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Cognitive effects of one season of head impacts in a cohort of collegiate contact sport athletes

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ABSTRACT

Objective: To determine whether exposure to repetitive head impacts over a single season negatively affects cognitive performance in collegiate contact sport athletes.

Methods: This is a prospective cohort study at 3 Division I National Collegiate Athletic Association athletic programs. Participants were 214 Division I college varsity football and ice hockey players who wore instrumented helmets that recorded the acceleration-time history of the head following impact, and 45 noncontact sport athletes. All athletes were assessed prior to and shortly after the season with a cognitive screening battery (ImPACT) and a subgroup of athletes also were assessed with 7 measures from a neuropsychological test battery.

Results: Few cognitive differences were found between the athlete groups at the preseason or postseason assessments. However, a higher percentage of the contact sport athletes performed more poorly than predicted postseason on a measure of new learning (California Verbal Learning Test) compared to the noncontact athletes (24% vs 3.6%; $p < 0.006$). On 2 postseason cognitive measures (ImPACT Reaction Time and Trails 4/B), poorer performance was significantly associated with higher scores on several head impact exposure metrics.

Conclusion: Repetitive head impacts over the course of a single season may negatively impact learning in some collegiate athletes. Further work is needed to assess whether such effects are short term or persistent. ***Neurology***® **2012;78:1777–1784**

GLOSSARY

ANCOVA = analysis of covariance; **ANOVA** = analysis of variance; **BVMT-R** = Brief Visual Memory Test–Revised; **CG** = center of gravity; **CVLT** = California Verbal Learning Test; **D-KEFS** = Delis-Kaplan Executive Function System; **HIE** = head impact exposure; **HITsp** = measure of head impact severity; **ImPACT** = Immediate Post-Concussion Assessment and Cognitive Test; **MTBI** = mild traumatic brain injury; **NCAA** = National Collegiate Athletic Association; **PASAT** = Paced Auditory Serial Addition Task; **WRAT IV** = Wide Range Achievement Test 4.

Estimates of the incidence of sports-related mild traumatic brain injury (MTBI) or concussion range from 1.6 to 3.8 million individuals annually in the United States, and are particularly common in football and ice hockey.[1–4] Although the majority of athletes recover within 7 days, recovery may take longer in a small percentage of individuals[5,6] and concerns have been raised about long-term effects.[7–11]

Most head impacts do not result in a concussion,[12–14] though many impacts exceed 98 *g*s, a threshold reported to be 75% specific to concussive injury in a study of National Football League concussions.[15] Studies of repetitive impacts are few and contradictory. For example, some nonconcussed high school football players had abnormal cognitive indices in season and postseason.[16] However, 58 collegiate football players showed postseason cognitive improvements, probably related to practice effects.[17] Whether the football players showed less of a

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practice effect (i.e., "improved less") than noncontact athletes tested at similar intervals was not studied.

In this study, we tested the hypothesis that repetitive head impacts sustained over 1 season would negatively affect cognitive performance, and that change in cognition would be related to head impact exposure.

METHODS

Overview. This report is part of an ongoing study of the biomechanical basis of concussion and the effects of repetitive head impacts in 3 National Collegiate Athletic Association (NCAA) athletic programs (Brown University, Dartmouth College, and Virginia Tech). In this article, we report only on athletes enrolled in the study between 2007 and 2010 who were not diagnosed with concussion during the index season.

Participants. Two cohorts of athletes were studied. The contact sport cohort consisted of football players at the 3 institutions and ice hockey players (men and women) from 2 of the 3 institutions. The noncontact sport cohort consisted of varsity athletes on a variety of teams including track, crew, and Nordic skiing. Study participation was offered to all members of these contact and noncontact teams. Athletes were excluded if they had significant systemic medical illness or current psychiatric disorders. For the noncontact sport cohort, self-reported history of prior concussion was an additional exclusion criterion.

Standard protocol approvals, registrations, and patient consents. The protocol was approved by the institutional review board at each collaborating institution and all participants gave written informed consent.

Assessments. ***Cognition.*** All participants underwent the Immediate Post-Concussion Assessment and Cognitive Test[18] (ImPACT), a widely used computerized neuropsychological screening tool, preseason and again postseason.

Athletes from 1 of the schools also underwent a 2.5-hour battery of standardized neuropsychological tests at both time points assessing general level of intellectual functioning (Wide Range Achievement Test 4 [WRAT IV] Reading[19]), attention/concentration, working memory, verbal and visual learning and memory, verbal fluency, and processing speed. Although there is evidence for convergent validity of these 2 assessments of cognition,[20] a full battery approach is considered the gold standard in terms of cognitive assessment.

Head impact measurement. During all practices and games, players wore Riddell football helmets (Riddell Inc., Rosemont, IL), or Easton S9 (Easton Sports, Scotts Valley, CA) or CCM Vector (Reebok, Saint-Laurent, Quebec, Canada) hockey helmets instrumented with the HIT System. A detailed description of the HIT System development, uses, and accuracy of the HIT algorithm have been published.[21–27] In brief, the HIT System integrates an array of single-axis accelerometers into a helmet insert. Each accelerometer is continuously sampled by an on-board, miniature data acquisition system. When any accelerometer exceeds a threshold (14.4 *g* in this study), 40 msec of data are transmitted, saved, and processed using a proprietary algorithm to solve for the peak linear and rotational acceleration magnitude at the head center of gravity (CG), impact duration, impact location,[21,22] and a nondimensional measure of head impact severity, HITsp.[14] HIT system measurements have a high correlation with data obtained from anthropomorphic test devices (i.e., dummy headforms) and provide accurate head acceleration measures for a wide range of impact velocities and locations.[24]

Analyses. ***Cognition.*** *Computer-based neuropsychological assessment.* The 5 ImPACT composite scores were chosen as the primary outcome measures for the computer-based cognitive assessment.

Neuropsychological battery. Prior to data analysis, 7 tests were chosen from the full neuropsychological test battery as the primary neuropsychological outcome measures based on sensitivity to MTBI in both the literature and our experience assessing cognitive performance shortly after MTBI.[28–30] These measures included the California Verbal Learning Test (CVLT; total acquisition trials 1–5)[31]; Delis-Kaplan Executive Function System (D-KEFS) Color-Word Interference Test, Interference subtest[32]; D-KEFS Letter Fluency subtest[32]; the Trail Making Test (D-KEFS, Trials 2 and 4 or Reitan version, Trails A and B)[32,33]; the Paced Auditory Serial Addition Task[34] (PASAT); the Gordon Continuous Performance Test[35] (vigilance and reaction time); and the Brief Visual Memory Test–Revised[36] (BVMT-R, Total Learning score).

Head impact exposure. Prior to data analysis, 4 biomechanical variables were chosen as representative indicators of head impact exposure: number of hits, peak linear acceleration, peak rotational acceleration, and HITsp (derived from peak acceleration, impact duration, and impact location). Both maximum and cumulative metrics were created from these variables using the following equations:

$$\text{max } var = \max(var(t\text{: end of season}))$$

and

$$\text{sum } var = {}^{\text{end of season}}\sum_{t} var$$

where *var* is peak linear acceleration, peak rotational acceleration, and HITsp. Three values for initial time *t* were used: the first day of preseason practice, 1 week prior to the end of the season, and the last day of the season. This strategy allowed us to capture scenarios of low frequency, high magnitude events and high frequency, low magnitude events over different time intervals that might have detrimental effects on cognition.

Statistical analyses. Statistical analyses were conducted separately for athletes who completed ImPACT testing, and for the athletes who completed the neuropsychological battery. Distributions for cognitive performances and head impact exposure (HIE) were examined for outliers and distributional characteristics. Contact and noncontact sport athletes were compared using means and *t* tests for continuous variables and χ^2 tests for categorical variables with respect to basic demographic information and for test-retest intervals. WRAT IV Reading score differed between athlete cohorts (contact: 111 ± 11 vs noncontact: 116 ± 9.3, $p = 0.024$). Although both scores are in the high average range, WRAT IV Reading was used as a covariate in subsequent analyses. Performance on baseline (preseason) and postseason neuropsychological measures for the 2 athlete groups was compared using repeated-measures analysis of covariance (ANCOVA) (PROC Mixed in SAS) with WRAT IV Reading (standard score) as a covariate. For ImPACT variables, between-group performance was compared preseason and postseason using a repeated-measures analysis of variance (ANOVA) (PROC Mixed in SAS), as no reading estimate was available for participants at 2 of the sites. Time by group interactions were examined to assess the groups in terms of changes from baseline, thus controlling for practice effects. Test-retest interval between the baseline and follow-up assessments was also included as a covariate to further control the variability in practice effects.

Results were also analyzed using a regression-based *z*-score approach.[37] This approach, similar in some respects to a reliable change index, allows for the identification of individuals who are performing "worse than predicted" at a given time point. The noncontact athletes data were used to establish a predicted range of postseason performance based on preseason performance and test-retest interval; *z*-scores representing change (from preseason to postseason) for each cognitive variable were computed using multiple-regression analysis with adjustment for test-retest interval, and when appropriate, WRAT IV Reading score. Prior to data analysis, a value of >1.5 SD lower than the predicted value was chosen as an indicator of significantly poorer than expected postseason performance. Using a χ^2 test, the frequency of poorer than expected postseason performers among the contact and noncontact sport groups was compared to test the hypothesis that a subgroup of contact athletes might be more vulnerable to repetitive impacts. For example, if many contact athletes had robust practice effects comparable to, or greater than, the noncontact group, results of group comparisons might be unrevealing. Using the *z*-score analysis permits setting of a reasonable threshold of "lower than expected postseason performance" to determine whether the 2 groups differed with respect to how many participants did in fact score lower "than they should have."

Two sets of linear regression models were used to estimate the partial correlation coefficients among the HIE metrics over the 3 time intervals, and the postseason neuropsychological test and ImPACT variables. All models were adjusted for the preseason cognitive performance, gender, and time between pre and post tests. Both contact and noncontact players were included in the analysis, with a regression term for contact status. HIE was assigned a value of zero for noncontact athletes. Site was included as an adjusting variable in the ImPACT analysis. For the neuropsychological test models, WRAT IV Reading score was included. Partial correlation coefficients were estimated for the time-based HIE metrics. The inclusion of the term for contact athlete group status allows interpretation of the partial correlation coefficients as pertaining to contact athletes only. Models were first fit including all HIE metrics separately for each time period, and then a Wald test was performed to test the hypothesis that all HIE metric partial correlations for each time period were zero.

RESULTS

Participants. The results reported are from all 214 contact sport athletes and 45 noncontact sport athletes from the 3 sites who completed preseason and postseason assessments with ImPACT. The contact and noncontact sport groups did not differ significantly in gender, with 93% of the noncontact sport athletes and 81% of the contact sport athletes being male ($p = 0.07$). Contact sport athletes were studied, on average, 126.8 days after baseline (preseason) assessment (SD = 38.38), and, on average, 25 days after their last head impact exposure (SD = 31). Noncontact athletes were studied 129.9 days after baseline (SD = 29.47). The test-retest interval did not differ significantly between the contact and noncontact athlete groups ($p = 0.66$). However, because of the variability in test-retest interval and time from last head impact exposure to postseason testing, analyses were adjusted for these variables.

Forty-five contact sport athletes and 55 noncontact sport athletes from 1 site completed preseason and postseason assessments with the neuropsychological test battery in addition to ImPACT. The athlete groups did not differ in terms of age (contact: 19 ± 1.3 vs noncontact: 20 ± 1.4), percent male

Table 1 Summary of head impact exposure over the course of a single contact sport season, obtained using helmets instrumented with the HIT system[a]

HIT variable	Last day	Last week	Season
No. of hits, mean (SD)	13 (20)	44 (44)	469 (391)
Range	1-143	1-224	1-2,154
Max linear acceleration, *g*, mean (SD)	49 (36)	72 (43)	132 (47)
Range	10-300	11-324	17-324
Sum of linear acceleration, *g*, mean (SD)	338 (515)	1,134 (1,288)	11,963 (11,081)
Range	10-2,848	11-7,584	17-71,459
Max rotational acceleration, rads/s^2, mean (SD)	3,660 (2,418)	5,670 (3,418)	10,255 (3,723)
Range	46-11,555	124-28,544	1,684-28,544
Sum rotational acceleration, rads/s^2, mean (SD)	22,795 (34,230)	79,683 (90,382)	836,796 (763,168)
Range	46-196,994	124-590,851	1,684-5,593,784
Max HIT-sp, mean (SD)	30 (25)	47 (40)	99 (57)
Range	5.8-200	5.8-363	14-365
Sum HIT-sp, mean (SD)	202 (300)	708 (798)	7,432 (6,793)
Range	5.8-1,690	5.8-5,025	15-47,313

[a] Linear acceleration is measured in *g*, rotational acceleration in rads/s^2. HITsp is a unit-less, impact location weighted composite measure that combines peak head acceleration (both linear and rotational) and impact duration using scaling coefficients derived from principal component analysis.[24]

(contact: 84% vs noncontact: 73%), years of education (contact: 13 ± 1.2 vs noncontact: 13 ± 1.1), or parental education. Postseason neuropsychological assessment was completed a mean of 27 ± 24 days after athletes' final contact sport exposure.

Head impact exposure. Contact sport athletes were exposed to a mean of 469 separate impacts over the course of the season. Table 1 summarizes key HIE metrics for the contact sport athletes.

Cognitive performance. ***ImPACT performance.*** Table 2 summarizes the preseason and postseason results of the ImPACT scores for both athlete groups. Preseason profiles were similar although the contact sport group performed better on the Visual Memory Composite ($p = 0.037$). There were no significant between athlete group differences postseason and no significant athlete group by time interactions.

Neuropsychological battery performance. Table 2 also summarizes the preseason and postseason results of the primary outcome measures from the neuropsychological test battery. Preseason performance did not differ significantly between athlete groups with the exception of the Letter Fluency test, where noncontact athletes scored significantly higher. Modest but statistically significant improvement was noted from preseason to postseason testing on several of the measures. Two tests (PASAT C and CVLT) showed significant athlete group by time interactions. On the PASAT C contact sport athletes performed more poorly at baseline than noncontact sport athletes, but better than the noncontact sport athletes at postseason testing. On the CVLT, the noncontact athletes showed greater improvement from preseason to postseason than the contact athlete group.

Regression-based z-score analysis. Table 3 summarizes the regression-based z-score results. A statistically significant higher percentage of individuals in the contact sport group performed more than 1.5 SD below their predicted level on the CVLT (22% vs 3.6%, $p = 0.006$). There were no ImPACT composite scores where contact sport athletes demonstrated a significantly greater percentage of players with scores 1.5 SD below the predicted postseason score based on a χ^2 test.

Table 2 **Pre and post scores for neuropsychological variables (site 1) and ImPACT composite scores (all sites) in contact sport vs noncontact sport athletes[a]**

	Noncontact athletes (n = 55)		Contact athletes (n = 45)	
Neuropsychological test score	**Pre unadjusted, mean (SE)**	**Post unadjusted, mean (SE)**	**Pre unadjusted, mean (SE)**	**Post unadjusted, mean (SE)**
CVLT: total trials 1–5[c,d]	59.3 (1.0)	62.7 (1.0)	56.5 (1.1)	58.1 (1.3)
Trail Making Test: Trial 4/Trails B[c]	0.49 (0.048)	0.65 (0.046)	0.38 (0.064)	0.43 (0.068)
D-KEFS: Interference (s)[b]	40.9 (1.0)	39.3 (1.0)	43.2 (1.5)	40.7 (1.5)
Letter Fluency (raw)[b,c]	46.9 (1.2)	48.2 (1.1)	42.8 (1.6)	44.7 (1.3)
PASAT C (raw score/60): Trial C[b,d]	40.9 (1.1)	43.7 (1.2)	39.1 (1.2)	44.2 (1.4)
CPT: vigilance, reaction time	343 (6.4)	332 (6.4)	333 (9.0)	329 (6.3)
BVMT: total learning	29.9 (0.47)	30.4 (0.51)	30.1 (0.77)	29.8 (0.72)
	Noncontact athletes (n = 45)		**Contact athletes (n = 214)**	
ImPACT composite score	**Pre, mean (SE)**	**Post, mean (SE)**	**Pre, mean (SE)**	**Post, mean (SE)**
Verbal Memory Composite[b]	89.7 (1.1)	91.8 (1.1)	88.9 (0.63)	91.1 (0.62)
Visual Memory Composite[b]	77.0 (1.9)	81.1 (2.0)	81.0 (0.73)	82.3 (0.79)
Visual Motor Composite[c]	43.4 (0.81)	44.8 (1.2)	41.6 (0.49)	41.7 (0.60)
Reaction Time Composite[c]	0.54 (0.008)	0.54 (0.008)	0.56 (0.005)	0.56 (0.007)
Impulse Control Composite[b]	5.6 (0.56)	6.7 (0.74)	5.3 (0.27)	6.2 (0.33)
Total symptom score	3.8 (0.85)	3.2 (0.68)	2.6 (0.34)	2.7 (0.33)

Abbreviations: BVMT = Brief Visual Memory Test; CPT = Continuous Performance Test; CVLT = California Verbal Learning Test; D-KEFS = Delis-Kaplan Executive Function System; ImPACT = Immediate Post-Concussion Assessment and Cognitive Test; PASAT = Paced Auditory Serial Addition Task; WRAT = Wide Range Achievement Test.

[a] Mean (SE) values shown are unadjusted. Pre–post changes were compared between athlete groups to control for practice effects with analysis of covariance, adjusting for WRAT Reading score and test-retest interval for the neuropsychological data and test-retest interval for the ImPACT; composite scores. Neuropsychological test results are adjusted for WRAT Reading score and test-retest interval and ImPACT; composite score results are adjusted for test-retest interval.

[b] Statistically significant findings ($p < 0.05$) for main effect of time (preseason vs postseason differences).

[c] Statistically significant findings ($p < 0.05$) for main effect of athlete type (noncontact vs contact athletes).

[d] Statistically significant findings ($p < 0.05$) for athlete type by time interaction.

Table 3 Regression-based *z* scores for post-test neuropsychological variables (site 1) and ImPACT composite scores (all sites) in contact sport and noncontact sport athletes[a]

	Contact athletes		Noncontact athletes, % <1.5 SD	*p* Value contact vs noncontact athletes
	Mean (SD)	% <1.5 SD		
Neuropsychological *z* scores	No. = 45		No. = 55	
CVLT: total trials 1–5	−0.42 (1.3)	22	3.6	0.0055[b]
Trail Making Test: Trial 4/Trails B	−0.48 (1.4)	24	12	0.095
D-KEFS: Interference (s)	−0.078 (1.1)	8.9	3.7	0.41
Letter Fluency (raw)	−0.14 (1)	4.4	5.5	1
PASAT (raw score/60): Trial C	0.59 (1)	2.2	3.6	1
CPT: vigilance, reaction time	−0.15 (1)	6.8	3.6	0.65
BVMT: total learning	−0.0029 (0.8)	3.4	5.6	1
ImPACT *z* scores	No. = 214		No. = 46	
Verbal Memory Composite Score	−0.092 (1.1)	12	13	0.83
Visual Memory Composite Score	0.0093 (0.81)	5.6	4.4	1
Visual Motor Composite Score	−0.47 (1.1)	12	4.4	0.19
Reaction Time Composite Score	−0.21 (1.9)	16	8.9	0.26
Impulse Control Composite Score	0.059 (0.89)	2.3	2.2	1
Total symptom score	0.18 (1.1)	6.5	11	0.29
Sum of first 4 composite scores	−0.77 (3)	—	—	—
Sum of 5 composite scores	−0.71 (3.4)	—	—	—

Abbreviations: BVMT = Brief Visual Memory Test; CPT = Continuous Performance Test; CVLT = California Verbal Learning Test; D-KEFS = Delis-Kaplan Executive Function System; ImPACT = Immediate Post-Concussion Assessment and Cognitive Test; PASAT = Paced Auditory Serial Addition Task.

[a] Using the noncontact controls, regression-based *z* scores were calculated and used to predict postseason scores in the contact sport group given preseason performance and test-retest interval. Using 1.5 SD below predicted score as a marker for clinical significance, the 2 groups were compared with respect to frequency of low performers via χ^2 test. Note significant differences for CVLT.

[b] Significant.

Relationship of change in cognitive performance to head impact exposure. Results of the regression analyses of HIE metrics and cognitive measures are summarized in table 4. The Wald test showed a statistically significant relationship between HIE metrics and neuropsychological test performance for the last week of play (Trails 4/B with maximum linear and rotational acceleration, and maximum and sum HITsp), and between the ImPACT Reaction Time composite score and the season peak linear acceleration (table 4). In each case, greater impact exposure was associated with poorer test performance.

DISCUSSION

These findings indicate that at a group level repetitive head impacts over a single season of Division 1 college contact sports do not have a widespread short-term detrimental effect on all athletes. However, the finding that a higher percentage of contact sport athletes performed more than 1.5 SD below their predicted score on the CVLT suggests there may be a subgroup of athletes for whom repetitive head impacts affect learning and memory at least on a temporary basis, and is consistent with other reports in the literature.[16] Furthermore, the modest but significant correlations between performance on these measures and several measures of biomechanical impact exposure over the last week of the season and cumulatively over the course of a season suggests a potential connection between HIE at higher magnitudes and frequencies and cognitive performance. However, it should be noted that, due to the complex and observational nature of the data and the large number of measures of exposure and outcome examined, formal adjustments for multiple comparisons would considerably reduce the statistical significance of the reported *p* values.

We did not find systematic differences between athlete cohorts at the preseason assessment, suggesting that accumulated impacts over multiple previous seasons (i.e., prior to the index season) are not associated with reduced cognitive performance at the group level. These results are consistent with at least 1 other study[17] and may serve as an encouraging counterweight to recent concerns about cognitive effects associated with repetitive head impacts in contact sports. Our use of a noncontact sport athlete control group in the design and analysis also helps to

Table 4 Relationship of head impact exposure metrics to postseason cognitive performance[a]

	Neuropsychological variables (site 1)[a]							ImPACT composite scores (all sites)[a]					
Predictor	CVLT	DCWT	LTR total	PASAT C	VIGRT[b]	TR4B	BVMT total	Verbal memory	Visual memory	Visual motor	Impulse control[b]	Reaction time[b]	Total symptom score[b]
Last day HIE variables[b]													
Global *p* value for HIE variables	0.37	0.52	0.19	0.32	0.088	0.47	0.67	0.59	0.41	0.64	0.69	0.35	1.0
Last week HIE variables													
Global *p* value for HIE variables	0.21	0.42	0.45	0.55	0.096	0.034[c]	0.31	0.14	0.56	0.42	0.6	1.0	0.53
Season HIE variables													
Global *p* value for HIE variables	0.089	0.29	0.17	0.66	00.90	0.13	00.80	0.54	0.12	0.52	0.9	0.017[d]	0.084

Abbreviations: BVMT = Brief Visual Memory Test; CVLT = California Verbal Learning Test; DCWT = Delis-Kaplan Frontal Executive Systems Color Word Interference condition, seconds to complete; HIE = head impact exposure; HITsp = measure of head impact severity; LTR = Letter Fluency, Total Words; PASAT = Paced Auditory Serial Addition Task; TR4B = Trails 4/B; VIGRT = Gordon Continuous Performance Test, Vigilance Condition, Reaction Time; WRAT IV = Wide Range Achievement Test 4.

[a] Summary of multiple linear regressions covarying for baseline score, WRAT IV-Reading (neuropsychological battery only), contact sport status, and days from preseason to postseason testing.

[b] The HIE variables included were number of hits, peak HITsp, peak linear acceleration, sum of linear acceleration (*g*), peak rotational acceleration (rads/s^2), sum rotational acceleration (rads/s^2), sum HITsp.

[c] Statistically significant individual predictors were peak HITsp ($r = -0.27$), peak linear acceleration (*g*) ($r = -0.25$), peak rotational acceleration (rads/s^2) ($r = -0.27$), and sum HITsp ($r = -0.22$).

[d] Statistically significant individual predictor was peak linear acceleration ($r = -0.19$).

address the concern that subtle adverse changes in cognition in the contact sport athletes might manifest as reduced practice effects over relatively short test-retest intervals. As noted, the athlete groups did not differ significantly with respect to preseason to postseason test interval, and test-retest intervals were used additionally to adjust the major comparisons reported; thus, it seems unlikely that practice effect differences contributed in a major way to the results.

Several factors should be considered when interpreting these results. This cohort was limited to collegiate athletes, and therefore care must be taken in extrapolating the results to different age groups. This study did not assess potential changes in cognitive scores relative to baseline during the season or immediately following active HIE (mean of 26 days for ImPACT, 27 days for neuropsychological battery), although time to retest following end of season was considered as a covariate. It is possible that greater between-group differences might be found during the season, as previously reported.[16,38] The role of effort and motivation is also important to consider. Although both ImPACT and our neuropsychological battery contained measures to assess effort, these are imperfect indicators; we therefore cannot rule out the possibility that differences in effort at the group level may have obscured additional findings. For example, if the contact athlete group did not try as hard during the preseason evaluation (e.g., to minimize abnormal scores if they were concussed later in the season) and were motivated to try harder at the postseason assessment relative to the noncontact group, this might confound the findings. Alternatively, our cohort is a fairly bright, well-educated group, generally motivated to perform both athletically and cognitively, thus their effort to perform well on cognitive tests may not be generalizable to other less motivated populations. We have previously reported that cognitive performance in a group of individuals with MTBI was similar to that of a group of noninjured healthy controls; however, patterns of cerebral activation associated with a cognitive task differed across groups and could be interpreted as demonstrating that the MTBI group was working harder to achieve the same results.[28] It is also possible that results would differ in a predominantly female sample given that young women may be more susceptible to concussion and its effects.[4] Another factor to consider in the design of future studies would be whether individuals with 1 or more prior diagnosed concussions respond differently to repetitive impacts over the course of a season.

The findings of this study are somewhat reassuring in the context of the recent heightened concern about potential detrimental effects of contact sports.[8] The lack of a strong detrimental group effect of a season of repetitive head impacts on cognition may help to put in perspective the overall risk to contact sport athletes, and is consistent with the observation that thousands of individuals have played contact sports for many years without obvious functionally significant adverse effects, and without developing progressive neurodegenerative disorders. Nevertheless, these findings suggest the possibility that repetitive head impacts may have an adverse effect on some athletes. Furthermore we cannot exclude the possibility of detrimental cognitive effects that might be detected with a longer prospective design, for example over the course of 4 years of collegiate contact sports, an important next step.

It is also reasonable to speculate that individual differences such as polymorphisms in genes modulating response to neurotrauma[39] (e.g., *APOE*, *BDNF*, *ANKK1*) or other host factors may play a role in cognitive outcome following repetitive head impacts. For example, it is tempting to hypothesize that risk of chronic traumatic encephalopathy or other long-term effects of contact sports may represent a gene–environment interaction between repetitive mild neurotrauma and genetic vulnerability to heightened injury response or attenuated neural repair. Additional studies are warranted given the public health implications.

AUTHOR CONTRIBUTIONS

Thomas W. McAllister: conception and design, analysis and interpretation of data, drafting of manuscript, obtaining funding, supervision. Dr. McAllister had full access to all of the data in the study and takes responsibility for the integrity of the data and the accuracy of the data analysis. Laura A. Flashman: conception and design, analysis and interpretation of data, drafting of manuscript, obtaining funding, supervision. Arthur Maerlender: conception and design, analysis and interpretation of data, drafting of manuscript, obtaining funding. Richard M. Greenwald: conception and design, analysis and interpretation of data, critical revision of manuscript, obtaining funding, supervision. Jonathan G. Beckwith: analysis and interpretation of data, critical revision of manuscript, statistical analysis, technical support. Tor D. Tosteson: statistical design, analysis and interpretation of data, critical revision of manuscript, statistical analysis. Joseph J. Crisco: conception and design, critical revision of manuscript, supervision, obtaining funding. P. Gunnar Brolinson: conception and design, critical revision of manuscript, supervision, obtaining funding. Stefan M. Duma: conception and design, critical revision of manuscript, supervision, obtaining funding. Ann-Christine Duhaime: conception and design, critical revision of manuscript, technical support. Margaret R. Grove: analysis and interpretation of data, critical revision of manuscript, statistical analysis. John H. Turco: conception and design, critical revision of manuscript, supervision.

DISCLOSURE

Thomas W. McAllister, Laura A. Flashman, and Arthur Maerlender report no disclosures. Richard M. Greenwald (and Simbex) has a financial interest in the instruments (HIT System, Sideline Response System [Riddell, Inc.]) used to collect the biomechanical data reported in this study. Jonathan G. Beckwith and Tor D. Tosteson report no disclosures. Joseph J. Crisco (and Simbex) has a financial interest in the instruments (HIT System, Sideline Response System [Riddell, Inc.]) used to collect the biomechanical data reported in this study. P. Gunnar Brolinson, Stefan M. Duma, Ann-Christine Duhaime, Margaret R. Grove, and John H. Turco report no disclosures. **Go to Neurology.org for full disclosures.**

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