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Abstract:

Training load monitoring has grown in recent years with the acute:chronic workload ratio (ACWR) widely used to aggregate data to inform decision-making on injury risk. Several methods have been described to calculate the ACWR and numerous methodological issues have been raised. Therefore, this study examined the relationship between the ACWR and injury in a sample of 696 players from 13 professional rugby clubs over two seasons for 1718 injuries of all types and a further analysis of 383 soft tissue injuries specifically. Of the 192 comparisons undertaken for both injury groups, only 40% (all injury) and 31% (soft tissue injury) were significant. Furthermore, there appeared to be no calculation method that consistently demonstrated a relationship with injury. Some calculation methods supported previous work for a "sweet spot" in injury risk, while a substantial number of methods displayed no such relationship. This study is the largest to date to have investigated the relationship between the ACWR and injury risk and demonstrates that there appears to be no consistent association between the two. This suggests that alternative methods of training load aggregation may provide more useful information, but these should be considered in the wider context of other established risk factors.

Introduction:

Training load monitoring has become an integral component of injury risk management in recent years, largely due to the ease with which it can be modified and optimised for each athlete. The acute: chronic workload ratio (ACWR) is a measure of athlete training load that accounts for both the fatigue (acute) and fitness (chronic) status of the athlete [1]. Given the apparent ecological validity of the measure, ACWR has been widely adopted across team sports to aggregate athlete training load data with the aim of managing injury risk [1-3]. Typically, the ACWR has been calculated by dividing a chronic (28 day rolling average) value by an acute (7 day rolling average) load to produce a ratio, with values greater than one representing higher acute load relative to the four week average, and values less than one representing lower acute load relative to the four-week load [1,4]. However, a number of methodological considerations [5-8] and concerns regarding the applicability and validity of the measure [9-13] have questioned whether the measure offers any value in managing athlete injury risk.

The ACWR can be calculated using different averaging methods (rolling averages- RA, and exponentially weighted moving averages- EWMA [5,14]), different time periods [6], and using coupled or un-coupled loads [7]. Since the original use of 7 and 28-day acute and chronic time periods, other time-frames have been suggested ranging from 2-14 days (acute) and 12-56 days (chronic)[6,15], which may be more representative of the time periods over which fatigue and fitness decay. More recently, Dalen-Lorentsen and colleagues [13] have demonstrated that the link between the ACWR and injury is highly variable based on the methods used to calculate the ACWR (including RA and EWMA, and differing time periods). This indicates that the relationship is not consistent and a product of the calculation method itself, as opposed to a consistent link between ACWR derived training load and injury.

In rugby union, the risk of injury is high compared with that of other team sport (81 per 1000 match hours [16]) and therefore modifiable risk factors such as training load offer a potentially useful method for injury risk mitigation. While, little evidence exists in rugby union as to the utility of the ACWR [17,18], establishing the extent to which methodological parameters could be influencing the link between the ACWR and injury risk in this setting is prudent. Importantly, it is well established that injury aetiology is multifactorial in nature [19] and therefore when examining the link between training load and injury, other well known risk factors must be considered. In rugby union, these include (but are not limited to) previous injury [20], previous concussion [21], match minutes [20], playing position [22] and age [22,23]. Therefore the aim of this study is to investigate the association between the ACWR and injury risk in a league wide sample of 13 teams, while accounting for other known injury risk factors.

Methods:

Subjects:

Data were captured from 13 Premiership clubs in the 2015-16 and 2016-17 seasons (ten clubs for two seasons, three clubs for one season (due to relegation/promotion and one club not providing data in one season)). In 2015-16, 433 players were recruited and in 2016-17, 569 players were recruited, for a total of 1002 player-seasons (696 unique players). Injury data were collected as part of the Professional Rugby Injury Surveillance Project; each player was provided with a participant information sheet, with individual consent obtained voluntarily. The study was approved by the xxxxxx and meets the ethical standards of the journal [24].

Procedures:

Time-loss injuries were defined as “an injury that results in a player being unable to take a full part in future rugby training or match play for more than 24 hours from midnight at the end of the day the injury was sustained”[25] with all match and training injuries collected by club medical staff. Training load data were collected by club conditioning staff using the session Rating of Perceived Exertion (sRPE) method [26]. This measure was chosen for its ease of use, applicability to multiple session types, and widespread use in professional rugby [27,28]. Within 30 minutes of each session, participants were asked to rate their session (1-10) using a modified CR-10 Borg scale [26,29]. This number was then multiplied by the session length (in minutes) to produce a single global score for the whole session. Staff were instructed to blind the players to one another’s scores to ensure no bias was introduced in the collection. Data were collected daily and sent monthly to the lead researcher for collation in a standard format using Microsoft Excel.

Five well-documented injury risk factors were also included as covariates: position, age, previous injury, previous concussion and cumulative match minutes (all in the past 12 months). Player position and age were obtained using baseline data reported at the start of each season. Six position categories were used: front row, second row and back row (forwards) and half backs, centres and the back three (backs). Previous injury and previous concussion were captured by the primary researcher by retrospectively analysing the previous seasons injury data (count per player). Match minutes were summed over a rolling 12-month period. The selection of reference categories has previously been reported as a challenge to analysing the training load-injury risk relationship [1]. Therefore, the selection of reference categories was decided *a priori*. Both position and age reference categories were arbitrarily assigned as the “back three” and the 18-23 year old grouping, respectively. A “moderate-low” grouping of 1 previous injury was selected for previous injury as the data demonstrated that the majority of players were likely to experience one injury per 12 months (69% in 2015-16 and 77% in 2016-17). In contrast, the “Low” (no previous concussion in the past 12 months) previous concussion category was chosen as the majority of players did not experience one concussion over a rolling 12 month period (23% in 15-16 and 28% in 16-17). A "moderate-low" category for match minutes (455-888 minutes or 5.7-11.1 full match equivalents) was chosen as it has previously been shown as a high risk range in rugby union [20]. A binary injury indicator (0-No/ Yes-1) was included for each athlete on each day of the study period. All days (training days, match days and rest days) were included in the calculation the ACWR. However, because there was no risk of rugby-related injury on days with no rugby exposure, those days were not analysed to determine whether ACWR was associated with injury [31]. No latent period was included, as the derived measures were updated and analysed daily [32].

Statistical Analysis:

All covariate risk factors (position, age, previous injury, previous concussion and cumulative match minutes) and the fixed load measurement of interest (i.e. the ACWR) were included in multivariable analyses to identify key risk factors, as determined by the *GLMERSelect* stepwise selection procedure via the "*StatisticalModels*" package [33]. Polynomial and interaction terms were evaluated in this process. The covariates retained by the backwards selection of fixed effects (previous injury, previous concussion and cumulative match minutes) were included in the final models alongside three previously identified training load measures shown to represent distinct components of training load [34]. These measures were: an acute load (3,5,7 or 9 days), a chronic load (14, 21, 28 or 28 days) and the corresponding ACWR variable. Multicollinearity between covariates was assessed using Variance Inflation Factors (VIF), with a VIF of ≥10 deemed to show substantial collinearity [17,35].

The training load dataset file was imported into Matlab (Matlab 2018b, MathWorks) to programmatically produce the data combinations required for analysis. For each daily load value per player, each possible ACWR calculation method was produced, including RA and EWMA [14], coupled and uncoupled [7,36] and each time frame (3,5,7,9,14,21,28,35). This procedure resulted in the following ACWR measure for each player each day (Fig 1). These data were exported from Matlab into RStudio for analysis.

*********************** INSERT FIGURE 1 HERE **

Final analysis of the training load and injury risk relationship was undertaken for two separate outcome variables: all injury types and non-contact soft tissue injuries only. For the purpose of this analysis, soft tissue injuries were defined as any muscle, tendon or ligament issue occurring from a non-contact mechanism. Generalised linear mixed models were used to assess the relationship between each of the ACWR metrics and injury risk, using the "*lme4*" package [37]. Repeated observations within players were accounted for using a random effect for each player ID, which was nested within the player's club. Model fit was assessed using the Akaike Information Criterion (AIC) with a smaller AIC value representing a better model fit. Area Under the Curve (AUC) was also assessed, with a higher AUC value representing a better performing model [38]. The ACWR was modelled as a continuous variable [30] with a polynomial term to account for non-linear relationships. For each method of calculation, three comparisons on injury risk were made; moderate versus low ACWR (i.e. the mean ACWR to -1 standard deviation(SD)), moderate versus high (i.e. mean to +1SD) and low versus high (-1SD to +1SD) [13,39]. Estimated injury probability at each of these values (-1SD, Mean and +1SD) was expressed as the injury hazard (risk per player per exposure day), with comparisons between groups expressed as hazard ratios with 90% confidence intervals [32]. In this study, an ACWR "Sweet Spot" was deemed to be when the moderate category represented the lowest risk and was significantly lower than either the low or high category. Confidence intervals were set at 90% to allow for the possibility that the true value lies 5% either below the lower limit or above the upper limit [40]. All analysis was undertaken using RStudio (RStudio, Inc. Version 1.1.463).

Results:

Acute: chronic workload ratio and all injury type

Over the study period 129,448 training load values were collected (excluding days off), while 1718 injuries were recorded (383 soft tissue). Individual comparisons between ACWR groups for each of the calculation methods are outlined in supplementary figures (All Injury Types: S1- Coupled and rolling, S2- Coupled and EWMA, S3- Uncoupled and rolling, S4- Uncoupled and EWMA, Soft Tissue Injuries only: S5- Coupled and rolling, S6- Coupled and EWMA, S7- Uncoupled and rolling, S8- Uncoupled and EWMA). For all injuries, of the 192 comparisons made (i.e. Moderate to Low ACWR, Moderate to High ACWR, Low to High ACWR for all ACWR calculation methods), 77 (40%) significant results were produced (Figure 2A). The coupled EWMA 3-to-14 day calculation method produced the best model fit (AIC = 20108, AUC = 0.69). The uncoupled EWMA ACWR showed the greatest support for a "sweet spot" (63%: Figure 3).

Adjusted covariate effect:

The three selected covariates (previous injury, previous concussion, and match minutes) were also included in the generalised linear mixed model. Table 1 and 2 demonstrate the adjusted relative risks for the three covariates, for all injury and soft tissue injuries, respectively. For each new ACWR interaction (Figure 1), the acute and chronic time frames were changed to match the ACWR. For all injury types, previous injury, match minutes and acute and chronic loads demonstrated significant effects on injury risk. For soft tissue injury, only previous injury demonstrated a significant effect.

*********************** INSERT FIGURE 2 HERE **

*********************** INSERT TABLE 1 HERE ***

************************ INSERT FIGURE 3 HERE **

Acute: chronic workload ratio and soft tissue non-contact injury

Of the 192 comparisons made for soft tissue injuries, 60 (31%) were found to have significant findings (Figure 2B). The calculation with the best model fit according to AIC was the uncoupled rolling average 3-to-14 day method (AIC: 5692), with a coupled EWMA 5-to-14 days ACWR representing the highest AUC (0.64). An uncoupled EWMA ACWR demonstrated the largest number of significant findings (65%). This method also showed the greatest support for a "sweet spot" (75%) (Figure 4).

************************ INSERT TABLE 2 HERE ***

************************ INSERT FIGURE 4 HERE **

Discussion:

Training load monitoring has grown exponentially in recent years, with the ACWR being a widely adopted method of aggregating the data to inform decision making on injury risk [1]. However, recent evidence suggests that this metric may not be valid for undertaking such analysis, with a number of papers questioning its utility [8,9,12,13]. The current study, which includes ~130,000 training load values and ~1700 injuries, has demonstrated the substantial variation that exists between the method used to calculate ACWR and injury risk outcomes. For all injury types, the calculation method producing the highest AUC in this setting was a coupled EWMA 3-to-14 ACWR (AUC: 0.69), whilst for soft tissue injuries it was a coupled EWMA 5-to-14 ACWR (AUC: 0.64). Of the 192 comparisons undertaken for all injury types, 77 (40%) were statistically significant, while 60/192 (31%) of the comparisons for soft tissue injuries were statistically significant. Despite the large number of significant findings, there was no consistent manner through which the ACWR was associated with injury risk. One of the most commonly cited findings in this field of work (an ACWR "Sweet Spot) was supported using some ACWR calculation methods, however, a substantial number of the methods displayed no such relationships.

Associations between the ACWR and Injury risk

The most widely used method for calculating ACWR in previous studies has been a coupled rolling 7-to-28 day ACWR [2]. For both all injury types and soft tissue injuries, this study supported this finding with at least one significant result (e.g. Table S5). While these findings support previous work, several other methods of calculation demonstrate significant findings, while others show no association at all. Of the 192 possible comparisons for each injury type, only 40% (all injury) and 31% (soft tissue injury) demonstrated significant findings, which is higher than those reported in youth soccer in a similar analysis (19%:[13]) and is likely a result of a bigger sample size. Although 40% and 31% of calculation methods produced significant findings, the apparent random nature by which these were distributed across calculation methods do not allow us to identify any methods (time frames, averaging methods or coupling methods) which consistently produce a clear outcome. This apparently random distribution of significant associations between ACWR and injury make implementing one method to manage injury risk very difficult to support.

In accordance with previous work [2,41], the EWMA method of averaging data was more likely to find a significant finding than the rolling average equivalent in all cases (Figure 3&4). In the case of all injury types, coupled loads demonstrated a higher proportion of significant findings (Figure 3), however with soft tissue injuries, given the high proportion of EWMA uncoupled values producing significant effects (65%: Figure 4), uncoupled load showed a higher number of significant findings. Given the work of Lolli et al. [7] questioning whether the correlation between the ACWR and injury when using coupled loads is spurious, the findings of this study appear to support this spurious relationship, with inconsistent links between different calculation methods and injury risk. Based on the inconsistencies in finding significant results demonstrated by the current study, this study of league wide data accentuates the apparent randomness of associations between the ACWR and injury [12]. This further questions whether this metric adds any value above examining acute and chronic loads in isolation, which provide similar information without the use of ratios, which have previously been shown as problematic [9,12].

ACWR Sweet Spot and Injury

The concept of an ACWR "sweet spot", whereby injury risk is highest when you have a low (<0.8) or high (>1.3) ACWR value, was first introduced in 2016 [1]. Since then, several others have reported sweet spots, however with differing sweet spot values in each case [38,42,43], with subsequent questions as to whether demonstration of a sweet spot is a robust concept or a methodological artefact. In this study, of the 64 different calculation methods assessed, only 15 (23%) showed a significant ACWR "sweet spot" for all injury risk and 18 (28%) for soft tissue injuries. As such, in 77% (all injury) and 72% (soft tissue injury) of cases no such finding was apparent. When specifically considering analysis using a 7-to-28 day acute and chronic period, a greater number (6/8) of methods resulted in a significant finding, but even here none of the calculations reached an AUC of 0.70 which is described as "acceptable" level of discrimination [44].

Why do we see such variation?

This is not the first study to demonstrate differences in the association between the ACWR calculation method and injury risk [6,12,13,41]. There are several reasons as to why this variation may exist. In the current literature, no clear causal link between training load and injury risk has been established, given the inability of observational cohort studies to infer causation. One theory reports the accumulation of fatigue and consequential reduced stress bearing capacity of the tissue to be the link between the two [45]. However, in the context of this study, the accumulation of fatigue does not support the findings in which low ACWR values represent an increased risk [8]. The lack of literature further limits our level of support for the method, with no study yet to employ a randomised control trial (RCT) study design. Even in the presence of an RCT, given the number of covariates that likely moderate training load and given the emerging evidence of the complexity of the interaction between those covariates in injury [46], isolating the effect of training load alone on injury risk is challenging.

In the context of this study, the reasons for differences in injury risk depending on the calculation method may be a product of what is included in each of those time periods. Previously, it has been shown that training scheduling confounds the ACWR-injury relationship [47] and therefore in this study when comparing different time periods, the difference in match and training load between the lowest and highest periods is substantial. However, there do not appear to be any time periods which demonstrate consistent associations with injury, again supporting the random nature of interactions between ACWR and injury as opposed to a link between the content of that time period and injury risk.

Finally, there is growing evidence that the use of a ratio adds little more than noise to the use of either variable alone [12], which in isolation are sufficient in understanding an athlete's training status. The evidence suggesting the limited utility of the ACWR have demonstrated that this may be a product of spurious correlation due to mathematical coupling [7]. Furthermore, it has been proposed that the use of a ratio serves as a tool to simply rescale the acute load, which has been shown to increase the effect estimates and decrease the variance [12]. When considering the substantial variation caused by calculation methods in this, and other studies [13], the support for the use of the ACWR to monitor injury risk in rugby union is low. This, however, does not mean that training load is not important in managing injury risk and future studies should focus on other measures of load, which do not include a ratio.

Limitations

This study was conducted in a large group of 13 clubs over a 2-season period and therefore one of the limitations of this study is that only one measure of load was used; sRPE. This metric was chosen for its applicability across a number of training modalities and has also been reported as a valid and reliable internal load measure [48]. It therefore must be acknowledged that other measures of load (either internal or external) may display more consistent patterns, however in the context of the league-wide data capture in this study, sRPE was the most practical load measurement to be included. Similarly, although this study assessed and accounted for several contextual factors, when making decisions on injury risk in athletes, a broad range of factors must be considered as opposed to looking at any one training load metric [49,50]. A second limitation is the lack of a lag-period in the analysis, which has previously been reported as important as spikes in load can increase risk in injury for up to four weeks [15,51,52]. While it may be important to consider this, there is currently no consensus on the best methodological approach for doing so [32]. Furthermore, analysis of the relationship between training load and injury risk outcomes, was only undertaken on days on which the athlete was exposed to rugby (either match or training) [31].

Conclusion

The inconsistency with which the ACWR is associated with injury indicates that results are largely driven by the methods chosen to calculate the ACWR, and not the 'athlete preparedness' construct it is purported to represent. As such, evidence for a causal relationship between the ACWR and injury risk is currently lacking. More advanced statistical approaches, such as machine learning, may help to elucidate the causal role of training load for injury risk in the future. For rugby union practitioners and in the absence of an alternative, the ACWR may currently be viewed as a simple heuristic to inform training progression, but one that should be considered alongside other established risk factors (i.e., match exposure, previous injury, and previous concussions) when managing injury risk.

Figure Captions:

Figure 1: Schematic representing the number of different ACWR calculation methods produced from each daily load variable.

Figure 2: Heatmap outlining significance of each comparison (Low to Moderate, Moderate to High, Low to High) for each ACWR calculation method (as outlined in table 1). A represents outcomes for all injury types, B represents non-contact soft tissue injuries only. Low= -1SD, Moderate= Mean ACWR, High= +1SD. EWMA=Exponentially Weighted Moving Average. 0.00 represents a value of <0.01.

Figure 3: Summary of ACWR associations with all injury types.

Figure 4: Summary of ACWR associations with soft tissue injury types.

Table Captions:

Table 1: Adjusted relative risk for all injury types after inclusion in multivariate model

Table 2: Adjusted relative risk for soft tissue injuries after inclusion in multivariate model

Supplementary Table Captions:

Table S1: Model Fit, Injury Hazard and between group comparisons for **all** injuries, using a **coupled rolling** average method. Groups: Low= -1 standard deviation of ACWR, Moderate= Mean ACWR score, High= +1 standard deviation of ACWR. Significant comparisons are highlighted in bold.

Table S2: Model Fit, Injury Hazard and between group comparisons for **all** injuries, using a **coupled exponentially weighted moving average** method. Groups: Low= -1 standard deviation of ACWR, Moderate= Mean ACWR score, High= +1 standard deviation of ACWR. Significant comparisons are highlighted in bold.

Table S3: Model Fit, Injury Hazard and between group comparisons for **all** injuries, using a **uncoupled rolling** average method. Groups: Low= -1 standard deviation of ACWR, Moderate= Mean ACWR score, High= +1 standard deviation of ACWR. Significant comparisons are highlighted in bold.

Table S4: Model Fit, Injury Hazard and between group comparisons for **all** injuries, using a **uncoupled exponentially weighted moving average** method. Groups: Low= -1 standard deviation of ACWR, Moderate= Mean ACWR score, High= +1 standard deviation of ACWR. Significant comparisons are highlighted in bold.

Table S5: Model Fit, Injury Hazard and between group comparisons for **soft tissue non-contact** injuries, using a **coupled rolling** average method. Groups: Low= -1 standard deviation of ACWR, Moderate= Mean ACWR score, High= +1 standard deviation of ACWR. Significant comparisons are highlighted in bold.

Table S6: Model Fit, Injury Hazard and between group comparisons for **soft tissue non-contact** injuries, using a **coupled exponentially weighted moving average** method. Groups: Low= -1 standard deviation of ACWR, Moderate= Mean ACWR score, High= +1 standard deviation of ACWR. Significant comparisons are highlighted in bold.

Table S7: Model Fit, Injury Hazard and between group comparisons for **soft tissue non-contact** injuries, using a **uncoupled rolling** average method. Groups: Low= -1 standard deviation of ACWR, Moderate= Mean ACWR score, High= +1 standard deviation of ACWR. Significant comparisons are highlighted in bold.

Table S8: Model Fit, Injury Hazard and between group comparisons for **soft tissue non-contact** injuries, using a **uncoupled exponentially weighted moving average** method. Groups: Low= -1 standard deviation of ACWR, Moderate= Mean ACWR score, High= +1 standard deviation of ACWR. Significant comparisons are highlighted in bold.

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