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ORIGINAL RESEARCH ARTICLE

Estimated Age of First Exposure to American Football and Neurocognitive Performance Amongst NCAA Male Student-Athletes: A Cohort Study

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Abstract

Background Repetitive head impacts in young athletes are potentially detrimental to later life (e.g., age 50 + years) neurological function; however, it is unknown what the short-term effects (e.g., age 20 years) are in collegiate student-athletes.
Objective The purpose of this study was to determine the effect of the estimated age of first exposure to American tackle football participation on neurocognitive performance and symptom severity scores in collegiate student-athletes.
Methods We used a cohort study in which neurocognitive performance was assessed using the Immediate Post-Concussion Assessment and Cognitive Testing (ImPACT) test in 4376 male athletes (age 19.3 ± 1.5 years, mass 96.3 ± 20.3 kg, height 185.0 ± 7.4 cm). Athletes were grouped by sport participation [American football (n = 3462) or non-contact (n = 914)] and estimated age of first exposure [< 12 years (n = 3022) or ≥ 12 years (n = 1354)]. The outcome measures were the four primary cognitive scores and the symptom severity score from ImPACT. We assessed primary outcomes across groups, controlling for age, learning accommodations, and concussion history.
Results Neurocognitive performance was not associated with the estimated age of first exposure-by-group interaction.
Conclusion Our findings indicate that participation in American tackle football before age 12 years does not result in neurocognitive deficits in college. Therefore, we suggest the following: the consequences of early exposure to repetitive head impacts do not manifest by college, the ImPACT test was not sensitive enough to identify the effects of an earlier estimated age of first exposure, or there is no association between an earlier estimated age of first exposure and neurocognitive functioning. Future longitudinal studies are warranted.

This article is part of a Topical Collection on The NCAA-DoD Concussion Assessment, Research and Education (CARE) Consortium.

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Key Points

We defined the estimated age of first exposure (eAFE) as the participant's age at the time of assessment minus the number of years the participant reported playing his primary sport.

Neurocognitive performance was not associated with the eAFE-by-group interaction.

Our findings indicate that participation in American tackle football before age 12 years does not result in neurocognitive deficits in college.

We suggest the consequences of early exposure to repetitive head impacts do not manifest by college, the Immediate Post-Concussion Assessment and Cognitive Testing (ImPACT) test was not sensitive enough to identify the effects of earlier eAFE, or there is no association between earlier eAFE and neurocognitive functioning.

1 Introduction

Nearly 5 million athletes participate in organized tackle football each year [1–3], and head impacts are an inherent risk in tackle football. While the acute effects of concussion have been identified [4], the long-term effects are still being elucidated [5]. More recently, there has been concern that exposure to repetitive head impacts, which do not result in clinically identifiable concussion, may also be associated with short- and long-term neurological impairments [6–8]. Exposure to repetitive head impacts in tackle football is frequent, ranging from hundreds to thousands depending on the position and level of play [1, 9–13]. For example, a defensive lineman who begins tackle football at age 10 years may experience up to 5000 head impacts by the end of high school and, should they continue to play in college, over 8000 head impacts by the end of college [14]. Montenigro et al. proposed that as few as 2723 head impacts have been associated with an increased risk of impaired later life executive function [14]. This suggests that by the end of high school, football players who begin playing before age 12 years may already have experienced enough head impacts to cause long-term neurological impairments.

The literature on the long-term consequences of repetitive head impact exposure is inconsistent, as evidenced by the controversy surrounding the etiology of chronic traumatic encephalopathy (CTE) [15]. Yet, some have suggested that CTE may be associated with exposure to repetitive head impacts, whereby the severity of CTE pathology increases with the level and duration of play [16]. Others, however, have suggested no association between football participation and later life neurodegenerative syndromes or suicidality [17–19]. Ultimately, a cause-and-effect relationship has not yet been demonstrated between CTE and sport-related concussions or exposure to contact sports [15]. As such, there is much to learn about the potential consequences of repetitive head-impact exposure and concussions, as well as other risk factors/modifying factors [i.e., genetic, environmental, age of first exposure (AFE)] [15]. For example, several studies have suggested that earlier AFE, that is, exposure to tackle football prior to age 12 years, may result in greater cognitive and neuropsychiatric impairments later in life [20–23], although these findings have been challenged [24]. Ages 10–12 are years of rapid brain growth and maturation, including increased myelination and cerebral blood flow [25–30], and some have speculated that repetitive head impacts during this critical period of neurodevelopment may have both short- and long-term consequences [20–23]. However, studies examining AFE have been limited to later life, long-term outcomes across small sample sizes, and to a single institution. These findings may not be generalizable to all football players as they largely included former National Football League players and lack a control group to examine the effects of early exposure to repetitive head impacts compared to early exposure to sport participation more broadly.

To understand the manifestation or progression of the later life neurological impairments associated with exposure to repetitive head impacts, particularly with respect to tackle football during critical stages of neurodevelopment (i.e., ages 10–12 years) [25–30], we must assess neurological function across varying levels of sport participation and throughout the lifespan. Considering that, by the end of high school, football players may already have experienced enough head impacts to cause long-term neurological impairments, it is feasible that athletes exposed to tackle football participation before age 12 years (AFE < 12) have observable neurocognitive impairments in college relative to those with AFE ≥ age 12 years (AFE ≥ 12). Because neurodevelopment does not taper off toward adult levels until about age 20 years [26–31], observable neurocognitive impairments in college may inhibit cognitive tasks, such as planning, integrative information, abstract thinking, problem solving, judgment, and reasoning that develop during later stages of adolescent neurodevelopment [31]. Therefore, we aimed to determine the effects of estimated AFE (eAFE) to sport participation (i.e., eAFE < 12 vs. eAFE ≥ 12), the effects of collision-sport participation (i.e., football vs. control), and the interaction of eAFE-by-sport (i.e., eAFE < 12, football vs. eAFE ≥ 12, football vs. eAFE < 12, non-contact vs. eAFE ≥ 12, non-contact) on Immediate Post-Concussion Assessment and Cognitive Testing (ImPACT) composite scores in National Collegiate Athletic Association (NCAA) collegiate athletes. We defined eAFE as the participant's age at the time of assessment minus the number of years the participant reported playing his primary sport. Although the predictive validity and diagnostic accuracy of the ImPACT test have been questioned, the ImPACT test is still the most widely used neurocognitive assessment by athletic trainers and physicians in sport-related concussion evaluation [32–35]. We hypothesized that ImPACT scores would be worse among those athletes exposed to tackle football participation before age 12 years (eAFE < 12).

2 Methods

This study was part of the NCAA-Department of Defense Concussion Assessment, Research and Education (CARE) Consortium, an ongoing study on the effects of concussion in collegiate athletes and US military service academy members that began in Autumn 2014 and has enrolled over 37,000 student-athletes and military service academy students across 30 colleges/universities [36]. We only used the baseline ImPACT test (used at 25 colleges/universities) and demographic information, collected as part of 'Level A' testing in this study. Because some athletes participated in the CARE Consortium study during more than one season, only the first season's baseline data were included in analyses.

2.1 Participants

Participants included current NCAA collegiate athletes ($n = 4376$, age 19.3 ± 1.5 years, mass 96.3 ± 20.3 kg, height 185.0 ± 7.4 cm) that met inclusion/exclusion criteria and were enrolled in the CARE Consortium between June 2014 and August 2018. Inclusion criteria for the experimental group were male football players while the control group consisted of non-contact sport athletes (i.e., baseball, cross country/track, fencing, field events, gymnastics, volleyball, golf, rifle, rowing/crew, sailing, swimming, and tennis) [37]. Exclusion criteria included female athletes and non-contact sport athletes with a history of collision/contact sport participation (i.e., basketball, diving, field hockey, football, ice hockey, lacrosse, martial arts, rugby, soccer, water polo, and wrestling), or non-contact sport athletes who were also US military service academy members, as they may experience repetitive head impacts because of their military training (Fig. 1) [37–41]. The University of Michigan Institutional Review Board, the US Army Medical Research and Materiel Command Human Research Protection Office, as well as the local institutional review board at each of the performance sites reviewed all study procedures. Participants provided written informed consent prior to participation. The study was performed in accordance with the standards of ethics outlined in the Declaration of Helsinki.

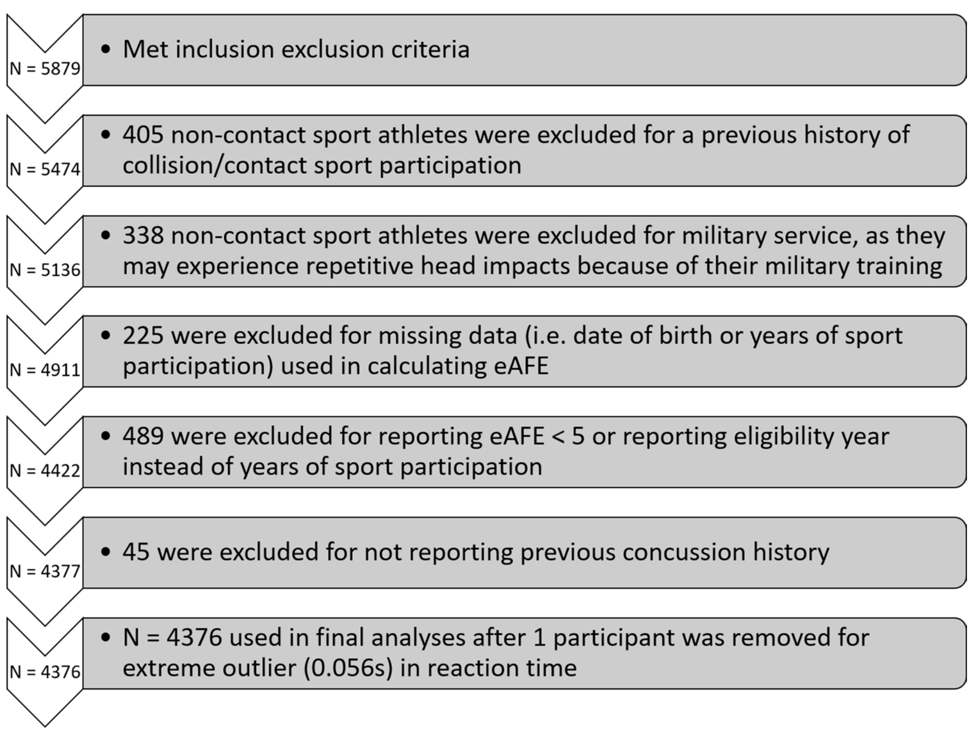

Fig. 1 Inclusion/exclusion sequence

2.2 Estimated Age of First Exposure

We defined the eAFE as the participant's age at the time of assessment minus the number of years the participant reported playing his primary sport. The eAFE was used to divide participants into two cohorts: eAFE < 12 and eAFE ≥ 12 [20–23]. Of the 5136 participants who potentially met inclusion/exclusion criteria, 714 did not provide enough information to calculate eAFE, or provided inaccurate information (Fig. 1). The minimum eAFE for this study was 5 years as this is the youngest age for Pop Warner football and any participant indicating eAFE prior to age 5 years was excluded.

2.3 Outcome Measures

The ImPACT (ImPACT Applications Inc., Pittsburgh, PA, USA) is a computerized neurocognitive assessment designed specifically for the assessment and management of sport-related concussions and tests attention, memory, reaction time, and information-processing speed [42]. It consists of eight modules: immediate and delayed word recall, immediate and delayed design recall, a symbol-match test, a three-letter recall, the X's and O's test, and a color-match test. From these eight modules, five composite scores are calculated: visual memory, verbal memory, visual motor speed, and reaction time, and impulse control. The impulse control composite score is used to determine if the participant provided a good effort (impulse control < 30) [42]. Finally, the ImPACT test provides the Post-Concussion Symptom Scale (PCSS), which is a 22-item self-report, symptom checklist, including common concussion symptoms such as headache, dizziness, nausea, difficulty concentrating, and fatigue. The PCSS yields a total symptom severity composite score ranging from 0 to 132 [42]. The reliability and validity of the ImPACT test have been assessed in the literature [34, 43–57]. Despite limitations, including a susceptibility to false-positives in concussion assessment, poorer scores with group testing, a learning effect with repeated administration, and moderate-to-low test–retest reliability [33, 34, 46, 58], the cognitive domains represented by ImPACT have good construct validity with standard paper and pencil neurocognitive tests that are sensitive to cognitive functions associated with sport-related concussion [52, 53]. For example, the ImPACT Visual Memory composite score was correlated (r = 0.590, p < 0.001) with the Brief Visuospatial Memory Test-Revised, a neuropsychological test of visual memory [53]. Moreover, the ImPACT test is the most widely used neurocognitive assessment by athletic trainers and physicians in sport-related concussion evaluation [32–35]. The five ImPACT composite scores used as outcome measures in this study include visual memory, verbal memory, visual motor speed, reaction time, and symptom severity. Only participants with valid baseline ImPACT composite scores were included in the database.

2.4 Statistical Analysis

Generalized linear modeling was used for the prediction of each cognitive domain score and the symptom severity score. Predictor variables were entered in the following order: a dichotomous variable for the group (football vs. non-contact), a dichotomous variable for the eAFE (eAFE < 12 vs. eAFE ≥ 12), an interaction term, group-by-eAFE, and covariates for learning accommodation status, number of previous concussions, and age [24]. The self-reported learning accommodation status, i.e., Individualized Education Program, 504 Plan (i.e., a plan developed to ensure that a child who has a disability identified under the law and is attending an elementary or secondary educational institution receives accommodations that will ensure their academic success and access to the learning environment), or other learning accommodations, was input as a dichotomous variable, and the number of previous concussions and age were input as continuous variables (Table 1). We initially fitted generalized linear models for each cognitive domain score based on a normal (Gaussian) distribution and identity link functions but then considered models with alternative distributions and link functions and selected the model with the lowest Akaike information criterion value (i.e., best fit). Reaction time scores were positively skewed; an inverse Gaussian distribution with a power link function best fit these data. For the symptom score, which has a high zero count and extreme positive skewing, a negative binomial distribution with a log link achieved the lowest Akaike information criterion value. Significance was defined a priori as p < 0.05. All analyses were conducted using SPSS Version 24 (IBM, Armonk, NY, USA).

3 Results

There were 4376 male athletes included in the final analysis (Table 1). One participant had an outlier (more than three standard deviations from the mean) for reaction time and was removed from analyses. The results of the generalized linear modeling for each ImPACT score are presented in Table 2.

In these models, the interaction term, group-by-eAFE, was only a significant predictor of symptom severity scores; pairwise comparisons suggested that football, eAFE < 12 interaction reported lower severity scores than all other groups (non-contact, eAFE < 12: mean difference = – 0.97, p < 0.001, Cohen's d = 0.11; non-contact, eAFE ≥ 12: mean difference = – 0.92, p < 0.001, Cohen's d = 0.11; football, eAFE ≥ 12: mean difference = – 0.56, p < 0.001, Cohen's

Table 1 Participant demographic information

	n	Age ± SD, years	Current academic year, n (%)	Weight ± SD, kg	Height ± SD, cm	Concussion, n (%)	Learning accommodations, n (%)
Football, eAFE ≥ 12	1026	19.7 ± 1.7	Freshman, 438 (42.7) Sophomore, 172 (16.8) Junior, 242 (23.6) Senior, 110 (10.7) Fifth year senior, 34 (3.3) Graduate student, 29 (2.8)	104.3 ± 21.7	186.3 ± 7.3	341 (33.2)	87 (8.5)
Football, eAFE < 12	2436	19.1 ± 1.4	Freshman, 1380 (56.7) Sophomore, 381 (15.6) Junior, 397 (16.3) Senior, 180 (7.4) Fifth year senior, 60 (2.5) Graduate student, 31 (1.3)	99.8 ± 18.0	185.4 ± 7.0	819 (33.6)	144 (5.9)
Non-contact, eAFE ≥ 12	328	19.5 ± 1.5	Freshman, 145 (44.2) Sophomore, 59 (18.0) Junior, 67 (20.4) Senior, 46 (14.0) Fifth year senior, 9 (2.7) Graduate student, 1 (.3)	74.6 ± 13.5	181.6 ± 8.4	32 (9.8)	18 (5.4)
Non-contact, eAFE < 12	586	19.4 ± 1.4	Freshman, 267 (45.6) Sophomore, 108 (18.4) Junior, 129 (22.0) Senior, 71 (12.1) Fifth year senior, 3 (.5) Graduate student, 7 (1.2)	79.7 ± 10.6	183.0 ± 7.6	49 (8.4)	25 (4.3)
Total	4376	19.3 ± 1.5	Freshman, 2230 (51.0) Sophomore, 720 (16.5) Junior, 835 (19.1) Senior, 407 (9.3) Fifth year senior, 106 (2.4) Graduate student, 68 (1.6)	96.3 ± 20.3	185.0 ± 7.4	1241 (28.4)	274 (6.3)

Concussion and self-reported learning accommodation status (i.e., Individualized Education Program, 504 Plan, or other learning accommodations) sample sizes represent those student-athletes endorsing "yes" to a concussion history or learning accommodation. The median number of reported concussions was 0 (range 0–6)

eAFE estimated age of first exposure, *SD* standard deviation

Table 2 Cognitive performances and symptom ratings among collegiate football and non-contact sport athletes

ImPACT composite	Verbal memory			Visual memory			Visual motor speed			Reaction time			Symptom severity		
Overall model	$X^2_6 = 72.842$, $\pi < 0.001$			$X^2_6 = 62.604$, $\pi < 0.001$			$X^2_6 = 144.592$, $\pi < 0.001$			$X^2_6 = 120.582$, $\pi < 0.001$			$X^2_6 = 132.658$, $\pi < 0.001$		
	$n = 4376$			$n = 4372$			$n = 4371$			$n = 4375$			$n = 4235$		
	Mean ± SE	95% CI	Sig	Mean ± SE	95% CI	Sig	Mean ± SE	95% CI	Sig	Mean ± SE	95% CI	Sig	Mean ± SE	95% CI	Sig
Contact															
Football	85.31 ± 0.21	84.90–85.72	0.745	76.54 ± 0.26	76.04–77.04	0.953	39.49 ± 0.13	39.25–39.74	0.001*	0.619 ± 0.002	0.616–0.623	0.001*	2.79 ± 0.06	2.67–2.91	0.127
Non-contact	84.64 ± 0.39	83.87–85.41		75.91 ± 0.48	74.97–76.84		40.74 ± 0.24	40.28–41.21		0.596 ± 0.003	0.590–0.602		3.47 ± 0.14	3.19–3.74	
eAFE															
eAFE ≥ 12	84.77 ± 0.36	84.07–85.47	0.049*	76.38 ± 0.44	75.53–77.23	0.463	39.98 ± 0.22	39.55–40.40	0.026*	0.604 ± 0.003	0.599–0.610	0.223	3.26 ± 0.12	3.02–3.49	0.001*
eAFE < 12	85.17 ± 0.26	84.66–85.68		76.07 ± 0.32	75.45–76.69		40.26 ± 0.16	39.96–40.57		0.611 ± 0.002	0.607–0.615		2.97 ± 0.08	2.81–3.12	
Interaction															
Football, eAFE ≥ 12	84.89 ± 0.35	84.20–85.58	0.323	76.36 ± 0.43	75.51–77.20	0.198	39.21 ± 0.21	38.79–39.63	0.293	0.617 ± 0.003	0.611–0.623	0.554	3.08 ± 0.11	2.86–3.30	0.019*
Football, eAFE < 12	85.72 ± 0.23	85.27–86.17		76.73 ± 0.28	76.19–77.28		39.78 ± 0.14	39.51–40.05		0.622 ± 0.002	0.618–0.625		2.52 ± 0.06	2.40–2.64	
Non-contact, eAFE ≥ 12	84.66 ± 0.62	83.44–85.88		76.41 ± 0.76	74.92–77.89		40.74 ± 0.38	40.00–41.48		0.591 ± 0.005	0.582–0.601		3.45 ± 0.22	3.02–3.88	
Non-contact, eAFE < 12	84.62 ± 0.47	83.70–85.54		75.41 ± 0.57	74.29–76.52		40.75 ± 0.28	40.19–41.30		0.600 ± 0.004	0.593–0.608		3.49 ± 0.17	3.16–3.82	
Covariates															
Learning accomod.			< 0.001			< 0.001			< 0.001			< 0.001			< 0.001
Age			0.006			0.007			0.757			0.461			< 0.001
Previous concussion			< 0.001			< 0.001			< 0.001			< 0.001			< 0.001

Values represent model means, standard errors (SEs), and 95% confidence intervals (CIs). Except for reaction time scores, higher scores represent better or stronger cognitive abilities. Greater symptom scores represent worse symptom ratings

accomod. accommodation, *eAFE* estimated age of first exposure, *ImPACT* Immediate Post-concussion Assessment and Cognitive Testing, *Sig* * represents significant differences between groups

$d = 0.08$), and that football, eAFE ≥ 12 interaction reported lower symptom severity scores than non-contact, eAFE < 12 (mean difference = − 0.41, $p < 0.044$, Cohen's $d = 0.02$). Considering the small effect sizes, these findings suggest that outcomes did not differ across groups.

The main effect for the group was only a significant predictor of visual motor speed (mean difference = − 1.25, $p < 0.001$, Cohen's $d = 0.13$) and reaction time (mean difference = 0.02 s, $p < 0.001$, Cohen's $d = 0.18$), whereby football participants had lower visual motor speed and slower reaction time than non-contact participants, but considering the small effect sizes, these findings are likely of minimal clinical significance. Finally, the few but small significant eAFE differences among participants in verbal memory (mean difference = 0.40, $p = 0.049$, Cohen's $d = 0.08$), visual motor speed (mean difference = 0.29, $p = 0.026$, Cohen's $d = 0.07$), and symptom severity score (mean difference = 0.29, $p < 0.001$, Cohen's $d = 0.07$) are likely of minimal clinical significance, though they suggest that eAFE < 12 has higher verbal memory and visual motor speed and lower symptom severity than eAFE ≥ 12.

4 Discussion

Some studies have reported that repetitive head impacts in young athletes may potentially be detrimental to later life neurological function; however, it is unknown what the short-term effects (e.g., at age 20 years) are in collegiate student-athletes [20–23]. Our goal was to determine the effect of the eAFE to repetitive head impacts on neurocognitive performance and symptom severity scores in football and non-contact collegiate student-athletes. Our findings suggest that participation in tackle football before age 12 years, when evaluated by the ImPACT test, did not result in neurocognitive deficits in college. Participation in tackle football before age 12 years did, however, result in lower (better) symptom severity scores than all other groups (i.e., non-contact, eAFE < 12; non-contact, eAFE > 12; football, eAFE > 12), although the differences between groups were within the established reliable change index (10), and had small effect sizes, suggesting that these findings are not clinically meaningful [59]. While we did observe lower (worse) visual motor speed and slower (worse) reaction time in football participants than non-contact participants, regardless of eAFE, these differences had small effect sizes and were within the established reliable change indices (visual motor speed = 3; reaction time = 0.06 s) [59]. We also observed higher (better) verbal memory and visual motor speed and lower (better) symptom severity in participants, both football and non-contact, who participated in sport before age 12 years, but again these differences were within the established reliable change indices (verbal memory = 9; visual motor speed = 3; symptom severity = 10) and had small effect sizes [59]. Finally, learning disabilities and previous concussion history were significant covariates in the model suggesting that they were modifiers for the neurocognitive test outcomes. Taken together, these findings suggest that we identified several statistically significant differences in sport and eAFE in a large cohort of collegiate student-athletes, but these findings are likely of minimal clinical significance.

We hypothesized that ImPACT composite scores would be worse among those athletes exposed to tackle football participation before age 12 years (eAFE < 12). However, this hypothesis was not supported; there was no significant eAFE-by-sport interaction suggesting that early participation in football did not result in neurocognitive performance deficits in our population of current collegiate student-athletes. When compared to normative data for the ImPACT test, both football and non-contact athletes had "average" composite scores for sex and age across all domains [37, 60]. Studies by Stamm et al. and Alosco et al. reported differences between AFE < 12 and AFE ≥ 12 in later life (i.e., largely over 50 years) cognitive function (i.e., the Wisconsin Card Sort Test, the Neuropsychological Assessment Battery List Learning test, and the Wide Range Achievement Test, Fourth Edition performance), white matter microstructure, neuropsychiatric outcomes, thalamic volumes, and age of neurobehavioral symptom onset in retired professional and amateur football players, whereby those athletes who participated in tackle football prior to age 12 years had greater neurological impairments and a younger age of neurobehavioral symptom onset [20–23, 61], although younger AFE to tackle football was not associated with CTE pathological severity [61].

Our studies differed from those by Stamm et al. in several key areas—our cohorts were different: the average age of our participants was 19 years, including college freshmen through seniors, who played tackle football for an average of 10 years, and were apparently healthy; whereas, their cohort included retired athletes, who were largely aged over 50 years, reported an average of 19 years of participation in tackle football, and reported a worsening of cognitive, behavioral, and mood symptoms for at least the previous 6 months [20–23]. Although we did not observe differences between football, eAFE < 12 and football, eAFE ≥ 12 in neurocognitive performance, it is possible that symptoms of early exposure to repetitive head impacts will not manifest until later in life. For example, the neuroprotective effect of exercise is well documented, and aerobic exercise training is associated with modest improvements in attention and processing speed, executive function, and memory [62]. Perhaps throughout college, when student-athletes are young and still actively participating in sport, they have sufficient cognitive reserves or compensatory neurocognitive capabilities to adapt and overcome potential degradation. However, as athletes age and become less active, they may no longer able to compensate and only then present with neurological impairments. In addition, it is possible that symptoms of neurological impairment will progress with increased exposure to repetitive head impacts (e.g., throughout college and professional play). For example, Montenigro et al. suggested that beyond 2723 head impacts, there is a worsening dose–response relationship between the number of head impacts and neurological impairments [14]. We expect that many participants captured in this study were just beyond a cumulative repetitive head impact exposure of 3000 impacts [14]. If we were to capture all participants at the end of their college career or beyond collegiate play, perhaps these findings may differ.

Our findings agree with Solomon and colleagues who reported no correlations between pre-high school years of exposure to tackle football and neurological outcomes across three domains of neuroradiological, neurobehavioral, and neuropsychological testing, including the ImPACT test, in retired National Football League players [24]. Like our findings, their ImPACT composite scores were not related to pre-high school years of exposure to tackle football. While there are known limitations to the ImPACT test, Solomon et al. also reported no statistically significant relationship between paper-and-pencil neurocognitive test scores and pre-high school years of exposure to tackle football. Unlike the studies by Stamm and colleagues, Solomon et al. did not recruit exclusively former National Football League players who were experiencing a worsening of cognitive, behavioral, and mood symptoms. In addition, Solomon et al. used multiple regression models with "number of years of pre-high school football" utilized as the predictor variable, as opposed to a cut-off age [24]. The cut-off age was selected by Stamm and colleagues because ages 10–12 are years of rapid brain growth and maturation, including increased myelination and cerebral blood flow [25–30], and some have speculated that repetitive head impacts during this critical period of neurodevelopment may have both short- and long-term consequences [20–23].

Our findings, taken with those of Solomon et al. do not support the presence of a relationship between AFE to tackle football and neurological impairments in samples of apparently healthy current and former football players, but do not rule out the possibility that a relationship may present in those former athletes who later experience a worsening of cognitive, behavioral, and mood symptoms [20–23]. Thus, prospective longitudinal studies are required to more thoroughly investigate the effects of repetitive head impacts on neurological health [36].

Although time allocated to academic study sometimes shows a corresponding reduction in sport participation, sport participation during youth results in better grade point averages and cognitive function, and positive influences on concentration, memory, and classroom behavior [63]. It would be conceivable then that participation in sport, football or non-contact, would positively affect neurocognitive performance during these critical neurodevelopmental phases through high school and college. There was an effect for eAFE, whereby athletes, both football and non-contact, who participated in sport before age 12 years, had higher (better) verbal memory, visual motor speed, and lower (better) symptom severity scores. However, these differences also had small effect sizes and were within the reliable change indices, suggesting that these findings are not clinically meaningful.

We observed that participation in tackle football before age 12 years, when evaluated by the ImPACT test, did not result in neurocognitive deficits in collegiate student-athletes. Though this is not a study of "retired" athletes, such as those conducted by Solomon et al., Stamm et al., and Alosco et al., and thus we cannot discern the effect of long-term neurocognitive impairment later in life, these results lend empirical evidence to the notion that AFE is not associated with neurocognitive functioning. However, to gain a more comprehensive understanding of the manifestation and progression of long-term neurological impairments in former football players, future research should prospectively examine neuroradiological, neurobehavioral, and neuropsychological tests across varying levels of sport participation and across the lifespan.

4.1 Limitations

We addressed some methodological limitations of previous studies. For example, Stamm and colleagues were critiqued for a small homogenous sample, lack of a control group of participants from non-contact sports, an abnormally high total number of concussions, and use of inappropriate neurocognitive tests [64]. However, we used the ImPACT test and PCSS as the only outcome measures. The ImPACT test and PCSS have been components of sport-related concussion assessment and are recommended as core assessments in the recent National Institutes of Health/National Institute of Neurological Disorders and Stroke Sports Concussion Common Data Elements [65]. Further, the ImPACT test was created to assess neurocognitive function following sport-related concussion when cognitive function demonstrates the largest impairment (i.e., relative to repetitive head impacts and throughout recovery following sport-related concussion) [66]; therefore, perhaps it is not sensitive enough to identify more subtle deficits. Incorporating more sensitive measures of neuroradiological, neurobehavioral, and neuropsychological testing may result in a more comprehensive approach.

We also do not know the previous number of times each athlete has taken the ImPACT test, and with the known learning effect of the ImPACT test, this may confound results. Like prior studies, eAFE was based on self-reporting in which athletes were asked to report the number of years of participation in their primary sport. While there are numerous limitations with self-reporting, these data are essential to behavioral and medical research [67].

In the current study, exposure to repetitive head impacts was delimited to tackle football, but athletes in other sports, such as ice hockey, soccer, and lacrosse, may also experience repetitive head impacts at a young age, but the current findings may not extend to those populations. Moreover, repetitive head impacts were not directly assessed; thus, future research should not only consider AFE, but also the number and magnitude of impacts experienced throughout the lifespan.

Finally, we did not account for group or eAFE differences in socioeconomic status or the age of the first concussion. The socioeconomic status and race of student-athletes has independently predicted baseline ImPACT scores, when concussion history and years exposed to sport were not predictive [68]. The age at which an individual has his or her first concussion may be associated with the age at which an individual begins playing sports and may be an important factor in determining long-lasting cognitive effects [69]. Therefore, future studies should incorporate measures of socioeconomic status and demographic variables, and age of first concussion in addition to eAFE.

5 Conclusion

In summary, we found no statistically significant or clinically important association between eAFE < 12 in American football and neurocognitive performance in collegiate student-athletes after analyzing ImPACT data in a large cohort of NCAA student-athletes. Therefore, we suggest the following: the consequences of early exposure to repetitive head impacts do not manifest until later in life, symptoms of neurological impairment progress with increased exposure to repetitive head impacts throughout and beyond collegiate play, the ImPACT test was not sensitive enough to identify the effects of earlier eAFE, or there is no association between earlier eAFE and neurocognitive functioning. Ultimately, these athletes must be followed for years after college sport participation to determine future manifestation and progression of neurological disruption.

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Compliance with Ethical Standards

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Conflict of interest Beyond the research grant received, in part for this work (described under funding), Jaclyn B. Caccese, Ryan M. DeWolf, Thomas W. Kaminski, Steven P. Broglio, Thomas W. McAllister, Michael McCrea, and Thomas A. Buckley have no conflicts of interest that are directly relevant to the content of this study.

Ethics approval The study was performed in accordance with the standards of ethics outlined in the Declaration of Helsinki. All study procedures were reviewed by the University of Michigan Institutional Review Board, the US Army Medical Research and Materiel Command Human Research Protection Office, as well as the local institutional review board at each of the performance sites.

Consent to participate Participants provided written informed consent prior to participation.

Data availability The CARE Consortium datasets generated and analyzed during the current study will be available in the Federal Interagency Traumatic Brain Injury Research repository (https://fitbir.nih.gov/) by the end of 2019.

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