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Association Between Head Impact Exposure, Psychological Needs, and Indicators of Mental Health Among U.S. High School Tackle Football Players

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Abstract

Purpose: Age of first exposure to tackle football and proxy indices have been used to examine the effect of head impacts on mental health outcomes. These proxy measures coupled with retrospective and cross-sectional designs have contributed to conflicting results. The purpose of this study was to identify the effect of one season of head impact exposure, age of first exposure to football, and psychological need satisfaction on acute adolescent mental health outcomes.

Methods: This prospective single season cohort study utilized sensor-installed mouthguards to collect head impact exposure along with surveys to assess age of first exposure to football, psychological satisfaction, depressive symptoms, anxiety symptoms, and thriving from football players at four high schools (n=91). Linear regression was used to test the association of head impact exposure, age of first exposure, and psychological satisfaction with acute mental health outcomes.

Results: A total of 9,428 impacts were recorded with a mean of 102±113 impacts/player. Cumulative head impact exposure and age of first exposure were not associated with acute mental health outcomes at post-season or change scores from pre- to post-season. Greater psychological satisfaction was associated with fewer depressive symptoms (β=−0.035, SE=0.008, p=<.001), fewer anxiety symptoms (β=−0.021, SE=0.008, p=0.010), and greater thriving scores (β=0.278, SE=0.040, p=<.001) at post-season.

Conclusion: This study does not support the premise that greater single season head impact exposure or earlier age of first exposure to tackle football are associated with worse acute adolescent mental health indicators over the course of a single season.

Keywords

head impacts; subconcussive; depression; anxiety; thriving; psychological needs; mental health; adolescence; football

INTRODUCTION

Declining adolescent mental health has become a growing public health concern in the U.S., as more than one in three high school students experience persistent feelings of sadness or hopelessness, equating to a 40 percent increase since 2009.[1] Adolescents are in a neurodevelopmental period marked by an exploration of self-identify. Various factors, such as social media, peer pressure, and social relationships, have been thought to negatively impact mental health.[2,3] One promising, scalable, and systematic strategy to counteract early development of mental illness is through youth sports participation, particularly team sports.[4]

Benefits from sports participation include not only physical health (e.g., metabolic/cardiovascular health),[4,5] but also psychosocial health, including the development of self-esteem and social identity, less social anxiety, improved confidence, less depressive symptoms, and protective effects against suicidal ideation.[4,5] Therefore, youth sports present the potential population-level impact required for sustaining mental and physical health. However, there are also concerns about the risks involved, especially in tackle football which has higher injury rates than most other sports. A particularly concerning aspect of tackle football is the exposure to repetitive subconcussive head impacts, defined as head impacts that do not result in concussion symptoms.[6] These head impacts present a unique challenge within the realm of sport safety due to their widespread occurrence with many contact sport athletes sustaining hundreds of head impacts in a single season.[6] If unabated, chronic exposure to repetitive head impacts, has been shown to trigger neuronal microstructural damage, altered brain activation, functional alterations, and early-onset cognitive impairments.[7–10] However, the relationship between head impact exposure and mental health, especially in adolescents, remains uncertain.

Researchers have used proxy measures for cumulative head impact exposure, such as age of first exposure to tackle football and head impact exposure indices to examine the effect of repetitive head impacts on mental health outcomes.[9,11–16] Yet, these proxy measures coupled with many retrospective and cross-sectional designs have contributed to conflicting results.[11–17] For example, Iverson et al[14] examined the association of age of first exposure to later-in-life brain and mental health and found no significant correlations to depression symptoms or post-concussion symptoms.[20] On the other hand, in a cross-sectional study of former amateur and professional American football players, Alosco et al[11] found younger age of first exposure to tackle football (*e.g.*, < 12 years old) to be associated with increased risks for development of neuropsychiatric symptoms and impairment in executive function.[17] Furthermore, a review by Alosco and Stern[18] found growing evidence of short- and long-term alterations in cognition, behavior, mood, and brain structure but also acknowledged many methodological shortcomings (*e.g.*, retrospective designs, small sample sizes, sample selection bias). Given that the degree of exposure to repetitive head impacts is largely influenced by playing position, age, drill type, starting status, drill intensity, and individual factors,[19–21] the use of proxy measures may be insufficient to explain complex neuropsychological outcomes.[19,20,22] Another limitation of the current body of head impact literature is the lack of inclusion of psychosocial influences.[23] As such, the current study included a measure of psychological need satisfaction. Self-determination theory informed the selection of this variable, which posits that satisfaction of three psychological needs (*i.e.*, autonomy, competence, and relatedness) predicts psychological well-being.[24]

In this multisite, cohort study, we aimed to address two questions: 1. the long-lasting effects of head impact exposure, as surrogated by age of first exposure to tackle football, on acute mental health outcomes and 2. the association between cumulative head impacts during one season, as measured by sensor-installed mouthguards, and acute changes in mental health outcomes. We explored three mental health outcomes: depressive symptoms, anxiety symptoms, and thriving. Our primary hypotheses were that greater cumulative single-season head impact exposure, earlier age of first exposure to tackle football, and lower psychological need satisfaction would each predict more negative mental health outcomes at post-season. Our secondary hypothesis was that greater cumulative head impact exposure during a season would be associated with worse acute changes in mental health measures over the course of the football season. When there was a significant relationship between head impact exposure and acute changes in mental health outcomes, exploratory analysis was conducted to test the potential preventive effects of greater psychological need satisfaction on preservation of mental health outcomes after the season. Lastly, we aimed to test whether mental health outcomes were associated with psychological need satisfaction at each time point.

METHODS

This multisite, prospective observational study during the 2021 high school football season included adolescent male football players (n=91) from four high schools in the Midwestern United States. Inclusion criteria were being active football players and willingness to wear sensor-installed mouthguards at football practices and games. Participants' mental health measures were assessed at two time points (pre-season in July and post-season in November). Approval was obtained from the district school board and school stakeholders. All participants and their legal guardians provided informed consent, and the Indiana University Institutional Review Board approved the study protocol (#1904461516).

Study Procedures

Participants completed an online questionnaire reporting their demographics, contact sport history, football contextual questions, and mental health scales. During the pre-season data collection, participants were custom-fitted with "boil-and-bite" mouthguards (Prevent Biometrics, Inc.) and wore the mouthguard for all contact practices (n=37–46), scrimmages (n=1–2), and games (n=4–12) from pre-season training camp (August 2) to the end of the season (October 29–November 12). Video of practices and games were recorded using Hudl video performance analysis software (Agile Sports Technologies, Inc.). Study personnel were deployed at each high school to monitor all practices and games to record the precise real times (e.g., 4:27–4:45PM for a practice drill) that drills and games occurred. This allowed an additional level of filtering/cross-referencing of the raw head impact dataset with the real time of practices and games to ensure removal of sensor recorded events that occurred outside of practices and games. This video allowed the research team to validate the head impact data by randomly selecting 20% of head impacts across all practices and games. The use of these video review procedures was supported by another study investigating head impact exposure differences between drill intensity levels.[25–27]

Measures

Head impacts—This study utilized a Prevent Biometrics Impact Monitor Mouthguard system, which is installed with triaxial accelerometer (ADXL372, Analog Devices, Boston MA) and gyroscope (BMG250, Bosch, Gerlingen Germany) to provide 6-degree-of-freedom estimates of linear and rotational head accelerations during impact.[28] When an axis of acceleration exceeds a preset threshold of 10 *g*, an impact event triggers data collection, and the data are transmitted wirelessly to a nearby mobile application and uploaded to a secure cloud-based portal. The sampling rate is 3.2kHz, and impact data are collected for 50 milliseconds. The on-board firmware in mouthguards can store up to 460 impact data and has internal sensors to confirm proper wearing of the mouthguard during play.[29] The mouthguard also has a built-in in-mouth sensor that detects coupling to the upper teeth to prevent false positives (e.g., dropping or tapping mouthguard).

Two approaches to measuring head impact exposure—This study used two different types of head impact exposure estimates: (1) season-long cumulative head impact exposure using the impact monitoring mouthguard and (2) self-reported age of first exposure to tackle football. Although peak linear acceleration (PLA) and peak rotational acceleration (PRA) have shown a near identical performance in laboratory validations (concordance correlation coefficient [CCC] of 0.980 and 0.982, respectively), because PRA (−6.8%) showed larger variability from the head-form reference than PLA (−1%),[30] we decided to use PLA as our primary predictor. However, it is important to acknowledge that rotational head impact kinematics, such as PRA, has been suggested to be more injurious to the brain and may better correlate with the extent of brain injury compared to PLA.[31] Given that frequency, PLA, and PRA are highly correlated to one another, there were no differential outcomes among the three kinematic variables. Thus, we selected cumulative PLA to reflect season-long head impact exposure. Age of first exposure to tackle football has been used as a proxy for lifelong exposure to head impacts[11,13,14,18] and was assessed with a sliding scale in this study (6 to 18 years of age).

Depressive symptoms—The Patient Health Questionnaire-9 item (PHQ-9)[32] was used to assess self-reported depressive symptoms. The PHQ-9 consists of nine items scored on a four-point Likert scale (0–3) with a total score ranging from 0 to 27, with higher scores reflecting greater depressive severity. In adolescents, the PHQ-9 has demonstrated strong internal consistency, sensitivity, and specificity with an adequate Cronbach's alpha coefficient of 0.82.[33]

Anxiety symptoms—Participants rated their anxiety with the General Anxiety Disorder-7 (GAD-7) scale.[34] The GAD-7 consist of seven items measuring worry and anxiety symptoms. Each item is scored on a four-point Likert scale (0 to 3) with total scores ranging from 0 to 21 with higher scores reflecting greater anxiety severity. In adolescents, the GAD-7 has shown adequate sensitivity, specificity, and reliability (Cronbach's alpha = 0.91).[35]

Thriving—To measure the extent of thriving, we utilized the 10-item Brief Inventory of Thriving (BIT).[36] Thriving is broadly defined as a combination of happiness, accomplishments, and supportive and rewarding relationships.[36] The BIT had robust internal consistency with Cronbach's alpha coefficients above .90 in multiple cross-validation samples.[36] For the BIT, a score below the 25th percentile indicates an area of risk, whereas a score above the 75th percentile indicates an area of strength.[36] An assessment of thriving was selected as an outcome to capture a positive component of mental health beyond the more negatively associated symptoms of anxiety and depression.

Psychological need satisfaction—The Basic Psychological Needs Satisfaction and Frustration Scale (BPNSFS) was used to assess components of satisfaction (*i.e.*, autonomy, competence, and relatedness) on acute mental health outcomes as well as exploratory moderating effects on the relationship between head impact exposure and mental health. The

24-item scale utilizes eight items for each component. In a validation study of the BPNSFS across four countries, internal consistency ranged from 0.64 to 0.89, with subscales in the U.S. ranging from 0.71 to 0.89.[24] Satisfaction and frustration of autonomy, competence, and relatedness have each been shown to predict well-being (*i.e.*, need satisfaction) and ill-being (*i.e.*, need frustration).[24] Further, in line with past research using the BPSNFS,[37] we calculated an overall score from the six subscales to be used for our analyses. Mean cumulative scores from previous adolescent research across cultures were 73.7 and 75.4.[24] See Supplemental Methods 1 for a complete listing of items from each of the four neuropsychological scales.

Data analysis

Outcome measures (*i.e.*, depressive symptoms, anxiety symptoms, and thriving) were evaluated in two ways: (1) as post-season scores and (2) as change scores (*i.e.*, post-season score – pre-season score). Higher scores for depressive symptoms and anxiety symptoms indicate worse symptoms, whereas higher thriving scores indicate a greater level of thriving. A series of linear regression models were used to test the effect of cumulative season-long head impact exposure, age of first exposure to tackle football, and psychological need satisfaction on each mental health outcome at post-season. Participants' age and the high school they attended were used as control variables since participants clustered within high schools would be likely to have different experiences in terms of team culture, football coaching techniques, and win-loss records.

We were also interested in analyzing the association of cumulative season-long head impact exposure and psychological need satisfaction on acute changes in mental health outcomes over the course of one season of tackle football. These regression models assessed the association of cumulative head impact exposure on changes in (1) depressive symptoms, (2) anxiety symptoms, and (3) thriving over the course of the season. To probe the relationship from an added perspective, these models used quartiles of cumulative head impact exposure to assess if there were any significant differences between categories of head impact exposure (i.e., low vs. high). For change scores, positive changes reflect an increase from baseline to post-season, whereas negative change scores represent a decrease from baseline to post-season. From an exploratory standpoint, an interaction term was added to the models to probe whether psychological need satisfaction had influence on the relationship between head impact exposure and acute mental health outcomes. Data were checked for quality and accuracy by visually and descriptively examining variables, assessing assumptions (*i.e.*, normality, linearity, homoscedasticity, and multicollinearity), and log transformations were used when outliers were detected. Effect sizes using Cohen's f^2 and post-hoc power analyses were calculated. Analyses were performed in R 4.0.3, and the level of statistical significance was set to $p<0.008$ for objective 1 (post-season scores), 0.017 for objective 2 (change scores) after adjusting for Bonferroni corrections.

RESULTS

Ninety-one participants from four high schools wore sensor-installed mouthguards throughout the season and completed psychometric surveys at pre-season and post-season.

A total of 9,428 head impacts were recorded in the overall sample. The film validation of a randomly selected 1,785 head impacts (19%) resulted in 94% (n=1,670) of agreement between mouthguard data and film analysis (of the 6% of impacts that did not agree, 4% were from games and 2% from practices). Among the impacts video reviewed, 66% were from games, 34% from practices. Throughout the season, on average, participants sustained 102 ± 113 head impacts, 1,652 ± 1,895 *g*, and 117,602.4 ± 145,014.2 rad/s^2 cumulatively in a single season. The percentage of participants with scores ≥ 10 on the PHQ-9 was 4.4% for pre-season and 5.5% for post-season. For anxiety, 2.2% and 8.8% of participants scored ≥ 10 on GAD-7 at pre- and post-season, respectively; for thriving, participants had mean scores of 42.69 and 42.66 in the pre- and post-season, respectively. Demographic characteristics, head impact kinematic data, and psychological need satisfaction are presented in Table 1, and mental health symptom scales (PHQ-9, GAD-7, BIT) in Table 2. Bivariate correlations for study variables are presented in Supplemental Table 1.

Association between head impacts and post-season mental health outcomes

After adjusting for age and school, neither cumulative head impacts during the season nor age of first exposure was associated with post-season depressive symptoms, anxiety symptoms, or thriving scores. All statistical models in this section were sufficiently powered, except for the associations of thriving with age of first exposure and PLA. The results of the multiple linear regression analyses are presented in Table 3 (post-season outcomes) and Table 4 (change score outcomes). Cohen's f^2 effect sizes were small (0.05–0.14) and are reported in Table 3.

Effect of cumulative head impact exposure on mental health change scores

In addition to post-season scores for the mental health outcomes, we also examined change scores from pre- to post-season. Players' cumulative head impact exposure during the season did not have a statistically significant effect on the change in mental health scores between pre- and post-season, after controlling for age and school; these results are presented in Table 4. PLA, psychological needs satisfaction, and age were treated categorically in this subset of analyses to provide sufficient power after computing post-hoc power analyses. Cohen's f^2 effect sizes were small to moderate (0.14– 0.22) and were reported in Table 4.

Association between psychological need satisfaction and mental health post-season and pre- to post-season change scores

After accounting for age and school, results of the regression models indicated that greater psychological need satisfaction was associated with fewer depressive symptoms, fewer anxiety symptoms, and greater thriving scores at pre- and post-season (PHQ_{pre}: $\beta=-0.038$, SE=0.007, $p<.001$; GAD_{pre}: $\beta=-0.029$, SE=0.007, $p<.001$; BIT_{pre}: $\beta=0.245$, SE=0.030, $p<.001$; PHQ_{post}: $\beta=-0.035$, SE=0.008, $p<0.001$; GAD_{post}: $\beta=-0.021$, SE=0.008, $p=0.010$; BIT_{post}: $\beta=0.278$, SE=0.040, $p<0.001$). Cohen's f^2 effect sizes were moderate to large (0.22–0.82) and are reported in Table 5. When looking at change scores as the outcome, psychological need satisfaction no longer predicted depressive symptoms or anxiety symptoms. For thriving, those with the highest tertile of psychological need satisfaction scored significantly better than those with the lowest tertile of psychological need satisfaction scores ($\beta=3.55$, SE=1.29, $p=0.007$).

DISCUSSION

The current multisite study assessed the effect of head impact exposure and age of first exposure to tackle football on adolescent mental health symptoms while investigating the influence of psychological need satisfaction. There were three key findings from this study. First, season-long head impact exposure and age of first exposure to tackle football were not associated with post-season self-reported depression, anxiety or thriving ratings. Second, higher psychological need satisfaction predicted fewer depressive symptoms, fewer anxiety symptoms, and greater thriving scores at post-season. Third, mental health symptoms over the course of the 16-week season did not get worse in those who experienced greater head impact exposure. Taken together, these data do not support the premise that playing one season of high school tackle football is associated with worse mental health indicators, at least in the short term; nor do they support the premise that earlier age of first exposure is associated with decreased mental health indicators during adolescence.

Researchers are continuing to use different methods to assess the effects of head impact exposure in tackle football (*e.g.*, sensor-installed mouthguards, helmet mounted systems, age of first exposure to tackle football).[9,38] Across methodologies, many studies have found associations between these measures of head impact exposure and neurological, cognitive, behavioral, and neuropsychological dysfunction.[7–11] However, there is also a growing body of literature opposing that premise.[12–14,17,38] For example, two studies found socioeconomic status, race, and academic aptitude to outperform head impact exposure estimates in predicting neurocognitive scores, with no significant association between head impact exposure and neurocognitive outcomes.[41] Moreover, in a study of over 4,000 college football players, Caccese et al[13] did not find an association between age of first exposure and worse neurocognitive performance,[19] and results from Roberts et al[39] suggested earlier age of first exposure posed no greater risk for anxiety, depression, or cognitive impairment later in life. Our first key finding that neither acute (*i.e.*, one season) nor chronic head impact exposure (*i.e.*, age of first exposure) predicted worse acute mental health outcomes builds on the growing body of literature that does not support the notion that greater head impact exposure is associated with decreased neuropsychological outcomes in adolescent football players.

Our second key finding was that higher psychological need satisfaction predicted better mental health outcome scores at post-season. This supports the emphasis by Hutchison et al[23] that it is imperative to account for psychosocial modifiers or confounders such as self-esteem, need satisfaction, or confidence when studying the effects of head impact exposure on neurological and psychological outcomes. To our knowledge, this is the first study to incorporate self-determination theory (*i.e.*, psychological need satisfaction) as a critical component within a study of head impact exposure and acute mental health outcomes. In line with self-determination theory, this finding supports the importance of satisfying basic psychological needs in hopes of maintaining positive mental health in this sample of adolescent football players.

The rigor of our methods and findings is bolstered by our head impact measures via sensor-installed mouthguards. Studies have shown this technology to be superior in terms of correctly estimating head impact exposure, as helmet-mounted and head-mounted devices do not rigidly fit to the skull and have resulted in overestimation of head impact exposure errors ranging from 74% to 500% in dummy and human soccer heading models.[40,41] Sensor-installed mouthguards, such as the impact monitoring mouthguard used in this study, have shown superior validity in detecting true head impact events. In previous laboratory validation studies, both Kieffer et al[42] and Liu et al[43] reported that the impact monitoring mouthguard showed exceptionally high agreement between the sensor and reference measurements in a dummy model with less than 4% of errors, outperforming other devices by 10% to 28%. Our film validation result of 93.6% matches with a recent validation study's positive predictive value of 0.94,[30] which supported the validity of our findings. Additionally, since individual variance can account for up to 48% of variance in head impact exposure,[19] it may be critical to utilize head impact kinematic technology rather than proxy exposure estimates such as age of first exposure or other indices. Accordingly, the third key finding that greater cumulative season-long head impact exposure and psychological need satisfaction did not predict worse mental health outcomes over the course of the season portends to three possible reasons: (1) the study period of approximately 4 months is likely too short to detect significant short-term changes in mental health outcomes; (2) there is no clear mechanistic link between football head impacts and mental wellbeing in adolescents; or (3) external factors such as teams' morale, winning/losing season, and social lifestyle may play a nontrivial role in mental health outcomes.

The findings in this study should be interpreted within the study limitations. This study sample is predominantly white and non-Hispanic and the methodology should be replicated in a multisite, diverse setting including participants from underrepresented racial and ethnic backgrounds. Although a limitation of tackle football is that it is driven by male participation, it provides a valuable research environment due to the exponentially greater amount of head impacts occurring in larger sample sizes compared to other sports. Thus, the current findings may not extend to other populations (*i.e.*, across sexes and sports) but should be investigated further. Nevertheless, four schools participated in the current study, representing a range of team cultures and win-loss records, which supports the applicability of the findings. The present multisite study's cohort design with a one-year pre-post component is an improvement on many previous retrospective, cross-sectional study designs. However, a multi-year time frame in schools from diverse geographical and cultural background and using more sensitive and a broader range of psychological assessments is required to observe the longitudinal changes in mental and neurological health in adolescent football players. Additionally, while "age of first exposure" has been repeatedly used as a surrogate to estimate the chronic head impact effects on brain health, this type of self-reported measure is inherent to recall bias and not a precise measure of lifetime head impact exposures, though such a measure does not exist at moment. The lack of sensitivity in this proxy measure is highlighted by recent studies demonstrating that there is no association between age of first exposure to football and cognitive and mental declines in retired football players.[14,44]

In conclusion, this study does not support the premise that greater single season head impact exposure or earlier age of first exposure to football are associated with worse mental health indicators acutely during adolescence. Psychological satisfaction was related to positive mental health outcomes and should be considered for inclusion in future studies. These results point to similar multi-school assessments with a fundamental component of utilizing reliable head impact kinematic technology but with the addition of a multi-year time frame that may yield a more complete picture of the neuropsychological outcomes associated with exposure to head impacts.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

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Abbreviations:

PHQ	Patient Health Questionnaire-9
GAD	General Anxiety Disorder-7
BIT	Brief Inventory of Thriving
BPSNFS	Basic Psychological Needs Satisfaction and Frustration Scale
PLA	Peak Linear Acceleration

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IMPLICATIONS AND CONTRIBUTION

This study does not support the premise that greater single season head impact exposure or earlier age of first exposure to football in adolescence are associated with worse acute mental health indicators over the course of a single football season. Psychological need satisfaction was related to positive mental health outcomes and should be considered for future studies.

Table 1.

Demographic characteristics and descriptive statistics of predictor variables[a]

Variables	Overall	School A	School B	School C	School D
n	91	42	14	16	19
Sex (%)	91M (100.0)	42M (46.2)	14M (15.4)	16M (17.6)	19M (20.9)
Age, y	15.31 (1.0)	15.49 (1.1)	15.35 (1.0)	15.59 (1.0)	14.69 (0.7)
BMI, kg/m^2	26.1 ± 5.3	26.4 ± 5.2	25.8 ± 4.0	28.0 ± 6.9	23.8 ± 4.5
No. of previous concussion					
0, *n* (%)	77 (84.6)	38 (90.5)	11 (78.6)	12 (75.0)	16 (84.2)
1, *n* (%)	11 (12.1)	4 (9.5)	2 (14.3)	4 (25.0)	1 (5.3)
2, *n* (%)	3 (3.3)	0 (0.0)	1 (7.1)	0 (0.0)	2 (10.5)
Race, *n* (%)					
White	81 (89.0)	35 (85.4)	13 (92.9)	15 (93.8)	18 (90.0)
Black/African American	7 (7.7)	4 (9.8)	1 (7.1)	1 (6.3)	1 (5.0)
Asian	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)
American Indian or Alaska Native	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)
Native Hawaiian or Pacific Islander	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)
Multiracial	3 (3.3)	2 (4.9)	0 (0)	0 (0)	1 (5.0)
Ethnicity, *n* (%)					
Not Latino/Hispanic	85 (93.4)	36 (87.8)	13 (92.9)	16 (100)	20 (100)
Latino/Hispanic	6 (6.6)	5 (12.2)	1 (7.1)	0 (0)	0 (0)
Position Group					
Linemen (OL, DL)	33 (36.3)	15 (35.7)	5 (35.7)	8 (50.0)	5 (26.3)
Hybrid (RB, LB, TE)	31 (34.1)	12 (28.6)	6 (42.9)	7 (43.8)	6 (31.6)
Skill (WR, DB, QB)	27 (29.7)	15 (35.7)	3 (21.4)	1 (6.3)	8 (42.1)
Predictors of interest					
Age of first exposure to tackle football (AFE)	10.9 (3.0)	11.22 (3.0)	11.5 (2.1)	8.4 (3.0)	11.7 (2.5)
Cumulative impact count per player	101.8 (112.8)	129.9 (126.6)	84.5 (80.7)	70.4 (73.7)	81.3 (120.7)
Season-long cumulative peak linear acceleration (PLA) per player, *g*	1,652.4 (1,894.6)	2,156.4 (2,225.6)	1411.3 (1402.2)	1081.2 (1123.6)	1245.1 (1786.6)
Season-long cumulative peak rotational acceleration per player, rad/s^2	117,602.4 (145,014.2)	157,337.6 (170,419.1)	88,435.1 (79,266.6)	65043.3 (65120.7)	98,609.7 (155,184.7)
Psychological need satisfaction, pre-season	97.6 (11.0)	98.7 (11.7)	98.5 (11.8)	98.8 (11.1)	93.8 (8.3)

Note: BMI, body mass index. OL, offensive line. DL, defensive line. RB, running back. LB, linebacker. TE, tight end. WR, wide receiver. DB, defensive back. QB, quarterback.

[a]Continuous variables reported by mean (SD); categorical variables reported by number (%).

Table 2.

Change scores, pre-season, and post-season for mental health outcomes

	Overall	School A	School B	School C	School D
Pre-season scores					
PHQ-9	2.33 (3.52)	2.59 (4.49)	2.07 (2.53)	1.81 (2.20)	2.40 (2.76)
GAD-7	1.91 (2.62)	1.93 (2.61)	1.21 (1.53)	2.31 (3.30)	2.05 (2.72)
BIT	42.69 (4.09)	43.44 (3.99)	41.71 (3.60)	42.75 (4.42)	41.80 (4.31)
Post-season scores					
PHQ-9	2.79 (4.43)	2.15 (3.54)	1.29 (2.13)	5.06 (6.79)	3.35 (4.45)
GAD-7	2.41 (3.75)	1.68 (2.62)	1.14 (1.75)	3.75 (5.29)	3.70 (4.75)
BIT	42.66 (5.07)	43.39 (5.10)	42.64 (4.41)	40.81 (4.79)	42.65 (5.62)
Change Scores					
PHQ-9	0.46 (4.08)	−0.44 (3.54)	−0.79 (1.31)	3.25 (6.45)	0.95 (2.93)
GAD-7	0.49 (2.98)	0.24 (2.27)	−0.07 (1.14)	1.44 (3.98)	1.65 (3.79)
BIT	−0.03 (4.97)	−0.05 (4.51)	0.93 (3.12)	−1.94 (7.47)	0.85 (4.33)

Note: PHQ-9, Patient Health Questionnaire-9. GAD-7, General Anxiety Disorder-7. BIT, Brief Inventory of Thriving. Values presented as mean (SD).

Table 3.

Regression results of primary predictors of interest for post-season mental health outcomes.

	Age of First Exposure (AFE)			Cumulative Peak Linear Acceleration (PLA)		
	β (SE), *p*-value					
Model number	**1**	**2**	**3**	**4**	**5**	**6**
Depressive symptoms	0.048 (0.035), 0.166			−0.085 (0.068), 0.215		
Anxiety symptoms		0.015 (0.033), 0.644			−0.079 (0.064), 0.221	
Thriving			−0.221 (0.197), 0.265			0.400 (0.388), 0.305
Multiple R^2	0.112	0.110	0.051	0.108	0.123	0.049
Effect size (f^2)	0.126	0.124	0.054[a]	0.124	0.140	0.053[a]

Note: SE = standard error.

* $p < .05$;

** $p < .01$;

*** $p < .001$.

a = underpowered models.

See Supplemental Table 2 for full regression model results for mental health outcomes at post-season.

Table 4.

Regression results of primary predictors association to changes in mental health outcomes.

	Cumulative Peak Linear Acceleration (PLA)					
	Quartile 1 (14.8–362.8g)	**Quartile 2 (362.8–977.3g)**	**Quartile 3 (977.3–2520.6g)**	**Quartile 4 (2520.6–10964.7g)**	**R^2**	**Effect size (f^2)**
Depressive symptoms	.08 (.23), .720	−.02 (.24), .943	.02 (0.23), .925	-	.178	.22
Anxiety symptoms	.02 (.24), .944	−.50 (.24), .040	−.33 (.23), .164	-	.140	.16
Thriving	.34 (1.55), .826	−.03 (1.59), .986	1.52 (1.53), .324	-	.116	.14

Note: Values presented as β (SE), *p*-value. SE = standard error.

* $p < .05$;

** $p < .01$;

*** $p < .001$.

See Supplemental Table 3 for full regression model results for changes in mental health outcomes.

Table 5.

Regression results for association of psychological need satisfaction to mental health outcomes.

	Pre-season			Post-season		
Depressive symptoms	−0.038 (0.007), <001 ***	-	-	−0.035 (0.008), <001 ***	-	-
Anxiety symptoms	-	−0.029 (0.007), <001 ***	-	-	−0.021 (0.008), 0.010 **	-
Thriving	-	-	0.245 (0.030), <0.001 ***	-	-	0.278 (0.040), <0.001 ***
R^2	.32	.24	.45	.25	.18	.38
Effect size (f^2)	.47	.32	.82	.34	.22	.62

Note: Values presented are: β (SE), *p*-value. SE = standard error.

* $p < .05$;

** $p < .01$;

*** $p < .001$.