi:10.3171/2013.7.jns121822

Barr, W. B. (2003). Neuropsychological testing of high school athletes: Preliminary norms and test–retest indices, *Archives of Clinical Neuropsychology*, *18*, 91–101. doi:10.1093/arclin/18.1.91

Baugh, C. M., Stamm, J. M., Riley, D. O., Gavett, B. E., Shenton, M. E., Lin, A., ... Stern, R. A. (2012). Chronic traumatic encephalopathy: Neurodegeneration following repetitive concussive and subconcussive brain trauma, *Brain Imaging and Behavior*, *6*, 244–254. doi:10.1007/s11682-012-9164-5

Bazarian, J. J., Zhu, T., Blyth, B., Borrino, A., & Zhong, J. (2012). Subject-specific changes in brain white matter on diffusion tensor imaging after sports-related concussion, *Magnetic Resonance Imaging*, *30*, 171–180. doi:10.1016/j.mri.2011.10.001

Boden, B. P., Kirkendall, D. T., & Garrett, W. E., Jr. (1998). Concussion incidence in elite college soccer players, *American Journal of Sports Medicine*, *26*, 238–242.

Breedlove, E. L., Robinson, M., Talavage, T. M., Morigaki, K. E., Yoruk, U., O'Keefe, K., ... Nauman, E. A. (2012). Biomechanical correlates of symptomatic and asymptomatic neurophysiological impairment in high school football. *Journal of Biomechanics*, *45*, 1265–1272. doi:10.1016/j.jbiomech.2012.01.034

Broglio, S. P., Eckner, J. T., Martini, D., Sosnoff, J. J., Kutcher, J. S., & Randolph, C. (2011). Cumulative head impact burden in high school football. *Journal of Neurotrauma*, *28*, 2069–2078. doi:10.1089/neu.2011.1825

Broglio, S. P., Eckner, J. T., Paulson, H. L., & Kutcher, J. S. (2012). Cognitive decline and aging: The role of concussive and subconcussive impacts, *Exercise and Sport Sciences Reviews*, *40*, 138–144. doi:10.1097/jes.0b013e3182524273

Chamard, E., Théoret, H., Skopelja, E. N., Forwell, L. A., Johnson, A. M., & Echlin, P. S. (2012). A prospective study of physician-observed concussion during a varsity university hockey season: Metabolic changes in ice hockey players. Part 4 of 4, *Neurosurgical Focus*, *33*, E4. doi:10.3171/2012.10.focus12305

Daneshvar, D. H., Nowinski, C. J., McKee, A. C., & Cantu, R. C. (2011). The epidemiology of sport-related concussion, *Clinical Sports Medicine*, *30*, 1–17.

Datalys Center for Sports Injury Research and Prevention. (2013). *NATA NATION preliminary concussion rates, 2010–2012*. Indianapolis, IN: Institute of Medicine-National Research Council.

Denny-Brown, D., & Russell, W. R. (1941). Experimental cerebral concussion, *Brain*, *64*, 93–164. doi:10.1093/brain/64.2-3.93

Duma, S. M., Manoogian, S. J., Bussone, W. R., Brolinson, P. G., Goforth, M. W., Donnenwerth, J. J., ... Crisco, J. J. (2005). Analysis of real-time head accelerations in collegiate football players, *Clinical Journal of Sport Medicine*, *15*, 3–8. doi:10.1097/00042752-200501000-00002

Eckner, J. T., Sabin, M., Kutcher, J. S., & Broglio, S. P. (2011). No evidence for a cumulative impact effect on concussion injury threshold, *Journal of Neurotrauma*, *28*, 2079–2090. doi:10.1089/neu.2011.1910

Fainaru-Wada, M., & Fainaru, S. (2013). *League of denial: The NFL, concussions, and the battle for truth*. New York, NY: Crown Archetype.

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, *The Journal of Pediatrics*, *142*, 546–553. doi:10.1067/mpd.2003.190

Gardner, A., Iverson, G. I., Levi, C. R., Schofield, P. W., Kay-Lambkin, F., Kohler, R. M. N., & Stanwell, P. (2014). A systematic review of concussion in rugby league, *British Journal of Sports Medicine*, *49*, 495–498. doi:10.1136/bjsports-2013-093102

Gavett, B. E., Stern, R. A., & McKee, A. C. (2011). Chronic traumatic encephalopathy: A potential late effect of sport-related concussive and subconcussive head trauma, *Clinics in Sports Medicine*, *30*, 179–188. doi:10.1016/j.csm.2010.09.007

Giza, C. C., & Hovda, D. A. (2004). The pathophysiology of traumatic brain injury. In M. R. Lovell, R. J. Echemendia, J. T. Barth, & M. W. Collins (Eds.), *Traumatic brain injury in sports: An international neuropsychological perspective* (pp. 45–70). Lisse, The Netherlands: Swets & Zeitlinger.

Graham, R., Rivara, F. P., Ford, M. A., & Spicer, C. M. (Eds.). (2014). *Sports-related concussions in youth: Improving the science, changing the culture*. Washington, DC: National Academies Press.

Green, G. A., & Jordan, S. E. (1998). Are brain injuries a significant problem in soccer?, *Clinics in Sports Medicine*, *17*, 795–809. doi:10.1016/s0278-5919(05)70120-4

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*, 789–798.

Gysland, S. M., Mihalik, J. P., Register-Mihalik, J. K., Trulock, S. C., Shields, E. W., & Guskiewicz, K. M. (2012). The relationship between subconcussive impacts and concussion history on clinical measures of neurologic function in collegiate football players, *Annals of Biomedical Engineering*, *40*, 14–22. doi:10.1007/s10439-011-0421-3

Harmon, K. G., Drezner, J. A., Gammons, M., Guskiewicz, K M., Halstead, M., Herring, S. A., ... Roberts, W. O. (2013). American Medical Society for Sports Medicine position statement: Concussion in sport, *British Journal of Sports Medicine*, *47*, 15–26. doi:10.1136/bjsports-2012-091941

Lincoln, A. E., Caswell, S. V., Almquist, J. L., Dunn, R. E., Norris, J. B., & Hinton, R. Y. (2011). Trends in concussion incidence in high school sports: A prospective 11-year study, *American Journal of Sports Medicine*, *39*, 958–963. doi:10.1177/0363546510392326

Lipton, M. L., Kim, N., Zimmerman, M. E., Kim, M., Stewart, W. F., Branch, C. A., & Lipton, R. B. (2013). Soccer heading is associated with white matter microstructural and cognitive abnormalities, *Radiology*, *268*, 850–857. doi:10.1148/radiol.13130545

Lovell, M. R. (2006). The ImPACT neuropsychological test battery. In R. J. Echemendia (Ed.), *Sports neuropsychology: Assessment and management of traumatic brain injury* (pp. 193–215). New York, NY: Guilford.

Lovell, M. R., Collins, M. W., Iverson, G. L., Field, M., Maroon, J. C., Cantu, R., ... Fu, F. H. (2003). Recovery from mild concussion in high school athletes, *Journal of Neurosurgery*, *98*, 296–301. doi:10.3171/jns.2003.98.2.0296

Maroon, J. C., Lovell, M. R., Norwig, J., Podell, K., Powell, J. W., & Hartl, R. (2000). Cerebral concussion in athletes: Evaluation and neuropsychological testing, *Neurosurgery*, *47*, 659–672. doi:10.1097/00006123-200009000-00027

McAllister, T. W., Ford, J. C., Flashman, L. A., Maerlender, A., Greenwald, R. M., Beckwith, J. G., ... Jain, S. (2014). Effects of head impacts on diffusivity measures in a cohort of collegiate contact sport athletes, *Neurology*, *82*, 63–69. doi:10.1212/01.wnl.0000438220.16190.42

McCrory, P., Meeuwisse, W. H., Aubry, M., Cantu, B., Dvořák, J., Echemendia, R. J., ... Turner, M. (2013). Consensus statement on concussion in sport: The 4th International Conference on Concussion in Sport held in Zurich, November 2012, *British Journal of Sports Medicine*, *47*, 250–258.

McKee, A. C., Cantu, R. C., Nowinski, C. J., Hedley-Whyte, E. T., Gavett, B. E., Budson, A. E., ... Stern, R. A. (2009). Chronic traumatic encephalopathy in athletes: Progressive tauopathy after repetitive head injury, *Journal of Neuropathology and Experimental Neurology*, *68*, 709–735. doi:10.1097/nen.0b013e3181a9d503

Miller, J. R., Adamson, G. J., Pink, M. M., & Sweet, J. C. (2007). Comparison of preseason, midseason, and postseason neurocognitive scores in uninjured collegiate football players, *American Journal of Sports Medicine*, *35*, 1284–1288. doi:10.1177/0363546507300261

Rabadi, M. H., & Jordan, B. D. (2001). The cumulative effect of repetitive concussion in sports, *Clinical Journal of Sport Medicine*, *11*, 194–198. doi:10.1097/00042752-200107000-00011

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, *American Journal of Sports Medicine*, *42*, 1710–1715. doi:10.1177/0363546514530091

Schatz, P., & Glatts, C. (2013). 'Sandbagging' baseline test performance on ImPACT, without detection, is more difficult than it appears, *Archives of Clinical Neuropsychology*, *28*, 236–244. doi:10.1093/arclin/act009

Schatz, P., Pardini, J., Lovell, M., Collins, M., & Podell, K. (2006). Sensitivity and specificity of the ImPACT test battery for concussion in athletes, *Archives of Clinical Neuropsychology*, *21*, 91–99. doi:10.1016/j.acn.2005.08.001

Shuttleworth-Edwards, A. B., Whitefield-Alexander, V. J., Radloff, S. E., Taylor, A. M., & Lovell, M. R. (2009). Computerized neuropsychological profiles of South African versus US athletes: A basis for commentary on cross-cultural norming issues in the sports concussion arena, *The Physician and Sportsmedicine*, *37*, 45–52. doi:10.3810/psm.2009.12.1741

Stephens, R., Rutherford, A., Potter, D., & Fernie, G. (2010). Neuropsychological consequence of soccer play in adolescent U.K. school team soccer players, *Journal of Neuropsychiatry & Clinical Neuroscience*, *22*, 295–303. doi:10.1176/appi.neuropsych.22.3.295

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*(10S2), S460–S467. doi:10.1016/j.pmrj.2011.08.008

Talavage, T. M., Nauman, E. A., Breedlove, E. L., Yoruk, U., Dye, A. E., Morigaki, K. E., ... Levereux, L. J. (2013). Functionally-detected cognitive impairment in high school football players without clinically-diagnosed concussion, *Journal of Neurotrauma*, *31*, 327–338.

Webbe, F. M. (2006). Definition, physiology, and severity of cerebral concussion. In R. J. Echemendia (Ed.), *Sports neuropsychology: Assessment and management of traumatic brain injury* (pp. 45–70). New York, NY: Guilford.

Witol, A. D., & Webbe, F. M. (2003). Soccer heading frequency predicts neuropsychological deficits, *Archives of Clinical Neuropsychology*, *18*, 397–417. doi:10.1093/arclin/18.4.397