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## ABSTRACT

**Objectives:** To determine injury risk-workload associations in collegiate American Football.

**Design:** Retrospective analysis

**Methods:** Workload and injury data was recorded from 52 players during a full NCAA football season. Acute, chronic, and a range of acute:chronic workload ratios (ACWR: 7:14, 7:21 and 7:28 day) calculated using rolling and exponentially weighted moving averages (EWMA) were plotted against non-contact injuries (regardless of time lost or not) sustained within 3- and 7-days. Injury risks were also determined relative to position and experience.

**Results:** 105 non-contact injuries (18 game- and 87 training-related) were observed with almost 40% sustained during the pre-season. 7-21 day EWMA ACWR's with a 3-day injury lag were most closely associated with injury ($R^2$=0.54). Relative injury risks were >3× greater with high compared to moderate and low ratios and magnified when combined with low 21-day chronic workloads (injury probability = 92.1%). Injury risks were similar across positions. 'Juniors' presented *likely* and *possibly* increased overall injury risk compared to 'Freshman' (RR: 1.94, CI 1.07-3.52) and 'Seniors' (RR: 1.7, CI 0.92-3.14), yet no specific ACWR–experience or –position interactions were identified.

**Conclusion:** High injury rates during college football pre-season training may be associated with high acute loads. In-season injury risks were greatest with high ACWR and evident even when including (more common and less serious) non-time loss injuries. Substantially increased injury risks when low 21-day chronic workloads and concurrently high EWMA ACWR highlights the importance of load management for individuals with chronic game- (non-involved on game day) and or training (following injury) absences.

**Key Terms:** Muscle Injuries, Load monitoring, Injury prevention, GPS Playerload

## Introduction

American Collegiate football (NCAA) teams have a responsibility to take measures to protect student athletes' health and welfare whilst maximising their athletic preparation to optimise performance.[1] Injury reduction strategies are thus paramount. However, injury rates as high as 36 per 1000 athletic exposures (AE's) have been reported, with more than 25% of these injuries attributed to preventable non-contact events.[2] Injuries appear to be more common during the American Football pre-season and have been empirically associated with the high workloads applied within training camps.[2, 3] To combat this, it has become commonplace to monitor athletic workloads in team sports to manage fatigue, overtraining, injury risk and optimise individual adaptation through micro-electrico-mechanical systems including global positioning systems (GPS) and built in inertial measurement units (IMU).[4]

Accelerometer data is often used to provide a holistic view of workloads in NCAA football. However, to our knowledge only one study has reported directly on the association between workloads and injury in NCAA football.[5] In this study, injury risks were decreased with high average season workloads and increased when monotonous inertial training loads determined from the variability in session PlayerLoad$^{TM}$, (a combination of three dimensional velocity and acceleration; Catapult Innovations, Melbourne, Australia) were observed.[5] However, whilst high loads are known to protect against injury,[6, 7] one should consider that the PlayerLoad$^{TM}$ algorithm is sensitive to changes in direction, jumping/landing and contact.[8, 9] As such, a lack of variability in this metric may not reflect monotony as a similar PlayerLoad$^{TM}$ may be gained although two sessions that comprise differential accumulation of the training strain.[10] Increased injury risks are however consistently observed with GPS derived load fluctuations including PlayerLoad$^{TM}$ in other contact team sports when quantifying current (acute) relative to accumulative (chronic) workloads to calculate an acute:chronic workload ratio (ACWR).[6, 11, 12]

Recently, acute workloads ranging from 2-9 days and chronic workloads from 14-35 days have been examined to assess the most appropriate ACWR[12] and exponentially weighted moving averages (EWMA) have been proposed as a more perceptive method.[13] Indeed, EWMA workload-injury risks have been shown to be more sensitive than the traditional 'rolling average' method in Australian Football.[14] However, variable workload periods have not been compared when calculating EWMA's and it is unclear if one model would be appropriate for all sports. American football for example has a unique playing structure (separate offensive and defensive 'teams') and playing season (16-17 weeks inclusive of pre-season) that is substantially shorter than other contact sports (Rugby League and Australian football) where ACWR spikes have been associated with elevated injury risks.[6, 11, 12] Furthermore, there is variation in the number of injuries observed across positional groups in NCAA football[5] and it is known that injury risk is greater in more senior players.[15] This is in contrast to observations in Gaelic football, where players with less experience were shown to have the greatest injury risk.[16] Interestingly Malone and colleagues also showed that first year players were less able to tolerate ACWR spikes.[16] However, whilst it is also known that NCAA football workloads are highly variable relative to positional demands,[17, 18] ACWR-injury risks in American football have yet to be determined. This investigation will therefore examine workload injury risk relationships in NCAA football.

## Methods

A cohort of 52 American college footballers comprising 27 offensive (offensive linemen (OL), quarterbacks (QB); running backs (RB); tight ends (TE); wide receivers (WR)) and 25 defensive (defensive linemen (DL); defensive backs (DB); linebackers (LB)) players (age: 20.7±1.5 y, mass: 103.0±20.0 kg, height: 187.6±8.4 cm) who compete in the same Division I-A team participated in this study. All players signed an informed consent form indicating that de-identified data collected as part of their athletic participation may be used for research. The University Research Compliance Services approved all experimental procedures.

Workloads (Playerload$^{TM}$) determined from GPS/IMU devices containing a 10Hz GPS engine and 100Hz accelerometer (Optimeye S5; Catapult Innovations, Melbourne, Australia) were retrospectively analysed relative to the incidence of non-contact injury during one full season of NCAA division 1 College Football. Participants wore the same device during every training session and match.

PlayerLoads™ were calculated and expressed as arbitrary units (AU) via the manufacturer's software (OpenField 1.11, Catapult Innovations, Melbourne, Australia). 5159 individual workload files were analysed. The data set included the 3-week pre-season conditioning phase, three × weekly in-season conditioning sessions, two × weekly in-season walk-through sessions and weekly game workloads (11 games). No game data was recorded for the final game of the season (week 17). In the event of missing pre-season workload data (37 files of generalised conditioning), the player's weekly pre-season average was added to the data set. Missing in-season workloads (GPS devices were typically only worn during one of the two weekly walk-through sessions and on occasion when data was absent from conditioning sessions (60 files)) were inserted as the players average calculated relative to the specific training-day. Any player without workload data files from every type of training (included walk-through sessions) was excluded from the entire data set.

All non-contact soft-tissue injuries were documented by the teams athletic training group (classified by incident date, side, body part, type, mechanism, lost days and games missed) using the University's medical software were included in the analysis regardless of whether time-loss (missed, or incomplete training/game) ensued or not. Only non-contact soft-tissue injuries were included as this type of injury is considered largely preventable[19] and as such would more likely be associated with the training load. Injury rates are expressed as total number of injuries / total number of training athletic exposures (AE) and reported per 1000 AE's. All injuries were analysed as independent events.

Acute workloads were calculated for each week of the season and differentiated (during the in-season) relative to a player's inclusion in the travel squad (involvement in game day) and associated addition of load (game-time or no game-time) on game day. The impact of training load on non-contact injury events within 3- and 7-day lag periods were calculated using 7:14, 7:21 and 7:28 day rolling daily averages[12] and EWMA[13] models.

The *r2glmm* package[20] was used to extract and compare $R^2$ values for differing ACWR time-frames, injury lag-times, and average calculation methods (rolling average verses EWMA). The model that provided the best overall fit to the injury data was used for all subsequent analyses. The association between acute weekly load and injury was assessed via a Spearmans-rho correlation coefficient. A generalized linear mixed-effects model (GLMM) was used to model the association between ACWR and subsequent injury risk. We examined whether responses were non-linear by including a quadratic term in the model. Where non-linear effects were present (as indicated by a statistically significant squared term), the ACWR was parsed into categories to enable the interaction with chronic workload to be explored, whilst still allowing for non-linear responses. The ACWR was parsed into low (<0.80), moderate (0.80-1.30), and high (>1.30) categories.[7] The odds ratios obtained from the GLMM model were converted to relative risks (RR) in order to interpret their magnitude[21]. Magnitude-based inferences were used to provide an interpretation of the real-world relevance of the outcomes.[22] The smallest important increase in injury risk was a relative risk of 1.11, and the smallest important decrease in risk was 0.90.[23] An effect was deemed '*unclear*' if the chance that the true value was beneficial was >25%, with odds of benefit relative to odds of harm (odds ratio) of <66. Otherwise, the effect was deemed clear, and was qualified with a probabilistic term using the following scale: <0.5%, *most unlikely*; 0.5-5%, *very unlikely*; 5-25%, *unlikely*; 25-75%, *possible*; 75-95%, *likely*; 95-99.5%, *very likely*; >99.5%, *most likely*.[22] The data is presented as means ±90% confidence intervals (CI) with injury rates relative to the number of athletic exposures (AE). An exploratory analysis of the individual differences in observed injury rates across groups considering experience (Freshman, first year; Sophomore, 2nd year; Junior, 3rd year; and Senior, 4th year) and position (Offensive linemen (OL), Defensive backs (DB), Defensive linemen (DL), Linebackers (LB), Quarterbacks (QB), Running backs (RB), Wide receivers (WR) and Tight end, (TE)) was undertaken using the non-parametric Kruskal-Wallis test, as the data was not normally distributed.

## Results

In this group 46 of the 52 players sustained an injury. A total of 105 (20.4/1000 AE's) non-contact injuries were observed, with 31 resulting in time-loss. Non-contact and contact injuries were analysed collectively to provide sufficient power to detect moderate associations between the injury risk factor (workload) and injury.[24] 75% of the injuries were recorded in the lower limb, 13% in the upper limbs and 12% in the back/spine/neck. 62% of the injuries were diagnosed as a sprain or strain, 10% as bursitis/tendonitis, 10% as pain, 5% as a disc injury and the remaining 13% as blister, cyst, dysfunction, hyperextension, impingement, muscular imbalance, plantar fasciitis, plica, or spasm.41 injuries were recorded during the pre-season (43.8/1000 AE's) and 64 (18 game-related, 46 training-related) during the in-season (23.2/1000 AE's). Correspondingly, the risk of non-contact injury during the pre-season was 1.89 greater than the in-season. A significant workload and injury correlation (r= 0.73) was observed when including every week of the season, however when examining in-season workload and injury, no significant correlation was observed (r= 0.50).

$R^2$ models for injury risk were calculated with rolling and EWMA ACWR. An $R^{2\,=}$ 0.54 was observed with 7:21 day EWMA ACWR calculations with a 3-day injury lag. Very weak $R^2$ values were observed in all other models (7:14 day rolling ACWR, 0.01 (3-day lag) and 0.02 (7-day lag); 7:14 day EWMA, 0.06 (3-day lag) and 0.08 (7-day lag); 7:21 rolling ACWR, 0.04 (3-day lag) and 0.03 (7-day lag); 7:21 day EWMA 7:21, 0.19 (7-day lag); 7:28 day rolling ACWR, 0.03 (3-day lag), 0.04 (7-day lag); and 7:28 day EWMA 0.10 (3-day lag) and 0.16 (7-day injury lag)).

Further analysis of 7:21 day EWMA ACWR (3-day injury lag) parsed into categories indicated that the risk of injury was *very likely* greater with a high (>1.30) compared to moderate (0.8-1.30; RR: 3.33, CI 1.35-8.19; injury probability = 97.8%) and low (<0.8; RR: 3.05, CI 1.38-6.76; injury probability = 98.2%) EWMA ACWR (Figure 1). An exceptionally high risk of injury (injury probability = 92.1%) was observed when low 21-day chronic workloads (85 AU) were combined with high 7:21 EWMA ACWR compared to moderate (RR: 30.67, CI 3.03-310.51, injury probability = 3.1%) and low (RR: 14.15, CI 2.36-84.91, injury probability = 6.5%) EWMA ACWR (figure 2). A moderate 7:21 day EWMA ACWR combined with a high 21-day chronic workload (425 AU) also elevated injury risk (injury probability = 9.6%) when compared to low (RR: 2.59, CI 1.36-4.93; injury probability = 3.7%) and high (RR: 14.52, CI 2.38-88.66; injury probability = 0.7%) 7:21 day EWMA ACWR / high 21-day chronic load combinations.

**INSERT FIGURE 1 HERE**

**INSERT FIGURE 2 HERE**

The workload threshold for injury was diverse (figure 3) with 6 players recording no injuries; 18 players sustaining one injury; and multiple (ranging from two to six) injury reports recorded in 28 players. Junior (3rd year) players (≈2.9 injuries per player) displayed a *likely* and *possibly* increased injury risk when compared to Freshman (≈1.5 injuries per player, RR: 1.94, CI 1.07-3.52, injury probability = 93.8%,) and Seniors (≈1.7 injuries per player, RR: 1.7, CI 0.92-3.14, injury probability = 87.3%,) respectively. The injury rate of Sophomores (≈2.3 injuries per player) was not different to any other group of relative playing experience.

Injury rates across positional groups averaged 2.0 (OL), 2.3 (DB), 2.5 (DL), 1.7 (LB) 1.0 (QB), 1.5 (RB), 2.2 (WR) and 1.0 (TE) injuries per player. Average body mass index values across positional groups were 31.6 (OL), 26.2 (DB), 34.8 (DL), 29.4 (LB) 24.4 (QB), 30.0 (RB), 25.2 (WR) and 30.2 (TE) with *likely* (OL *vs* DL; DB *vs* LB; LB *vs* WR; LB *vs* QB), *very likely* (OL *vs* DB; OL *vs* QB; DL *vs* QB; DB *vs* RB; LB *vs* WR)  and *most likely* (OL *vs* WR; Dl *vs* DB; DL *vs* LB; DL *vs* RB; DL *vs* WR; RB *vs* WR) differences observed. However, no differences of clinical significance in the number of injuries between playing groups, and no clear interaction effects between ACWR and playing experience or ACWR and playing group were observed.

**INSERT FIGURE 3 ABOUT HERE**

## Discussion

This investigation confirms previous assumptions that high pre-season workloads are associated with high injury rates in NCAA football. Indeed, the highest number of injuries was observed alongside the highest weekly workloads in order from first, second and third weeks of the pre-season. However, no correlation between in-season injury rates and acute weekly workloads was observed. During the in-season period, non-contact injuries were most closely associated with a 7:21 day EWMA ACWR and injury risks were elevated when high 7:21 EWMA ACWR and low 21 day chronic workload combinations were observed.

Whilst speculative, the lack of association between acute weekly loads and in-season injury rates may reflect the reduced in season weekly load compared to pre-season. The loading patterns found in this study are in contrast to other sports where longer pre-season periods allow for a gradual transition to higher loads. Yet our observations are not unique with existing reports also noting the highest load of the season in the first week of the College Football pre-season period.[25] The high injury rates during the traditional high-load intense "camp" conditioning phase of College Football may suggest that this approach is somewhat flawed. However, the injury data included in this investigation including non-contact injuries that did not result in time loss and as such may be considered trivial. Furthermore, a number of recorded injuries were related to "pain" that can be considered a common sensation related to physical overload and overreaching that may not insinuate injury.[26] We also recognise that the pre-season is an essential preparatory period for the rigorous demands of competition and within the NCAA is regulated by legislation around length and session number[27] and that greater pre-season participation has been associated with lower in-season injury risk.[16] It is known that injury risk factors are multifactorial and influenced by a range of internal and extrinsic risks.[28] The substantial reduction in injury rates observed herein and elsewhere during the college football in-season[2, 3] could however be interpreted as a positive consequence of the rigorous pre-season training regimen, with unusually high initial workloads followed by sharp workload reductions may also be purposefully applied in an attempt to 'peak' at the start of the competitive season.[29] However, such a strategy is in contrast to progressive workload recommendations and may represent a substantial 'spike' in the ACWR.[11]

In recent years, in-season workload-injury risks have been associated with ACWR 'spikes' in similar team sports.[11, 12, 16, 30] Yet, ACWR-injury risk relationships have not previously been confirmed in American Football. In this investigation, we examined 7-day acute and corresponding 14-, 21- and 28-day chronic workloads. Similar to others, a shorter 21-day chronic workload period was more sensitive to the risk of non-contact injury.[12] However, whilst Carey and colleagues (2016) observed more profound workload-injury risk models with rolling ACWR, only 21-day EWMA ACWR presented a reasonable $R^2$ model fit in this investigation. Notably however, Carey and colleagues (2016) also manipulated the acute workload window and included match-day injuries (where the majority of injuries were observed) in all time-lag periods. In contrast, only 7-day acute workloads were examined within the acute portion of the ACWR herein and the injury lag period rolled consistently throughout the season. Furthermore, the current investigation is the first to include non-time loss and time-loss injuries in the assessment of ACWR and injury risk and this injury definition may have influenced the associations observed.

The exceptionally high risk observed when low chronic workloads were combined with high 21 day EWMA ACWR is certainly of note for practitioners. Such conditions are likely to arise when an athlete returns to play following a time-loss injury. A layoff from athletic training following injury can result in detraining, lower fitness, strength and neuromuscular control and consequently elevate the risk of a future related injury.[31] Previous research has excluded injuries in players participating in rehabilitation from a previous injury[12] and in this group GPS data was not consistently recorded on players participating in “modified training” (i.e. undergoing rehabilitation). However, ACWR spikes remain likely when these players return to full training. Consequently, these athletes, whilst rehabilitated may not have been prepared for the demands of training and competition.[32] A second scenario that may result in a spike in the ACWR on the base of low chronic workloads may also occur when a player is suddenly included in the travel squad following a period of absence. American College football game-time can represent >50% of a weeks workload.[25] Higher chronic loads thus accumulate from regular game-time and in contrast ACWR ‘spikes’ can emanate when suddenly gaining game-time minutes.

Individual ACWR-injury risk relationships were indeed present and represent the range of durability across individuals in a squad. Being cognisant of these differences may influence a coach’s approach to practice periodisation within the NCAA confines and whether they adopt a high workload for all (‘survival of the fittest’) or are more cautious (‘minimum effective dose’). In this population although risks were notably increased in Junior players, no other differences relative to experience or across positional groups were observed. These observations are in contrast to those of Malone and colleagues who note increased risk in less experienced players[16] though this may be indicative of the different practice structure across sports.[15] The increased risk of injury in the more experienced "junior" players in this group of American footballers may be attributed to increased game time, and/or increased participation in full-contact training drills with the lack of a similar association in "seniors" perhaps being explained by the injury definition used herein.[15] However, no clear ACWR –Experience or –positional group interactions were observed in this investigation.

A number of confounding variables should also be considered when interpreting these results. Firstly, whilst the Playerload™ used in this investigation may detect running and contact workloads[33], other activities performed on the football field contribute to the overall workload. For example, American football quarter-backs have high throwing workloads that may influence the ACWR and present an injury risk in itself.[30] As such, whilst the risk of injury is generally associated with the intensity of field-based sessions, more sensitive models may be obtained should future technologies improve to allow 'other' workloads to be appropriately quantified. Secondly, whilst collectively examining time-loss and non-time loss injuries was a unique element of this study that may highlight the association between training load spikes, soreness, pain and minor (non-time loss) injury, the relative importance of injuries that do not result in time loss may be trivial. In addition, one should also consider the multifactorial nature of injuries and recognise that training workloads represent only one of a number of extrinsic and intrinsic risk factors that influence the risk of injury[28]. Correspondingly, given large mass and BMI differences and the known variance in workload previously across the positional groups,[17, 18] a more in-depth assessment of injury risks relative position is certainly warranted. However, given the lack of statistical power associated with the reduced number of more severe (time loss injury) and low participant numbers within the discrete positional groups, a comprehensive assessment of ACWR and injury risk could not be performed.[24] Furthermore, with respect to this and other investigations examining associations between workloads and injury,[6, 34, 35] the methods for estimating missing data should be considered. In the current study, the 'mean imputation' method was used as it offers a clear and simple approach that is appropriate when the number of missing cases represents a small number of the total data set and is considered far superior to removing these cases and reducing statistical power.[36] However, one must also consider that any method of averaging missing data may underestimate the variance in the data set.

## Conclusion

In this study, the highest number of non-contact injuries were observed in the pre-season and the efficacy of high pre-season workload practices and subsequent training progressions in American Football should be considered. In–season, 21-day EWMA ACWR were associated with injury sustained within 3-days even when less severe non-contact injuries that did not result in time loss were included in the analysis. The greatest risk of injury was however evident when high 21-day EWMA ACWR and low chronic workloads were collectively observed. Practitioners are therefore advised to build chronic loads and be particularly diligent when players present with low 21-day chronic workloads. Furthermore, although practitioners are advised to consider risk with respect to the varied positional demands and relative experience of the individual, simplistic categorisation is unlikely to distinguish risk and a coach's awareness of player 'robustness' should not be underestimated.

## Practical Applications

- Various ACWR calculation methods should be trialled to determine the 'best fit' for the playing group with high chronic loads developed whilst maintaining an EWMA ACWR <1.30.
- Considering the exceptionally high injury risk observed in the college football pre-season and when acute workload spikes are imposed on a low chronic workload base, strategies to:
    - i) build chronic workloads through 'on field' training in the off-season,
    - ii) accrue workload in the absence of game-time for individuals not included in the travel squad and
    - iii) manage workloads during the return to play process to integrate players safely back into training should be carefully considered.

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## Figure descriptions

**Figure 1:** Mean quadratic trend for the relationship between EWMA ACWR and subsequent injury risk.

**Figure 2:** Predicted injury probability considering combined effects of 21 day chronic workload and associated 7:21 day EWMA

**Figure 3:** Individual 7:21 day EMWA ACWR injury risk curves