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S.I. : Concussions

Association Between Head Impact Biomechanics and Physical Load in College Football

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Abstract—Head impacts and physical exertion are ubiquitous in American football, but the relationship between these factors is poorly understood across a competitive season or even within an individual session. Gameplay characteristics, including player position and session type, may contribute to these relationships but have not been prospectively examined. The current study aimed to determine if an association exists between head impact biomechanics and physical load metrics. We prospectively studied college football players during the 2017–2021 football seasons across representative playing positions (15 offensive and defensive linemen, 11 linebackers and tight ends, and 15 defensive backs, running backs, and receivers). Participants wore halters embedded with Catapult Vector GPS monitoring systems to quantify player load and participant helmets were equipped with the Head Impact Telemetry System to quantify head impact biomechanics and repetitive head impact exposure (RHIE). Generalized linear models and linear regression models were employed to analyze in-session and season-long outcomes, while addressing factors such as player position and session type on our data. Player load was associated with RHIE ($p < 0.001$). Season-long player load predicted season-long RHIE ($R^2 = 0.31$; $p < 0.001$). Position group affected in-session player load ($p = 0.025$). Both player load and RHIE were greater in games than in practices ($p < 0.001$), and position group did not affect RHIE ($p = 0.343$). Physical load burden was associated with RHIE within sessions and across an entire season. Session type affected both RHIE and player load, while position group only affected player load. Our data point to tracking physical load burden as a potential proxy for monitoring anticipated RHIE during the season.

Keywords—Concussion, Mechanics, Mild traumatic brain injury, Performance, Physical stress, Wearable sensors.

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INTRODUCTION

The potential short and long-term risks for sustaining repetitive head impacts among American football players are growing concerns for sports medicine clinicians and researchers. Seventy thousand high school athletes and 4000 Division I college athletes will annually sustain a concussion during football participation.[9] Given these prevalence values, football has received significant public attention amid nascent evidence that repetitive head impact exposure (RHIE) sustained during participation are associated with long-term psychological[18] and neurodegenerative outcomes.[26] More recently, several reports suggest a potential link between concussion incidence and increased musculoskeletal injury risk.[14,17,22,23] The clinical implications for these findings highlight the need to examine the associations between RHIE and physical load burden experienced by athletes during regular participation throughout a competitive football season.

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Preliminary evidence linking concussion incidence and musculoskeletal injury risk has recently emerged but is poorly understood.[17,23] Thus, any study seeking to associate RHIE with physical load burden among healthy college football players would be an important contribution to a literary body that will seek to understand the mechanistic and physiological underpinnings of this clinical phenomenon.[25] Existing technologies permit scientists to begin studying the association between physical load burden and RHIE. Head impact monitoring systems [e.g., Head Impact Telemetry (HIT) System] can measure linear and rotational accelerations imposed from head/-body impact events. The more popular systems are either helmet- or mouthguard-bases systems, and they have been extensively employed in college football settings.[3,4,16] Additionally, commercially available physical load tracking technologies are also pervasive throughout college athletes. This may include Global Positioning System (GPS) technology to track—and then compute—physical load metrics during training sessions or other routine sports participation.[2,13] Thus, combining these technologies—head impact monitoring and physical load tracking—may readily combine two dynamic and powerful data structures together to elucidate potential external mechanisms for concussion, musculoskeletal injuries, or the association between the two. Importantly, we know that evidence pertaining to both RHIE and physical load burden can be translated into impactful interventions, and policy changes benefiting athlete health and safety by reducing concussion and musculoskeletal injury risks.[2,34] Additionally, while the available evidence has linked post-injury data,[27] little information is available to address the pre-injury relationships that may inform injury risk reduction strategies, including practice planning, scheduling, and effective player monitoring.[3,13]

Therefore, the purposes of this study were to (1) determine the association between RHIE and physical load burden within individual sessions and across a season, and (2) examine gameplay characteristics (position, session type) that may influence these associations. The association between RHIE and physical load burden during American football is not fully understood and our study presents a unique approach to converging these two important domains together.

MATERIALS AND METHODS

Study Design and Participants

We prospectively studied 41 male Division I college varsity football players (Table 1) across four competitive seasons (2017–2019, 2021). Athletes during this time initially consented to participate in a study related to head impact biomechanics that was previously approved by our institution's Office of Human Research Ethics. We also included in our analyses the athletes within this cohort for whom we were also able to recover physical load tracking data, a metric captured by our institution's strength and conditioning team as part of the athlete's routine sport involvement, which was standard for most players in our football program. We were permitted to merge the two data elements (physical load and head impacts) under a protocol approved as exempt non-human subjects' research. The 2020 season was excluded due to limited research capabilities during COVID-19.

TABLE 1. Mean and standard deviation (mean ± SD) for participant height and mass across position groups for 41 total participants contributing data from 53 player-seasons.

Position groups	*N*	Height (cm)	Mass (kg)
BIGS	15	194.9 ± 4.4	136.9 ± 7.7
BIG SKILL	11	189.3 ± 2.5	109.2 ± 6.4
SKILL	15	181.7 ± 4.9	86.8 ± 4.4
Total	41	188.5 ± 7.0	111.2 ± 22.4

Instrumentation

Head Impact Telemetry (HIT) System

The HIT System (Riddell, Elyria, OH) collected head impact kinematic data and was composed of an accelerometer array and the Sideline Response System. The accelerometer array included six spring-loaded single-axis accelerometers and was fitted appropriately into a Riddell helmet. The accelerometers were triggered to begin collecting at 1 kHz for 40 ms (8 ms pre-trigger and 32 ms post-trigger) once a single accelerometer detected a linear acceleration exceeding 9.6 g. The accelerometers then transmitted these data in real-time to the Sideline Response System, which stored all the data related to each head impact event. Data were routed through a company-owned (Riddell) proprietary cloud-based filtering/processing pipeline to populate peak resultant linear acceleration, peak resultant rotational acceleration, and head impact location before being available for data export and analysis. The accelerometer units were visually verified daily to ensure functionality and inspected weekly during regular helmet maintenance throughout the season.[4]

Catapult Vector

The Catapult Vector GPS monitoring system collected physical load variables and comprised small, compact units embedded in halters worn by each study participant during regular participation (Fig. 1). These units use either Local Positioning System (LPS) to

FIGURE 1. The Catapult Vector GPS monitoring system collects physical load data through embedded compact units worn in halters by each study participant during regular participation.

collect indoor measurements at 10 Hz, and GPS to collect outdoor measurements at 18 Hz. The data collection platform and software extracted the raw data, performed proprietary post-processing, and computed session-specific outcomes related to total player load, load rate, and session time.[20] The Catapult Vector system has excellent intra- and inter-device accuracy and reliability.[30]

Procedures

Research team members ensured the HIT System and Sideline Response System components, including individual helmet sensors, batteries, and computer software, were maintained throughout the season. In addition, our staff monitored all sustained head impacts and ensured that the HIT System's Sideline Response System was operational throughout each session. If we were unable to set up and operationalize the Sideline Response System (e.g., inclement weather, lack of access to power, *etc*.), all head impact data were collected and stored in non-volatile memory directly on the accelerometer units and later downloaded to the software. Our institution's strength and conditioning team maintained the Catapult Vector system and ensured the units were operational and correctly worn by athletes during each session throughout the study period.

Data Reduction

For session-specific comparisons, we computed RHIE using Stemper *et al*. methods[35] by employing the following equation:

$$\sum \frac{1}{1 + e^{-(-10.2+0.0433*\ddot{x}+0.000873*\ddot{\theta}-0.000000920*\ddot{x}*\ddot{\theta})}}$$

where $\ddot{x}$ and $\ddot{\theta}$ are the impact event's recorded linear and rotational accelerations, respectively.[35] Session RHIE included the sum of all impacts sustained by the participant during a single session. The Catapult Vector GPS system computed session-based physical load data and were retained in their current form in our analyses. To obtain RHIE across the season, we calculated the sum of RHIE values into a season-long RHIE outcome. Similarly, player load data were summed across the season for each player to derive a cumulative season-long player load outcome.

All available data were merged to create a single analysis dataset, then reduced to correct for any imbalances or missing data. Quarterbacks, kickers, and punters were removed from the data set due to the small number of impacts sustained during gameplay compared to other groups.[28] Any individual sessions that did not contain simultaneous data for each collection device were excluded. Additionally, participants without both head impact or GPS-tracking data for at least half the season (through October 15th) were excluded. Furthermore, all data from extraneous practice sessions (i.e., summer camp, pregame and Sunday walkthrough practices, *etc*.) were removed. Head impacts measured by the HIT System were time-stamped, and therefore any impacts recorded outside of the indicated session time boundary were excluded. Finally, any major outliers ($\geq$ 3 standard deviations) were removed from the dataset.

Statistical Analyses

For our primary study purpose, we employed generalized linear mixed models (PROC MIXED) to predict RHIE from total player load across a single session and an entire season. These methods were used to analyze longitudinal data efficiently and comprehensively, especially when there may be missing data. For our secondary purpose, we employed linear regression models (PROC REG) to determine the association between gameplay characteristics (session type and position groups) on total player load and RHIE within a session. Position groups were assigned based on prior literature[15] as follows: BIGS were offensive and defensive linemen, SKILL were defensive backs, receivers, and running backs, and BIG SKILL were linebackers and tight ends. Player position (BIGS, SKILL, BIG SKILL), session type (practice, game), and player load (computed by Catapult Vector GPS monitoring system) were independent variables; session and season RHIE (computed from HIT System metrics as described above) were the dependent variables. We used an a priori alpha level of 0.05 and conducted all analyses using SAS 9.4 (SAS Institute, Cary, NC).

RESULTS

In total, 41 players contributed 2330 unique sessions, with 27,349 total head impacts recorded. Session frequencies, cumulative player load, and cumulative RHIE for each individual player are presented in Table 2 across all games, practices, and combined (game and practices). We observed that total player load was significantly associated with RHIE ($F_{1,1688} = 15.99$; $p < 0.0001$) such that when the total in-session player load increased, there was also an increased in-session RHIE. Season-long cumulative player load significantly predicted season-long RHIE ($R^2 = 0.31$; $F_{1,39} = 18.79$; $p < 0.0001$). Within this model, season-long cumulative player load explained 31% of the variability in season-long RHIE.

There was a significant effect of position on in-session total player load ($F_{2,1689} = 3.72$; $p = 0.025$) driven largely by SKILL players exhibiting greater player load than BIGS ($t_{1689} = -2.45$; $p = 0.038$) (Fig. 2). No significant differences between the other position groups were identified ($p > 0.05$). Session type had a significant effect on in-session total player load ($F_{2,1687} = 213.10$; $p < 0.0001$), such that game player load was significantly greater than player load in practices ($t_{1687} = 20.63$; $p < 0.001$). There was no significant effect of position group on in-session RHIE ($F_{2,1689} = 1.07$; $p = 0.343$); however, we observed a significant effect of session type on in-session RHIE ($F_{2,1687} = 17.90$; $p < 0.001$), such that game RHIE was significantly greater than practice RHIE ($t_{1687} = 5.97$; $p < 0.001$).

DISCUSSION

Our unique findings contribute to nascent evidence examining the intersection between player load and RHIE during gameplay. We hypothesized that a higher total player load would be associated with an increased RHIE in college football athletes. Physical load burden was associated with an increase in RHIE within individual sessions and across a season, supporting our hypothesis. In short, our data suggest an athlete may be more likely to sustain a greater head impact burden concomitant with increased physical load. While this seems intuitive (i.e., more engagement, more risk for head impact exposure), we did not observe this trend across all position groups. For example, linemen are exposed to multiple low-level head impacts during plays that are typically short closing distance plays. This playstyle can be markedly different from other playing positions where fewer head impacts—if any—are experienced during practice, and impacts (and associated physical load metrics) tend to represent longer closing distance plays. Therefore, we submit

TABLE 2. Mean and standard deviation (mean ± SD) for session frequency, season-long cumulative physical load, and season-long repetitive head impact exposure (RHIE) across session types (game, practice, and combined) for all 41 participants.

Variables	Game	Practice	Combined
Session frequency	10.7 ± 5.3	31.3 ± 14.0	41.8 ± 19.0
Cumulative player load	4791.5 ± 2972.4	10,179.3 ± 5299.1	14,878.3 ± 7963.4
Cumulative RHIE	1.1 ± 1.3	1.4 ± 2.0	2.5 ± 2.8

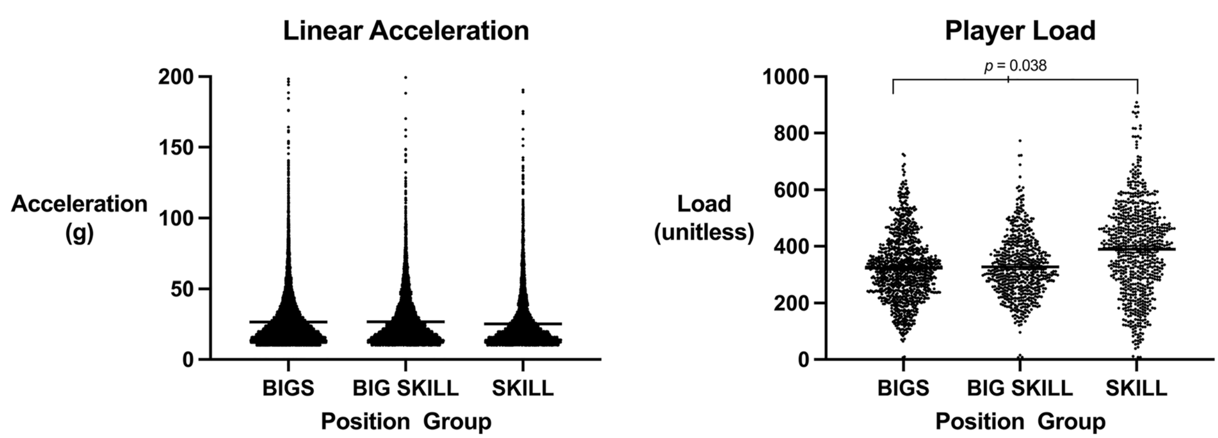

FIGURE 2. Data distribution for linear acceleration and physical load across the three playing position groups (BIGS, BIG SKILL, and SKILL). Significant differences between playing position were observed for physical load.

that a player's individual variability is affected by many factors that can influence their sustained physical load burden and RHIE.

Receivers and defensive backs had greater player load than linemen, which is consistent with literature as receivers and defensive backs travel further distances at higher speeds during gameplay than linemen.[10,36] Player load is a metric calculated by Catapult that considers horizontal accelerations, which are expected to be much higher in receivers and defensive backs as they travel further downfield on most plays when compared to linemen who mostly remain at the line of scrimmage.[1] Our analysis predicted receivers and defensive backs would endure greater RHIE based on the significance of their in-session and season-long player load compared with linemen. However, we found no significant differences between position groups for RHIE. These findings are inconsistent with previous research demonstrating linemen endure the greatest head impact frequency, which ultimately results in a greater RHIE.[7,8,28] Our model demonstrated that approximately 31% of the variability in season-long RHIE was explained by player load. While statistically significant, we must acknowledge that 69% of our model's variability is likely due to other factors we did not account for in our analyses. Anthropometrical differences are thought to affect physical load in college football players,[33] and therefore may also play a role in RHIE variability across a season. Other potential factors contributing to RHIE may include session intensity,[3,28] physical fatigue,[33] and activity and drill types. For example, individual and team drills are likely to have differing effects on player RHIE.[5]

Game sessions exhibited significantly higher player load outcomes than practice sessions. Previous research has compared player load values using GPS player-tracking in preseason practices, in-season practices, and games, finding that games exhibited the highest player load outcomes.[10,19,36] In our data analysis, game sessions were found to average around 4 h in length, with the average practice session between 2 and 2.5 h. In Australian football, a 30% reduction in session duration was associated with a concurrent 30% reduction in player load.[32] Session duration must be considered when determining which factors contribute to an increased in-session player load. Additionally, practices were previously characterized by less distance covered, smaller movement velocities, fewer accelerations, and fewer total head impacts than games in rugby athletes.[19] Similarly, in college football, more head impacts are sustained in games than during practices on a per-event basis.[7,21] This agrees with our findings that RHIE is higher in games than in practices for college football players. Given that RHIE accumulates based on both head impact frequency and magnitude within a session (or across a season), these findings can most likely be attributed to the intensity at which games are played relative to the typical practice session.

Limitations

This study has several limitations that must be considered. First, the current sample was limited to only one college football program. It may not have been reflective of a heterogeneous group of Division I college football players, nor can it be generalized to players at the professional, high school, or youth levels. While the instrumentation we employed is commonly used in the our pragmatic study environment and often cited in scientific studies, it is possible the HIT System and Catapult Vector systems may underestimate their respective metrics, which respectively served as the primary independent and dependent variables for the current study.[20,31] Catapult can underestimate loads by up to 15%,[30] while the HIT System detects around 70% of on-field head impacts.[4] This further demonstrates the need to investigate these associations within a larger sample size or by using video-confirmed head impacts. Furthermore, each participant's playing status may have changed during the study period and we were unable to accurately track this status in such a way as to appropriately inform our study analyses and results interpretation. Starters would have more playing time during games and likely receive more repetitions in practices, which may have led to position groups with unequal playing time distributions. Site-specific coaching strategies may also influence our study findings. For example, our study sample is derived from a program that has strategically placed outside linebackers on the line of scrimmage (in a 3-point stance) and requires from them similar responsibilities as a defensive lineman. The HIT System can only be installed in select Riddell football helmets; thus, our findings cannot represent players who wear different helmet brands and/or models incapable of accommodating the HIT System.

Practical Applications

The findings from this study have real-world implications on how we should manage player load over time and how this may affect head impact injury prevention. Physical load tracking is pervasive across college athletics and is not unique to football. Understanding the intersection between physical load and head impact burden can have far-reaching implications to other levels of football participation and many other sports. With further study, we posit physical load tracking may innovatively inform both RHIE and physical load burden during preseason practices, as well as regular season events, in such a manner as to provide real-time modifications that may mitigate concussion and musculoskeletal injury risk. Our authorship group believes this approach may currently be more pragmatic across multiple practices and games (e.g., 1, 2, or 3 weeks, *etc.*) than within an individual session. Our findings also apply to medical providers monitoring athletes returning to sport following concussion or musculoskeletal injury. This study contributes to the growing body of literature that non-injury data collection has made to improve competitive sports safety.

Conclusions

An objective approach to quantify sustained head impact burden and physical load burden during American football may provide actionable metrics for healthcare providers and other sports medicine team members. Based on our findings, RHIE was associated with physical load in individual sessions and throughout a competitive season among Division I college football athletes. Furthermore, the effect of position groups and session type on RHIE should be further investigated to establish well-defined associations in these and other populations. Physical load data obtained from player tracking technologies may provide clinicians and researchers insight into head impact burden and more effective player monitoring to reduce total head impact biomechanics sustained by college football players.

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CITATION DIVERSITY STATEMENT

Recent work in several fields of science has identified a bias in citation practices such that papers from women and other minority scholars are under cited relative to the number of papers in the field.[6,11,12,24,29] We recognize this bias and have worked diligently to ensure that we are referencing appropriate papers with fair gender and racial author inclusion.

REFERENCES

1. Baugh, C. M., P. T. Kiernan, E. Kroshus, D. H. Daneshvar, P. H. Montenigro, A. C. McKee, and R. A. Stern. Frequency of head-impact related outcomes by position in NCAA division I collegiate football players. *J. Neurotrauma*. 32:314–326, 2014.
2. Bourdon, P. C., M. Cardinale, A. Murray, P. Gastin, M. Kellmann, M. C. Varley, T. J. Gabbett, A. J. Coutts, D. J. Burgess, and W. Gregson. Monitoring athlete training loads: consensus statement. *Int. J. Sports. Physiol. Perform*. 12:S162-161-S162-170, 2017.
3. Broglio, S. P., R. M. Williams, K. L. O'Connor, and J. Goldstick. Football players' head-impact exposure after limiting of full-contact practices. *J. Athl. Train*. 51:511–518, 2016.
4. Campbell, K. R., S. W. Marshall, J. F. Luck, G. F. Pinton, J. D. Stitzel, J. S. Boone, K. M. Guskiewicz, and J. P. Mihalik. Head impact telemetry system's video-based impact detection and location accuracy. *Med. Sci. Sports. Exerc*. 52:2198–2206, 2020.
5. Campolettano, E. T., S. Rowson, and S. M. Duma. Drill-specific head impact exposure in youth football practice. *J. Neurosurg. Pediatr*. 18:536–541, 2016.
6. Caplar, N., S. Tacchella, and S. Birrer. Quantitative evaluation of gender bias in astronomical publications from citation counts. *Nat. Astron*. 1:1–5, 2017.
7. Crisco, J. J., R. Fiore, J. G. Beckwith, J. J. Chu, P. G. Brolinson, S. Duma, T. W. McAllister, A.-C. Duhaime, and R. M. Greenwald. Frequency and location of head impact exposures in individual collegiate football players. *J. Athl. Train*. 45:549–559, 2010.
8. Crisco, J. J., B. J. Wilcox, J. G. Beckwith, J. J. Chu, A.-C. Duhaime, S. Rowson, S. M. Duma, A. C. Maerlender, T. W. McAllister, and R. M. Greenwald. Head impact exposure in collegiate football players. *J. Biomech*. 44:2673–2678, 2011.
9. Daniel, R. W., S. Rowson, and S. M. Duma. Head impact exposure in youth football. *Ann. Biomed. Eng*. 40:976–981, 2012.
10. DeMartini, J. K., J. L. Martschinske, D. J. Casa, R. M. Lopez, M. S. Ganio, S. M. Walz, and E. E. Coris. Physical demands of national collegiate athletic association division I football players during preseason training in the heat. *J. Strength Cond. Res*. 25:2935–2943, 2011.
11. Dion, M. L., J. L. Sumner, and S. M. Mitchell. Gendered citation patterns across political science and social science methodology fields. *Polit. Anal*. 26:312–327, 2018.
12. Dworkin, J. D., K. A. Linn, E. G. Teich, P. Zurn, R. T. Shinohara, and D. S. Bassett. The extent and drivers of gender imbalance in neuroscience reference lists. *Nat. Neurosci*. 23:918–926, 2020.
13. Edwards, T., T. Spiteri, B. Piggott, G. G. Haff, and C. Joyce. A narrative review of the physical demands and injury incidence in American football: application of current knowledge and practices in workload management. *Sports Med*. 48:45–55, 2018.
14. Fino, P. C., L. N. Becker, N. F. Fino, B. Griesemer, M. Goforth, and P. G. Brolinson. Effects of recent concussion and injury history on instantaneous relative risk of lower

extremity injury in division I collegiate athletes. *Clin. J. Sport. Med.* 29:218–223, 2019.
[15]Ford, J. M., K. R. Campbell, C. B. Ford, K. E. Boyd, D. A. Padua, and J. P. Mihalik. Can functional movement assessment predict football head impact biomechanics? *Med. Sci. Sports. Exerc.* 50:1233–1240, 2018.
[16]Funk, J. R., S. Rowson, R. W. Daniel, and S. M. Duma. Validation of concussion risk curves for collegiate football players derived from HITS data. *Ann. Biomed. Eng.* 40:79–89, 2012.
[17]Gilbert, F. C., G. T. Burdette, A. B. Joyner, T. A. Llewellyn, and T. A. Buckley. Association between concussion and lower extremity injuries in collegiate athletes. *Sports Health.* 8:561–567, 2016.
[18]Halstead, M. E., K. D. Walter, K. Moffatt, M. Council on Sports and Fitness. Sport-related concussion in children and adolescents. *Pediatrics.* 142:e20183074, 2018.
[19]Higham, D. G., D. B. Pyne, J. M. Anson, W. G. Hopkins, and A. Eddy. Comparison of activity profiles and physiological demands between international rugby Sevens matches and training. *J. Strength Cond. Res.* 30:1287–1294, 2016.
[20]Hoppe, M. W., C. Baumgart, T. Polglaze, and J. Freiwald. Validity and reliability of GPS and LPS for measuring distances covered and sprint mechanical properties in team sports. *PLoS ONE.* 13:e0192708, 2018.
[21]Houck, Z., B. Asken, R. Bauer, J. Pothast, C. Michaudet, and J. Clugston. Epidemiology of sport-related concussion in an NCAA division I football bowl subdivision sample. *Am. J. Sports. Med.* 44:2269–2275, 2016.
[22]Lynall, R. C., T. C. Mauntel, D. A. Padua, and J. P. Mihalik. Acute lower extremity injury rates increase after concussion in college athletes. *Med. Sci. Sports. Exerc.* 47:2487–2492, 2015.
[23]Lynall, R. C., T. C. Mauntel, R. T. Pohlig, Z. Y. Kerr, T. P. Dompier, E. E. Hall, and T. A. Buckley. Lower extremity musculoskeletal injury risk after concussion recovery in high school athletes. *J. Athl. Train.* 52:1028–1034, 2017.
[24]Maliniak, D., R. Powers, and B. F. Walter. The gender citation gap in international relations. *Int. Organ.* 67:889–922, 2013.
[25]McPherson, A. L., T. Nagai, K. E. Webster, and T. E. Hewett. Musculoskeletal injury risk after sport-related concussion: a systematic review and meta-analysis. *Am. J. Sports Med.* 47:1754–1762, 2019.
[26]Mez, J., D. H. Daneshvar, P. T. Kiernan, B. Abdolmohammadi, V. E. Alvarez, B. R. Huber, M. L. Alosco, T. M. Solomon, C. J. Nowinski, L. McHale, K. A. Cormier, C. A. Kubilus, B. M. Martin, L. Murphy, C. M. Baugh, P. H. Montenigro, C. E. Chaisson, Y. Tripodis, N. W. Kowall, J. Weuve, M. D. McClean, R. C. Cantu, L. E. Goldstein, D. I. Katz, R. A. Stern, T. D. Stein, and A. C. McKee. Clinicopathological evaluation of chronic traumatic encephalopathy in players of American football. *JAMA.* 318:360–370, 2017.
[27]Mihalik, J., A. Chandran, J. Powell, P. Roby, K. Guskiewicz, B. Stemper, A. Shah, S. Rowson, S. Duma, J. Harezlak, L. Riggen, S. Broglio, T. McAllister, and M. McCrea. Do head injury biomechanics predict concussion clinical recovery in college American football players? *Ann. Biomed. Eng.* 48:2555–2565, 2020.
[28]Mihalik, J. P., D. R. Bell, S. W. Marshall, and K. M. Guskiewicz. Measurement of head impacts in collegiate football players: an investigation of positional and event-type differences. *Neurosurgery.* 61:1229–1235, 2007.
[29]Mitchell, S. M., S. Lange, and H. Brus. Gendered citation patterns in international relations journals. *Int. Stud. Perspect.* 14:485–492, 2013.
[30]Nicolella, D. P., L. Torres-Ronda, K. J. Saylor, and X. Schelling. Validity and reliability of an accelerometer-based player tracking device. *PLoS One.* 13:e0191823, 2018.
[31]O'Connor, K. L., S. Rowson, S. M. Duma, and S. P. Broglio. Head-impact measurement devices: a systematic review. *J. Athl. Train.* 52:206–227, 2017.
[32]Ritchie, D., W. G. Hopkins, M. Buchheit, J. Cordy, and J. D. Bartlett. Quantification of training and competition load across a season in an elite Australian football club. *Int. J. Sports. Physiol. Perform.* 11:474–479, 2016.
[33]Sampson, J. A., A. Murray, S. Williams, T. Halseth, J. Hanisch, G. Golden, and H. H. K. Fullagar. Injury risk-workload associations in NCAA American college football. *J. Sci. Med. Sport.* 21:1215–1220, 2018.
[34]Stemper B. D., A. S. Shah, J. Harezlak, S. Rowson, S. Duma, J. P. Mihalik, L. D. Riggen, A. Brooks, K. L. Cameron, C. C. Giza, M. N. Houston, J. Jackson, M. A. Posner, G. McGinty, J. DiFiori, S. P. Broglio, T. W. McAllister, M. McCrea, A. M. Hoy, J. B. Hazzard, L. A. Kelly, J. D. Ortega, N. Port, M. Putukian, T. D. Langford, R. Tierney, C. C. Giza, J. T. Goldman, H. J. Benjamin, T. Buckley, T. W. Kaminski, J. R. Clugston, J. D. Schmidt, L. A. Feigenbaum, J. T. Eckner, K. Guskiewicz, J. P. Mihalik, J. D. Miles, S. Anderson, C. L. Master, M. Collins, A. P. Kontos, J. J. Bazarian, S. P. O. Chrisman, A. Brooks, J. Jackson, G. McGinty, P. O'Donnell, K. Cameron, M. N. Houston, A. Susmarski, S. Duma, S. Rowson, C. T. Bullers, C. M. Miles, B. H. Dykhuizen, L. Lintner and C. C. I. and The Repetitive head impact exposure in college football following an NCAA rule change to eliminate two-a-day preseason practices: a study from the NCAA-DoD CARE consortium. *Ann. Biomed. Eng.* 47:2073–2085, 2019.
[35]Stemper, B. D., A. S. Shah, J. P. Mihalik, J. Harezlak, S. Rowson, S. Duma, L. D. Riggen, A. Brooks, K. L. Cameron, C. C. Giza, J. Goldman, M. N. Houston, J. Jackson, G. McGinty, S. P. Broglio, T. W. McAllister, and M. McCrea. Head impact exposure in college football after a reduction in preseason practices. *Med. Sci. Sports. Exerc.* 52:1629–1638, 2020.
[36]Wellman, A. D., S. C. Coad, G. C. Goulet, and C. P. McLellan. Quantification of competitive game demands of NCAA division I college football players using global positioning systems. *J. Strength Cond. Res.* 30:11–19, 2016.