Acute Lower Extremity Injury Rates Increase after Concussion in College Athletes

ROBERT C. LYNALL[1,2], TIMOTHY C. MAUNTEL[2,3], DARIN A. PADUA[2,3], and JASON P. MIHALIK[1,2,4]

[1]Matthew Gfeller Sport-Related Traumatic Brain Injury Research Center, Department of Exercise and Sport Science, University of North Carolina, Chapel Hill, NC; [2]Curriculum in Human Movement Science, Department of Allied Health Sciences, School of Medicine, University of North Carolina, Chapel Hill, NC; [3]Sports Medicine Research Laboratory, Department of Exercise and Sport Science, University of North Carolina, Chapel Hill, NC; and [4]Injury Prevention Research Center, University of North Carolina, Chapel Hill, NC

ABSTRACT

LYNALL, R. C., T. C. MAUNTEL, D. A. PADUA, and J. P. MIHALIK. Acute Lower Extremity Injury Rates Increase after Concussion in College Athletes. *Med. Sci. Sports Exerc.*, Vol. 47, No. 12, pp. 2487–2492, 2015. Dynamic postural control deficits and disrupted cortical pathways have been reported to persist beyond an athlete's return to activity after concussion, potentially increasing the risk of acute lower extremity musculoskeletal injury. **Purpose**: This study aimed to investigate acute lower extremity musculoskeletal injury rates before and after concussion in athletes with concussion and their matched control. **Methods**: College athletes with concussion (n = 44; age, 20.0 ± 1.2 yr) were physician-diagnosed. Nonconcussed college athletes (n = 58; age, 20.5 ± 1.3 yr) were matched to individuals with concussion. Acute lower extremity musculoskeletal injury data were collected for 2 yr (±1 yr of the diagnosed concussion) using electronic medical records. Control participants' 2-yr window for exposure and musculoskeletal injury data were anchored to their match's concussion injury date. Pre- and postconcussion musculoskeletal injury rates were calculated for 90-, 180-, and 365-d periods for both study cohorts. Risk ratios were calculated to determine differences within and between groups for all periods. **Results**: Within 1 yr after concussion, the group with concussion was 1.97 (95% confidence interval (CI), 1.19–3.28; P = 0.01) times more likely to have experienced an acute lower extremity musculoskeletal injury after concussion than before concussion and 1.64 times (95% CI, 1.07–2.51; P = 0.02) more likely to have experienced an acute lower extremity musculoskeletal injury after concussion than their matched nonconcussed cohort over the same period. Up to 180 d after concussion, the group with concussion was 2.02 (95% CI, 1.08–3.78; P = 0.02) times more likely to have experienced an acute lower extremity musculoskeletal injury after concussion than before concussion. **Conclusions**: Previous literature has identified dynamic postural control deficits along with increased motor evoked potential latency and decreased amplitude after concussion, suggesting that the brain may be unable to effectively coordinate movement. Our findings underscore the need to explore functional movement and dynamic postural control assessments in postconcussion injury assessment protocols. **Key Words:** MUSCULOSKELETAL INJURY RISK, POSTCONCUSSION DEFICITS, CONCUSSION, INJURY, COLLEGE ATHLETICS

Over two decades of clinical research has yielded valuable information about neurocognitive (16,29) and balance (9,28) deficits along with increased symptom reporting (18) after concussion. This knowledge led to guidelines advocating the use of clinical test batteries to diagnose and safely return athletes to activity after concussion (1,8,19). To date, these concussion assessment and return to activity guidelines represent the most widely accepted means of clinically managing concussion. Using these assessments as the gold standard for concussion management, 85% of collegiate-age athletes recover and begin a return to activity progression within 7 d of the concussive injury (17).

The standard concussion assessment battery, however, does not take into account demonstrable changes in functional movement patterns after return to activity after concussion (15,22). Neuromuscular control deficits (conservative adaptions and increased sway) have been observed during standard gait under dual-task conditions (gait in conjunction with a cognitive distractor task) (3,4,21–23). These neuromuscular control deficits are present acutely after concussion and often well beyond full return to activity. These are alarming findings, as deficits during relatively easy standard gait tasks may

Address for correspondence: Robert C. Lynall, M.S., 2207 Stallings-Evans Sports Medicine Center, Campus Box 8700, University of North Carolina, Chapel Hill, NC 27599; E-mail: rlynall@live.unc.edu.
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TABLE 1. Group demographics and athlete exposure reported as mean (SD).

	Concussion (*n* = 44)	Control (*n* = 58)	*P* Value
Age (yr)	20.0 (1.2)	20.5 (1.3)	0.30
Height (cm)	178.3 (10.4)	180.0 (24.3)	0.67
Weight (kg)	82.0 (22.0)	79.8 (22.2)	0.62
AE before concussion[a]	268.6 (122.7)	275.8 (120.0)	0.77
AE after concussion[a]	324.1 (73.8)	298.6 (98.1)	0.14
Female (*n*)	16 (36.4%)[b]	19 (32.8%)[c]	
Male (*n*)	28 (63.6%)[d]	39 (67.2%)[e]	
Sport (*n*)			
Men's cross country	1	2	
Field hockey	4	5	
Football	11	13	
Men's lacrosse	5	9	
Men's soccer	2	2	
Men's swimming	3	4	
Rowing	3	4	
Softball	2	3	
Wrestling	6	9	
Women's basketball	2	2	
Women's soccer	3	3	
Women's swimming	1	1	
Women's tennis	1	1	

[a]Athlete exposure, 1 d of data collection.
[b]Percentage of females in the concussion group.
[c]Percentage of females in the control group.
[d]Percentage of males in the concussion group.
[e]Percentage of males in the control group.
AE, athlete exposure.

be exacerbated during more demanding athletic activities, contributing to increased rates of musculoskeletal injury after concussion. Nordström et al. (20) were the first to report the potential association between concussion and increased musculoskeletal injury rates. Professional European soccer players who sustained a concussion were 2.2 times more likely to sustain a musculoskeletal injury than those who did not sustain a concussion (20). Interestingly, Nordström et al. (20) report a higher musculoskeletal injury rate both before and after concussion, suggesting that some athletes may be more prone to injury in general. After adjusting for the increased rate of musculoskeletal injury before concussion, the risk of musculoskeletal injury in the year after concussion remained higher than the risk after other injuries. More recently, it has been reported that concussion frequency is associated with musculoskeletal injury in retired National Football League players (24). These results are certainly compelling, but the analysis was limited in that the authors could not determine whether concussion occurred before musculoskeletal injury or *vice versa*. Addressing this important limitation and exploring other athlete cohorts will shed more light on the emerging connection between concussion and musculoskeletal injury.

Therefore, the purpose of this study was to investigate the risk of acute lower extremity musculoskeletal injury after concussion in a cohort of Division I college athletes for ±90, ±180, and ±365 d of concussive injury. Comparisons were made between a group of athletes with concussion and select nonconcussed matched control athletes, both before and after the concussion date. In addition, within-group comparisons were made to examine acute lower extremity musculoskeletal injury rates before and after concussion. We hypothesized that concussion would lead to increased risk of acute lower extremity musculoskeletal injury, both within the group with concussion (before with after concussion comparison) and between the group with concussion and nonconcussed matched control group. We explored only lower extremity injuries, as we hypothesized decreased neuromuscular control may have a greater effect on lower extremity injuries as compared to trunk or upper extremity injuries.

METHODS

Participants. Musculoskeletal injury and concussion data were collected from a cohort of National Collegiate Athletic Association Division I athletes from January 1, 2010, to October 8, 2013. The athletes participated in a variety of sports described in Table 1. During the period of interest, 83 athletes diagnosed with a concussion and who met the inclusion criteria were identified. We randomly selected 44 of these athletes to be included in our data analysis (Fig. 1). Concussions were diagnosed by the university's sports medicine staff, who followed an institutional concussion policy. This policy consisted, at minimum, of a thorough clinical examination complemented by neurocognitive and balance assessments and documenting symptom reports. Participants with concussion were excluded if the concussion resulted in any positive imaging findings, if the participant was admitted to the hospital for suspected severe head trauma, if the participant had sustained a previous concussion while at the university, if no appropriate matched control could be identified, or if there were incomplete notes in the athlete's medical record related to the concussion. Participants with concussion were matched to at least one control participant who had not experienced a concussion since arriving at the university. Control participants were matched to participants with concussion on several criteria, as follows: sex, sport, competition playing time, age, height, and weight. To account for competition playing time, publicly available statistics were explored for each participant with concussion. Different competition statistics were used for each sport (e.g., minutes per game and games played for women's basketball, at-bats

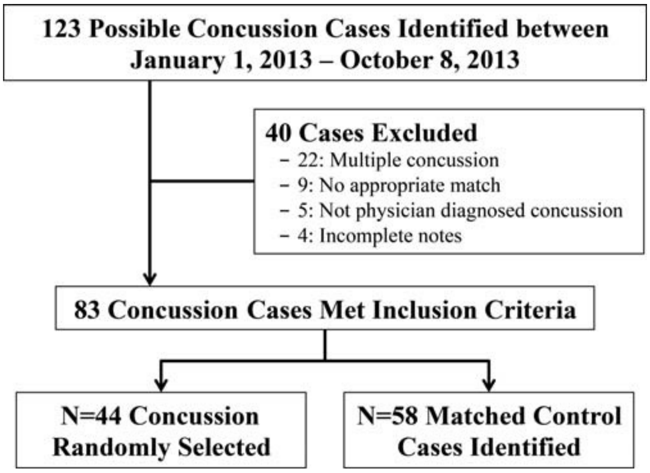

FIGURE 1—Description of sample selection.

and games played for softball, etc.). This systematic approach allowed for the identification of a matched control participant who most closely matched the game exposure of the participant with concussion. We attempted to match each athlete with concussion to two control athletes. However, because of the strict criteria listed earlier, finding two matches for each athlete with concussion was not always possible. Thus, 58 matched control participants were identified. Demographic information for both groups is displayed in Table 1. The university's institutional review board approved this study and data collection procedures.

Data collection. Musculoskeletal injury data were abstracted from the institution's electronic medical record system. A standardized form was used to record the information related to each musculoskeletal injury. Information about all injuries and illnesses was recorded for 365 d before the concussion of interest and 365 d after return to activity from the concussion for the group with concussion. A musculoskeletal injury was determined to be any injury recorded by a certified athletic trainer or team physician in the athlete's medical record (7). A musculoskeletal injury did not have to result in time lost from activity but rather was any musculoskeletal injury that was documented by the athletic trainer. Musculoskeletal injury data were collected for the matched controls for the same periods as their matched participant with concussion. Musculoskeletal injury data included the following: type of injury, location (body region) of injury, mechanism of injury, days out of sport activity because of the injury, and days of limited athletic participation due to the injury. Additional demographic information was collected via publicly available roster information or from the electronic medical record in cases where the public information could not be found.

Days of physical activity (i.e., athlete exposure) were defined as any day the participant was capable of completing physical activity and was an active member of the university athletic team (and therefore was under the care of the team's athletic trainer). This broad definition of athlete exposure was selected because it is common for athletes to complete physical activity outside their normal team-sanctioned physical activities. Therefore, athletes are susceptible to injury even when they are not actively participating in team-sanctioned activities. Any day of exposure, regardless of the number or length of sanctioned team event, was counted as one athlete exposure. In the event an athlete was new to the university within the preceding calendar year or left before 365 d after the concussion of interest, musculoskeletal injury data were not available for the complete data collection period (±365 d surrounding the concussion of interest). In cases where 365 d of data were not available, the total number of available days was recorded so that accurate injury rates could be determined. In the event an athlete remained at the university but was no longer an active member of an athletics team, the athletes' exposure in our study ended when their final competitive season ended or when it was clearly documented in the athlete's medical record that the athlete stopped participating in varsity team athletics. This methodology allowed us to account for days of exposure in which any injury sustained by the participants would have been recorded in their electronic medical record regardless of time of athletic season (preseason, in-season, postseason).

Each injury recorded in the athlete's electronic medical record contained detailed information about when and where the injury occurred. Only acute lower extremity musculoskeletal injuries related to sport activity were included in the final data set. These injuries included those that occurred during team-organized sporting activities and injuries that occurred while the athlete was participating in non–team-organized activities. Examples of non–team-organized activities include captain-organized scrimmages, weightlifting, conditioning sessions, and additional physical training (e.g., jogging for fitness). If an athlete injured his ankle while playing basketball even though his college sport was football, the injury was included in the data set. However, if an athlete injured his ankle while walking to class or tripping over something at his home, the injury was not included. In addition, injuries related to motor vehicle accidents were excluded.

Statistical analyses. Only acute lower extremity musculoskeletal injuries were included in statistical analyses. Musculoskeletal injuries that occurred to the torso, head or face, or upper extremities were excluded. In addition, chronic and overuse injuries and illnesses and infections were excluded. Thus, only acute lower extremity musculoskeletal injuries, which included sprains, strains, contusions, and fractures, were included in our final analyses. Independent-samples *t*-tests were used to compare demographic information between groups. Athlete exposure was defined as one data collection day for each athlete. Injury rates are expressed as injuries per 1000 athlete exposures. Within- and between-group and pre- and postconcussion comparisons were made using an injury rate ratio (IRR), with significance tested using *z*-statistics (11,12). Injury rate comparisons were made for three periods: 90 d before and after concussion, 180 d before and after concussion, and 365 d before and after concussion. These time points were chosen to give an indication as to how long injury rates may have been affected after concussion. The significance level was set *a priori* at ≤0.05 for all comparisons.

RESULTS

No differences were noted between groups regarding age, height, or weight. All demographic information and comparisons are presented in Table 1 along with mean athlete exposure information. The group with concussion experienced a significantly higher rate of acute lower extremity musculoskeletal injuries after concussion in the 180-d (IRR, 2.02; 95% confidence interval (CI), 1.08–3.78; $P = 0.02$) and 365-d (IRR, 1.97; 95% CI, 1.19–3.28; $P = 0.01$) comparisons but not in the 90-d comparison (IRR, 2.10; 95% CI, 0.91–4.81; $P = 0.07$). No statistical differences were observed within the control group ($P \geq 0.42$). All injury incidence

TABLE 2. Injury incidence per 1000 athlete exposures and risk ratios for (after/before) within-group comparisons.

	Group with Concussion					Control Group				
	Injury Incidence					Injury Incidence				
	Before	After	Risk Ratio	95% CI	*P* Value	Before	After	Risk Ratio	95% CI	*P* Value
90 d	2.17	4.55	2.10	0.91–4.81	0.07	3.27	3.10	0.95	0.48–1.90	0.89
180 d	2.05	4.14	2.02	1.08–3.78	0.02	3.08	2.55	0.83	0.48–1.42	0.50
365 d	1.78	3.51	1.97	1.19–3.28	0.01	2.56	2.14	0.83	0.53–1.30	0.42

Athlete exposure, 1 d of data collection.

rates and risk ratios for the within-group comparisons are presented in Table 2. There were no differences in injury rates between the group with concussion and the control group before concussion for any period ($P \geq 0.16$). The group with concussion displayed higher injury rates than the control group for the 365-d (IRR, 1.64; 95% CI, 1.07–2.51; $P = 0.02$) comparison after concussion. All between-group risk ratios are presented in Table 3.

DISCUSSION

College athletes are almost twice as likely to experience acute lower extremity musculoskeletal injury after concussion. These findings are in line with previously published data that professional European soccer players are at increased risk of musculoskeletal injury after concussion (20). The previously published data demonstrated that the risk of subsequent injury during the 12-month follow-up period was approximately two times greater in the athletes with concussion compared with that in nonconcussed athletes. Although this study was the first to highlight the association between concussion and musculoskeletal injury rates, the applicability of the findings was limited to European soccer players. We believe that our investigation constitutes the first published report of the acute lower extremity injury rates after concussion in collegiate athletes participating in a variety of sports. Furthermore, a key limitation to the previous research was the disparity of concussion management protocols. Because teams came from a wide variety of professional soccer clubs across Europe, concussion diagnostic criteria likely differed. Our study assessed athletes from the same institution operating under the same concussion management policy, limiting the effect of disparate concussion diagnostic criteria.

Several potential explanations exist for the increased injury rates after concussion. The time away from training due to concussion may have led to increased musculoskeletal injury risk after return to activity. We believe that this is an unlikely reason for increased rates of musculoskeletal injuries after concussion. Our findings are similar to those reported by Nordström et al. (20), in that we found increased rates of musculoskeletal injury for up to 365 d after concussion. Another potential explanation for increased musculoskeletal injury rates in athletes with concussion is that the athletes with concussion are more prone to injury in general as compared with other athletes. Although a possible contributor to increased musculoskeletal injury risk, our data showed similar injury rates between the group with concussion and the control group before athletes in the group with concussion sustained a concussion. This is in contrast to a previous report that observed athletes with concussion were more prone to injury before their concussion (20). Further long-term prospective investigation is needed to allow for better understanding of the effect of injury-prone athletes when investigating musculoskeletal injury rates after concussion.

It is important to note this study did not directly investigate possible mechanisms for the increased musculoskeletal injury rates. Future research should seek to identify the specific causes of increased musculoskeletal injury rates after concussion. In line with similar investigations (20,24), we propose several possible mechanisms in the following section to begin the discussion of future research in this area.

Previously published literature regarding functional movement after concussion may provide insight into the underlying cause of the increased musculoskeletal injury rates. Deficits have been noted in gait after concussion, both acutely (3,21,22) and beyond an athlete's return to activity (4,15,22,23). After concussion, athletes display more conservative gait strategies (2–5,21,22) and deficits in dynamic balance (2,3,10,21,22). These dynamic balance deficits after return to activity after concussion are not dissimilar to neuromuscular and postural control deficits noted in prospective lower extremity injury risk factor analyses. Previous research of healthy individuals demonstrated that postural (26) and neuromuscular control deficits can increase the risk of sustaining noncontact lower extremity injuries (30). In addition, females who displayed abnormally large side-to-side dynamic balance differences and individuals with trunk neuromuscular control deficiencies are at increased risk of lower extremity musculoskeletal injury (26,30). This is important to note because as the previously described gait studies show, there are alterations in trunk positioning and velocity after concussion. These

TABLE 3. Risk ratios (concussion/control) for between-group comparisons.

	Before Concussion			After Concussion		
	Risk Ratio	95% CI	*P* Value	Risk Ratio	95% CI	*P* Value
90 d	0.66	0.28–1.55	0.33	1.47	0.67–2.87	0.28
180 d	0.66	0.35–1.26	0.20	1.62	0.96–2.73	0.08
365 d	0.69	0.41–1.17	0.16	1.64	1.07–2.51	0.02

abnormal trunk biomechanics may increase an individual's risk of sustaining an injury after concussion.

Disrupted cortical pathways after concussion may also plausibly explain increased acute lower extremity musculoskeletal injury rates after concussion (6,13,14,27). Researchers have demonstrated lower intracortical facilitation (27), lower maximal voluntary muscle activation (27), increased intracortical inhibition (6), increased motor-evoked potential latency, and decreased motor-evoked potential amplitude (13,14). Similarly, individuals with chronic ankle instability have higher resting motor thresholds than individuals without chronic ankle instability and self-report more disability during activity (25). These findings suggest that reduced cortical excitability may be associated with functional disability. Although still a hypothesis, reduced cortical excitability observed after concussion may contribute to overall reductions in function ability. The brain's ability to effectively control and coordinate movement after concussion may be impaired. In a dynamic athletic setting, any disruption of the cortical pathways to the musculoskeletal system has the potential to negatively affect movement. Although it has yet to be directly investigated, we hypothesize that these disrupted cortical pathways may increase the interval between reaction and movement time. This increased latent period has the potential to increase musculoskeletal injury risk during the cognitively and physically challenging demands of high-level athletics. Cortical changes are fairly subtle and only detectable with sophisticated laboratory equipment. The current means of assessing static balance may not be sensitive enough to detect all impairments. In addition, these cortical changes may not affect simple static balance or standard gait but may become more pronounced during physically and cognitively challenging athletic tasks.

These data, along with our findings of increased lower extremity musculoskeletal injury rates after concussion, provide compelling evidence that deficiencies after concussion may be uniquely measured beyond standard neurocognitive, static balance, and symptom reporting deficits. Importantly, the underlying mechanism for these lingering balance deficits must be explored further. If our current measures of balance after concussion are not sensitive enough to detect deficits, more functional balance assessments should be identified. To our knowledge, researchers have yet to explore any functional movement deficiencies that may be present during sport-related activity after concussion such as cutting and jumping. Understanding the changes in neuromuscular control and functional movement during sport-related activities may provide the scientific basis for explaining the increased musculoskeletal injury rates we observed after concussion. Future research should explore lower extremity biomechanical outcomes during functional movement after concussion in addition to true functional reaction time measures.

There were several limitations to our research. Our sample size was relatively small. We believe that this is the reason we did not observe significant differences in injury rates within the 90- and 180-d window between the group with concussion and the control group after concussion and in the 90-d before-with-after-injury comparison within the group with concussion. The confidence intervals included in Tables 2 and 3 indicate the clinical significance of our findings in the absence of statistically significant findings. Our data collection was completed retrospectively on the basis of recorded notes of injuries; thus, we relied on the accuracy of clinicians reporting the injury information. Electronic medical records have some inherent limitations and have the potential to be unreliable. To help combat this potential issue, we used a standardized data collection form and strict operational definitions for abstracting injury data. All our data came from a single institution whose clinicians follow the same standardized injury-reporting protocols. Some lower extremity injuries experienced by those who sustained a concussion may have increased their risk of subsequent lower extremity injury. Although this is certainly possible, we believe that this is an unlikely explanation for within- and between-group differences because our groups had similar injury rates before the concussion. Concussions may have gone unreported in our sample, possibly affecting our outcomes. In addition, the results of our findings cannot be extrapolated to include athletes of other age groups (e.g., professional, high school, or youth) or skill levels. Future research should investigate these other cohorts to identify musculoskeletal injury rates after concussion.

CONCLUSIONS

College athletes are at increased risk of acute lower extremity musculoskeletal injury for up to 365 d after concussion. Future research should explore the underlying causes of the increased risk.

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REFERENCES

1. Broglio SP, Cantu RC, Gioia GA, et al. National Athletic Trainers' Association position statement: management of sport concussion. *J Athl Train*. 2014;49(2):245–65.
2. Catena RD, van Donkelaar P, Chou LS. Altered balance control following concussion is better detected with an attention test during gait. *Gait Posture*. 2007;25(3):406–11.
3. Catena RD, van Donkelaar P, Chou LS. Cognitive task effects on gait stability following concussion. *Exp Brain Res*. 2007;176(1):23–31.
4. Catena RD, van Donkelaar P, Chou LS. Different gait tasks distinguish immediate vs long-term effects of concussion on balance control. *J Neuroeng Rehabil*. 2009;6:25.

5. Catena RD, van Donkelaar P, Chou LS. The effects of attention capacity on dynamic balance control following concussion. *J Neuroeng Rehabil*. 2011;8:8.
6. De Beaumont L, Mongeon D, Tremblay S, et al. Persistent motor system abnormalities in formerly concussed athletes. *J Athl Train*. 2011;46(3):234–40.
7. Finch CF, Valuri G, Ozanne-Smith J. Injury surveillance during medical coverage of sporting events–development and testing of a standardised data collection form. *J Sci Med Sport*. 1999;2(1):42–56.
8. Giza CC, Kutcher JS, Ashwal S, 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*. 2013;80(24):2250–7.
9. Guskiewicz KM, Ross SE, Marshall SW. Postural Stability and Neuropsychological Deficits After Concussion in Collegiate Athletes. *J Athl Train*. 2001;36(3):263–73.
10. Howell DR, Osternig LR, Chou LS. Return to activity after concussion affects dual-task gait balance control recovery. *Med Sci Sports Exerc*. 2015;47(4):673–80.
11. Kristenson K, Walden M, Ekstrand J, Hagglund M. Lower injury rates for newcomers to professional soccer: a prospective cohort study over 9 consecutive seasons. *Am J Sports Med*. 2013;41(6):1419–25.
12. Lindenfeld TN, Schmitt DJ, Hendy MP, Mangine RE, Noyes FR. Incidence of injury in indoor soccer. *Am J Sports Med*. 1994;22(3):364–71.
13. Livingston SC, Goodkin HP, Hertel JN, Saliba EN, Barth JT, Ingersoll CD. Differential rates of recovery after acute sport-related concussion: electrophysiologic, symptomatic, and neurocognitive indices. *J Clin Neurophysiol*. 2012;29(1):23–32.
14. Livingston SC, Saliba EN, Goodkin HP, Barth JT, Hertel JN, Ingersoll CD. A preliminary investigation of motor evoked potential abnormalities following sport-related concussion. *Brain Inj*. 2010;24(6):904–13.
15. Martini DN, Sabin MJ, DePesa SA, et al. The chronic effects of concussion on gait. *Arch Phys Med Rehabil*. 2011;92(4):585–9.
16. McClincy MP, Lovell MR, Pardini J, Collins MW, Spore MK. Recovery from sports concussion in high school and collegiate athletes. *Brain Inj*. 2006;20(1):33–9.
17. McCrea M, Guskiewicz K, Randolph C, et al. Effects of a symptom-free waiting period on clinical outcome and risk of reinjury after sport-related concussion. *Neurosurgery*. 2009;65(5):876–82.
18. McCrea M, Guskiewicz KM, Marshall SW, et al. Acute effects and recovery time following concussion in collegiate football players: the NCAA Concussion Study. *JAMA*. 2003;290(19):2556–63.
19. McCrory P, Meeuwisse WH, Aubry M, et al. Consensus statement on concussion in sport: the 4th International Conference on Concussion in Sport held in Zurich, November 2012. *Br J Sports Med*. 2013;47(5):250–8.
20. Nordström A, Nordström P, Ekstrand J. Sports-related concussion increases the risk of subsequent injury by about 50% in elite male football players. *Br J Sports Med*. 2014;48(19):1447–50.
21. Parker TM, Osternig LR, Lee HJ, Van Donkelaar P, Chou LS. The effect of divided attention on gait stability following concussion. *Clin Biomech (Bristol, Avon)*. 2005;20(4):389–95.
22. Parker TM, Osternig LR, Van Donkelaar P, Chou LS. Gait stability following concussion. *Med Sci Sports Exerc*. 2006;38(6):1032–40.
23. Parker TM, Osternig LR, van Donkelaar P, Chou LS. Recovery of cognitive and dynamic motor function following concussion. *Br J Sports Med*. 2007;41(12):868–73.
24. Pietrosimone B, Golightly YM, Mihalik JP, Guskiewicz KM. Concussion Frequency Associates with Musculoskeletal Injury in Retired NFL Players. *Med Sci Sports Exerc*. 2015;47(11):2366–72.
25. Pietrosimone BG, Gribble PA. Chronic ankle instability and corticomotor excitability of the fibularis longus muscle. *J Athl Train*. 2012;47(6):621–6.
26. Plisky PJ, Rauh MJ, Kaminski TW, Underwood FB. Star Excursion Balance Test as a predictor of lower extremity injury in high school basketball players. *J Orthop Sports Phys Ther*. 2006;36(12):911–9.
27. Powers KC, Cinelli ME, Kalmar JM. Cortical hypoexcitability persists beyond the symptomatic phase of a concussion. *Brain Inj*. 2014;28(4):465–71.
28. Riemann BL, Guskiewicz KM. Effects of mild head injury on postural stability as measured through clinical balance testing. *J Athl Train*. 2000;35(1):19–25.
29. Schatz P, Pardini JE, Lovell MR, Collins MW, Podell K. Sensitivity and specificity of the ImPACT Test Battery for concussion in athletes. *Arch Clin Neuropsychol*. 2006;21(1):91–9.
30. Zazulak BT, Hewett TE, Reeves NP, Goldberg B, Cholewicki J. Deficits in neuromuscular control of the trunk predict knee injury risk: a prospective biomechanical-epidemiologic study. *Am J Sports Med*. 2007;35(7):1123–30.