Calculating acute:chronic workload ratios using exponentially weighted moving averages provides a more sensitive indicator of injury likelihood than rolling averages

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ABSTRACT

Objective To determine if any differences exist between the rolling averages and exponentially weighted moving averages (EWMA) models of acute:chronic workload ratio (ACWR) calculation and subsequent injury risk.

Methods A cohort of 59 elite Australian football players from 1 club participated in this 2-year study. Global positioning system (GPS) technology was used to quantify external workloads of players, and non-contact 'time-loss' injuries were recorded. The ACWR were calculated for a range of variables using 2 models: (1) rolling averages, and (2) EWMA. Logistic regression models were used to assess both the likelihood of sustaining an injury and the difference in injury likelihood between models.

Results There were significant differences in the ACWR values between models for moderate (ACWR 1.0–1.49; p=0.021), high (ACWR 1.50–1.99; p=0.012) and very high (ACWR >2.0; p=0.001) ACWR ranges. Although both models demonstrated significant (p<0.05) associations between a very high ACWR (ie, >2.0) and an increase in injury risk for total distance ((relative risk, RR)=6.52–21.28) and high-speed distance (RR=5.87–13.43), the EWMA model was more sensitive for detecting this increased risk. The variance (R^2) in injury explained by each ACWR model was significantly (p<0.05) greater using the EWMA model.

Conclusions These findings demonstrate that large spikes in workload are associated with an increased injury risk using both models, although the EWMA model is more sensitive to detect increases in injury risk with higher ACWR.

INTRODUCTION

The acute:chronic workload ratio (ACWR) is a model that provides an index of athlete preparedness. It takes into account the current workload (ie, acute; rolling 7-day workload) and the workload that an athlete has been prepared for (ie, chronic, rolling 28-day workload).[1–3] Based on early research by Banister *et al*[4 5] the ACWR is likened to the fitness-fatigue model, where the chronic load is analogous to a state of 'fitness' and the acute load is analogous to a state of 'fatigue'.[1 2] If performance represents the difference between fitness and fatigue, the ACWR aims to predict performance by comparing acute and chronic loads as a ratio.[1 4 5] Further, the ACWR has been used to quantify injury likelihood, where very high ACWR ranges were associated with a significantly increased risk of injury.[1–3]

The original work by Hulin *et al*[1] aimed to determine whether acute and chronic workload and the ACWR were associated with injury risk in elite cricket fast bowlers. They reported that large increases in acute bowling workload (ie, balls bowled), represented by a high ACWR, were associated with an increased risk of injury in the week following exposure (relative risk (RR)=2.1 (CI 1.81 to 2.44), p=0.01). In addition, a high ACWR for internal workload (measured via session rating of perceived exhaustion (session-RPE)) was associated with an increased risk of injury in the subsequent week (RR=2.2 (CI 1.91 to 2.53), p=0.009). Further work across a range of sports,[6] specifically elite rugby league,[7 8] Australian football (AF),[3] Gaelic football[9 10] and soccer,[11] has continued to examine the relationship between the ACWR and injury likelihood. The common theme of findings from these studies is that (1) sharp increases or 'spikes' in acute workload, resulting in a high ACWR, are significantly related to injury both in the week the workload is performed and the subsequent week,[12] and (2) higher chronic workloads may offer a protective effect against injury.[12 13]

A recent *British Journal of Sports Medicine (BJSM)* editorial[14] has raised concerns surrounding the use of rolling averages to assess workload, citing that they do not consider the time frame in which a given stimulus occurred, nor the decaying nature of fitness and fatigue effects over time.[14 15] While this may be the case, the ACWR model is evidence-based[2 16] and is considered a best-practice approach for modelling the relationship between load and injury across a range of sports.[17] It is hypothesised that a non-linear training load model may be better suited to quantify injury risk;[14] however, there is currently no evidence that this type of model is superior to the current ACWR model.[17]

Recently, Williams *et al*[18] proposed the use of 'exponentially weighted moving averages (EWMA)'[19] as a new method to calculate acute and chronic loads to address the decaying nature of fitness and fatigue. This method assigns a decreasing weighting to each older load value, thereby giving more weighting to the recent load undertaken by the athlete. This method differs from the current model of acute and chronic load calculation, where a rolling average considers a training session carried out the day before the analysis and a session occurring 4 weeks before as equal.[14] It is suggested that the EWMA approach may be better suited to calculate the ACWR and model load and injury relationships than the current rolling averages method.[18]

Until now, no research has investigated the difference between the previously established rolling average ACWR model and the newly proposed EWMA model. Therefore, the aim of the present study was to investigate if any differences existed between the rolling average and EWMA methods of ACWR calculation and subsequent injury risk in elite Australian footballers.

METHODS

Participants

Fifty-nine elite players from one club competing in the Australian Football League (AFL) (age, 23.5±4.4 years; height, 189.7±7.3 cm; mass, 88.9±8.6 kg) participated in this 2-year study. A total of 92 individual seasons were recorded, where 33 (56%) participants competed in both seasons and 26 (44%) participants competed in one season. Each season consisted of a 16-week preseason phase comprising running and football-based sessions, followed by a subsequent 23-week in-season competitive phase. All experimental procedures were approved by the Australian Catholic University Human Research Ethics Committee.

Quantifying workloads

Global positioning system (GPS) technology, sampling at 10 Hz (Optimeye S5; Catapult Innovations, Melbourne, Australia), was used to quantify training and match workloads of players. The GPS units also housed a triaxial accelerometer, gyroscope and magnetometer, each sampling at 100 Hz. This technology has demonstrated acceptable reliability and validity when measuring distance, velocity, acceleration and player load.[20 21] Workload variables consisted of: (1) total distance (m), (2) low-speed distance (<6.00 km/h), (3) moderate-speed distance (6.00–18.00 km/h), (4) high-speed distance (18.01–24.00 km/h), (5) very high-speed distance (>24.00 km/h), and (6) player load (au). Player load was measured as a modified vector magnitude using accelerometer data from each vector (X, Y, and Z axis), and was expressed as the instantaneous rate of change in each vector.[20]

Definition of injury

For the purpose of this study, and as previously used,[3 22] an injury was defined as any non-contact 'time-loss' injury sustained during training or competition that resulted in a subsequent missed training session or game. Medical staff at the football club classified and maintained injury records throughout the study. Injury likelihoods were calculated based on the total number of injuries relative to the total exposure to a given workload range. Injury likelihoods and RR were subsequently calculated.[23]

ACWR calculation

To calculate a daily rolling averages ACWR, 1-week rolling workload data represented the acute workload, and the rolling 4-week average workload data represented the chronic workload. If a player completed zero external workload (ie, 0 m run) in a week, these workload data were excluded in the week where no workload was performed, but these data were still included in the analysis of chronic workload. The ACWR was divided into the following ranges: (1) very low, ≤0.49, (2) low, 0.50–0.99, (3) moderate, 1.0–1.49, (4) high, 1.50–1.99, and (5) very high, ≥2.0.[1–3] Each ACWR contained a unique amount of observations based on the data, ranging from 468 to 5722 observations.

Rolling averages ACWR

The rolling averages ACWR was calculated by dividing the acute workload by the chronic workload.[1–3] Where the chronic workload was greater than the acute workload, a lower ACWR was recorded. Similarly, where the acute workload was greater than the chronic workload, a higher ACWR was recorded.

EWMA ACWR

The EWMA was calculated as described by Williams *et al*.[18] The EWMA for a given day was calculated as:

$$EWMA_{today} = Load_{today} \times \lambda_a + ((1 - \lambda_a) \times EWMA_{yesterday})$$

Where λ_a is a value between 0 and 1 that represents the degree of decay, with higher values discounting older observations in the model at a faster rate. The λ_a is calculated as:

$$\lambda_a = 2/(N + 1)$$

Where N is the chosen time decay constant, with a 1-week workload (ie, 7 days) and 4-week workload (ie, 28 days) used to represent acute and chronic workloads, respectively. To calculate an EWMA ACWR value, an EWMA for acute workload (ie, 7-day workload) and chronic workload (ie, 28-day workload) was calculated using the above formula. The EWMA ACWR value was then calculated by dividing the EWMA acute workload by the EWMA chronic workload. To begin the EWMA calculation, the first observation in the series is arbitrarily recorded as the first workload value in the series. From this value, the aforementioned EWMA calculation can be used for acute and chronic workload calculation.

Statistical analysis

Data were analysed using SPSS V.24.0 (SPSS, Chicago, Illinois, USA). The likelihood of sustaining an injury was analysed using two binary logistic regression models with significance set at $p<0.05$. The ACWR was independently modelled as the predictor variable, and injury/no injury as the dependent variable. The very high ACWR (ie, ≥2.0) was used as the reference group to which each other group was compared. Differences in ACWR calculation between the rolling averages ACWR model and the EWMA model for each ACWR ratio range were determined using a 1-way analysis of variance (ANOVA). The R^2 value for each model was determined, and logistic regression models were used to determine the differences between the models. Given the real-world nature of the study, magnitude-based inferences were used to determine any practically significant differences between groups, along with 95% CIs.[24 25] Likelihoods were subsequently generated and thresholds for assigning qualitative terms to chances were assigned as follows: <1%, almost certainly not; <5%, very unlikely; <25%, unlikely; <50%, possibly not; ≥50%, possibly; ≥75%, likely; ≥95%, very likely; ≥99%, almost certainly. The magnitudes of differences between groups were considered practically meaningful when the likelihood was ≥75%.[24 25]

RESULTS

Injuries

A total of 40 injuries were sustained during the 2-year period. Of these, 18 were sustained during the preseason period, and 22 were sustained during the in-season period. The hamstring (53%) was the most commonly injured site, followed by other thigh injuries (ie, quadriceps, adductors) (18%) and calf (18%).

Different methods of ACWR calculation

The average ACWR for each day over the duration of the study was calculated using the rolling averages and EWMA models and is displayed in figure 1. The two methods of ACWR calculation were significantly different (p=0.001) and poorly related (R^2=0.43). Using the EWMA model for ACWR calculation resulted in a significantly lower value than that calculated by the rolling averages ACWR model for the same daily observations for moderate (mean±SD, 1.07±0.22 vs 1.19±0.12; p=0.021), high (1.27±0.21 vs 1.64±0.12; p=0.012) and very high (1.51 ±0.22 vs 2.29±0.20; p=0.001) ACWR ranges. There were no significant differences (p>0.05) between the model calculations at a very low and low ACWR range.

Injury likelihoods for each ACWR model

Preseason

The likelihood of injury during the preseason phase is shown in figure 2. A rolling averages ACWR of >2.0 for total distance was significantly associated with an increased risk of injury compared with those with an ACWR of 1.0–1.49 (RR=8.41, 95% CI 1.09 to 64.93, p=0.048, 97.4% very likely). No other significant relationships were observed between the rolling averages ACWR and injury likelihood during the preseason period. Using the EWMA model, there were multiple significant relationships shown between an ACWR of >2.0 and an increased injury likelihood when compared with lower ACWR ranges. Specifically, compared with an ACWR of 1.0–1.49, the likelihood of injury was increased sixfold to ninefold for: total distance (RR=8.74, 95% CI 7.35 to 10.39, p=0.002, 99.9% almost certainly), moderate-speed distance (RR=6.03, 95% CI 2.21 to 16.47, p=0.028, 98.4% very likely), and player load (RR=9.53, 95% CI 5.31 to 17.11, p=0.013, 99.3% almost certainly).

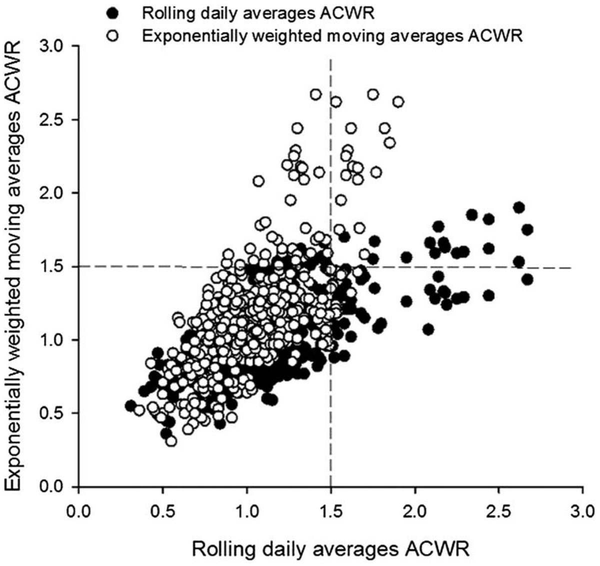

Figure 1 The acute:chronic workload ratio (ACWR) modelled using each method: rolling averages and exponentially weighted moving averages.

In-season

During the in-season period, a rolling average ACWR of >2.0 had an increased likelihood of injury compared with a lower ACWR for a range of variables. When compared with an ACWR of 1.0–1.49, an ACWR of >2.0 was associated with an increase in injury risk for total distance (RR=6.52, 95% CI 4.83 to 8.80, p=0.008, 99.6% almost certainly), high-speed distance (RR=4.66, 95% CI 4.12 to 5.27, p=0.004, 99.8% almost certainly), and player load (RR=5.87, 95% CI 4.12 to 8.36, p=0.010, 99.4% almost certainly). Using the EWMA model, players who exceeded an ACWR of >2.0 experienced an injury risk 5–21 times greater than players who maintained an ACWR of 1.0–1.49 for total distance (RR=21.28, 95% CI 20.02 to 22.62, p=0.001, 99.9% almost certainly), moderate-speed distance (RR=18.19, 95% CI 17.17 to 19.27, p=0.001, 99.9% almost certainly), and player load (RR=13.43, 95% CI 12.75 to 14.14, p=0.001, 99.9% almost certainly) (figure 3).

Between-model comparisons

The variance (R^2) in injury for each variable for each model of ACWR calculation are shown in table 1. While each model demonstrated significant relationships between very high ACWR results and injury likelihood during both the preseason and in-season periods, there were notable differences between the models. Using the rolling averages ACWR model, for total distance during the preseason phase the regression equation demonstrates that 21% (R^2=0.21) of the variance was explained using the ACWR. In comparison, 87% of the variance (R^2=0.87, p=0.042) in injury likelihood was explained by the EWMA. During the preseason period, the EWMA for high-speed distance and player load explained 77% (R^2=0.77, p=0.041) and 76% (R^2=0.76, p=0.044), respectively, while the variance explained by the rolling averages ACWR was much lower (R^2=0.13 and R^2=0.46). Similarly, during the in-season period, the R^2 value for each modelled variable was improved when using the EWMA model.

DISCUSSION

This study investigated if any differences existed between the previously described rolling averages model of ACWR calculation[1–3] and a new EWMA ACWR calculation[18] in determining injury likelihood. We found that spikes in workload, resulting in an ACWR of >2.0, were significantly associated with an increase in injury risk irrespective of the model used. We also found significant differences in the values reported at moderate-to-very high ACWR ranges (ie, 1.0–1.49, 1.50–1.99, and >2.0) between the two models, although no significant differences were reported at lower ACWR ranges (ie, <0.49, 0.50–0.99). Further, our findings demonstrate that the EWMA model offers greater sensitivity in identifying injury likelihood at higher ACWR ranges (ie, 1.50–1.99 and >2.0) during both the preseason and in-season periods.

Difference in ACWR calculation between the models

A key difference between the two proposed models of ACWR calculation is that the EWMA model assigns a decreasing weighting for each older workload value, whereas the rolling averages model suggests that each workload in an acute and chronic period (typically 7 days and 28 days, respectively) is equal.[18] Similar to the rolling averages ACWR model, the EWMA model requires the calculation of both an EWMA acute

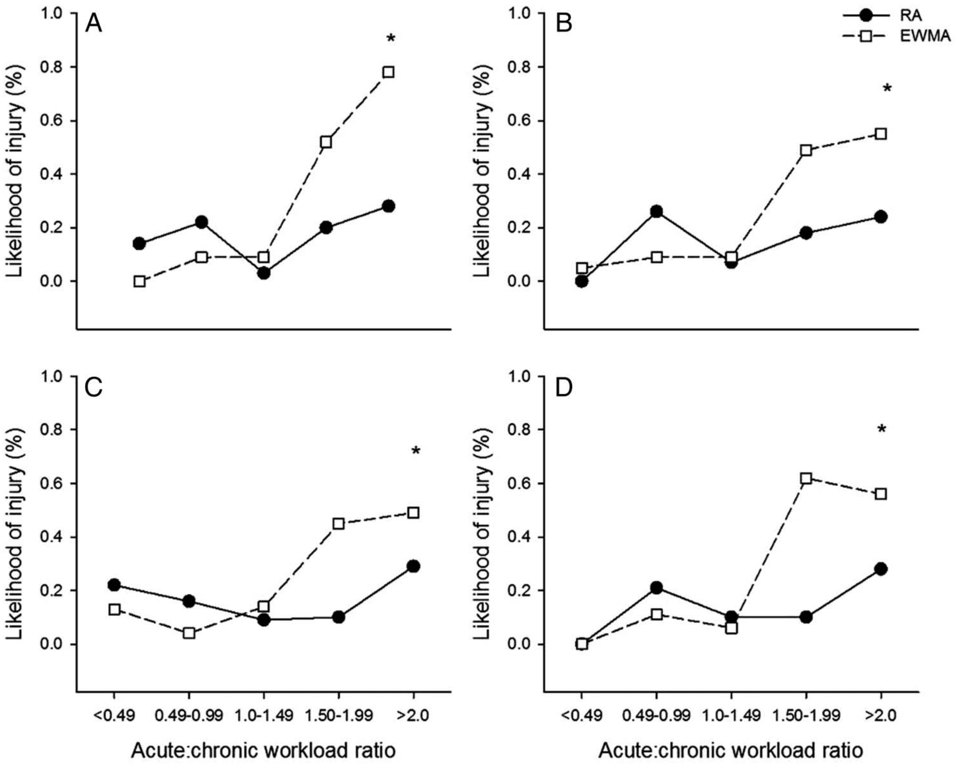

Figure 2 Likelihood of injury at each ACWR range during the preseason period for the current day for (A) total distance, (B) moderate-speed distance, (C) high-speed distance and (D) player load.*Denotes significantly different (p<0.05) from the rolling averages ACWR model. ACWR, acute:chronic workload ratio; EWMA, exponentially weighted moving averages; RA, rolling averages.

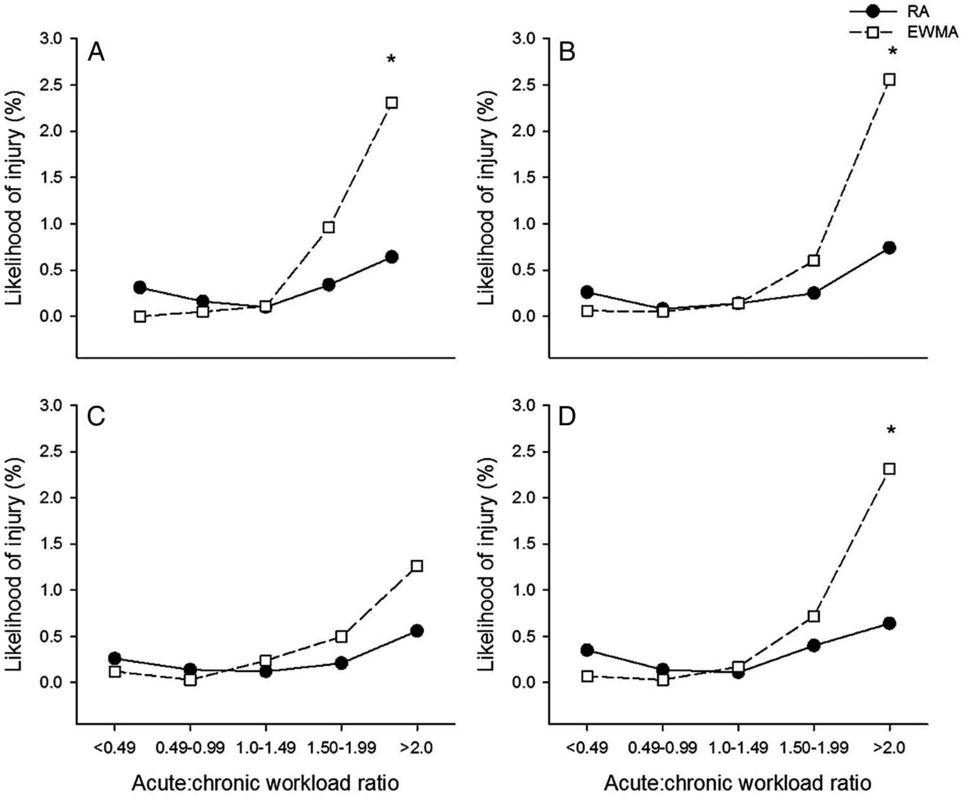

Figure 3 Likelihood of injury at each ACWR range during the in-season period for the current day for (A) total distance, (B) moderate-speed distance, (C) high-speed distance and (D) player load.*Denotes significantly different (p<0.05) from the rolling averages ACWR model. ACWR, acute:chronic workload ratio; EWMA, exponentially weighted moving averages; RA, rolling averages.

and EWMA chronic workload value before the calculation of the EWMA ACWR. Unlike the rolling averages ACWR model, the values obtained for an EWMA acute and chronic workload, provided using the aforementioned formula, are not able to be considered in isolation due to weighting applied by the λ_a value. This is an important consideration given the protective effect of moderate-to-high chronic workloads against injury.[2 3 8] We modelled the daily average ACWR value for each day of the study period using both models and found that significantly lower ACWR values were obtained using the EWMA model at

Table 1 Variance (R^2) in injury explained by the rolling daily averages and exponentially weighted moving averages acute:chronic workload ratio (ACWR) models

	Rolling daily averages ACWR model		Exponentially weighted moving averages ACWR model	
Workload variable	**Preseason**	**In-season**	**Preseason**	**In-season**
Total distance (m)	0.21 (−0.24 to 0.66)	0.40 (−0.07 to 0.87)	0.87 (0.72 to 1.00)*	0.78 (0.54 to 1.00)*
Low-speed distance (m)	0.47 (0.02 to 0.92)	0.43 (−0.03 to 0.89)	0.79 (0.56 to 1.00) *	0.75 (0.48 to 1.00)*
Moderate-speed distance (m)	0.32 (−0.16 to 0.80)	0.47 (0.02 to 0.92)	0.82 (0.62 to 1.00)*	0.77 (0.52 to 1.00)*
High-speed distance (m)	0.13 (−0.26 to 0.52)	0.37 (−0.11 to 0.85)	0.77 (0.52 to 1.00)*	0.67 (0.33 to 1.00)
Very high-speed distance (m)	0.23 (−0.23 to 0.69)	0.21 (−0.24 to 0.66)	0.69 (0.37 to 1.00)	0.66 (0.31 to 1.00)
Player load (au)	0.46 (0.01 to 0.91)	0.38 (−0.09 to 0.85)	0.76 (0.50 to 1.00)*	0.72 (0.43 to 1.00)*

Data are variance (R^2) with 95% CIs.
*Denotes significantly different (p<0.05) from the rolling daily averages ACWR model.

moderate, high and very high ACWR ranges while no differences were observed at very low and low ACWR ranges. Given the current understanding of the relationship between very high ACWR ranges and subsequent increases in injury risk,[1 2 6] the importance of this finding is twofold. First, rolling averages consider the relationship between load and injury as linear, and therefore all workload in a given time frame is considered equal —when it is not. The EWMA model places a greater emphasis on the most recent workload a player has performed which will alter the ACWR value for a given day. Second, since the EWMA model alters the value for a given day, it influences where a player sits on the ACWR spectrum. If this increases their ACWR value, it may place them in a 'danger zone' that would not be recognised using the rolling averages ACWR model. Therefore, if ACWR values differ at the higher end of the ACWR spectrum using each model, it is important to consider this and its subsequent effect on injury risk.

What happens when workloads are spiked?

The findings of this study demonstrate that large spikes in acute workload, relative to chronic workload, resulting in a very high ACWR were significantly associated with an increased risk of injury during both the preseason and in-season periods. This finding was replicated across both models, suggesting that regardless of which model of ACWR calculation was used, large spikes in workload, coupled with a very high ACWR, resulted in a significant increase in injury risk. The strength of the ACWR is that it considers the workload a player has performed, relative to the workload that the player has been prepared for,[2 6 26] while also acknowledging that the way the load is achieved is as important as the ACWR itself.[12 17] With that in mind, it is clear that irrespective of the model used, linear[1 2 17] or non-linear,[14 18] the use of the ACWR should be used to maximise performance in players through developing high chronic workloads to adequately prepare players for competition demands and minimising the risk of injury.[2 26]

The EWMA model may be more sensitive

A novel finding of this study is the relationship between a very high ACWR, calculated using the EWMA model, and an increase in injury risk during the preseason period. While the relationship between large spikes in workload and injury risk during the in-season period is well defined,[3] the relationship during the preseason period is not as clear. Unlike previous work in elite AF,[3] our results demonstrate that using the EWMA model, large spikes in workload during the preseason are associated with a significant rise in injury risk. It has previously been suggested that players are not as well equipped to handle spikes in workload during the in-season period as they are during the preseason period due to increased match and physical demands,[27 28] coupled with an increased emphasis on performance and recovery. While the preseason period is typically viewed as an opportunity to develop the required physical and physiological qualities to successfully compete during the in-season period,[29] it is crucial that high workloads are prescribed systematically to apply adequate workloads to elicit a positive physiological change, while also minimising the negative physiological response.[2 12 29] It has been shown that greater amounts of training during the preseason period may also offer a protective effect against injury during the subsequent in-season competitive period,[30 31] highlighting the further importance placed on the preseason period. Using the EWMA model, it appears that large workload spikes, during either the preseason or in-season period, are associated with a clear threshold (ie, ACWR>1.50) where injury risk increases rapidly. The use of the EWMA model has increased the sensitivity of injury likelihood, suggesting that the rolling averages ACWR model does not: (1) accurately represent the variations in how workloads are accumulated (ie, a workload performed 28 days ago is not equal to a workload performed 3 days ago),[14 18] and (2) account for the decaying nature of fitness and fatigue effects over time.[14 18]

Potential limitations

While the findings of this study hold important implications for sports science and medicine staff, there are limitations that warrant further discussion. First, the sample size was limited to 59 players from one club over a 2-year period. It is difficult to draw competition-wide specific conclusions, as the findings may be reflective of this particular cohort of players at this particular point in time. Further, a small number of injuries (n=40) were recorded due to the inclusion criteria of only non-contact soft-tissue 'time-loss' injuries as they are typically considered 'workload-related' injuries. Further studies with players from multiple clubs and a larger number of injuries would strengthen these findings. Second, no internal measures of workload (eg, session rating of perceived exertion or heart rate) were included in this study. The inclusion of these may be useful to further investigate the relationship between internal workload and injury likelihood. While the majority of statistical information provided in this study stems from logistic regression models, we acknowledge that by running multiple models, and thus multiple comparisons, the risk of a type I error may be inflated. Finally, our results may be influenced by a smaller sample size at the extremities of ACWR ranges (ie, >2.0). This may be due to established load monitoring systems to reduce the number of exposures to very high ACWR ranges.

CONCLUSIONS

In this first study to investigate the difference between two proposed models of ACWR calculation and injury likelihood in elite AF players, a high ACWR was significantly associated with an increase in injury risk for both models. Further, the EWMA model had significantly greater sensitivity to detect increases in injury likelihood at higher ACWR ranges during both the preseason and in-season periods. This finding supports the refinement of the current ACWR model, although the concept that a player performing a greater workload than what they are prepared for is reinforced. While the ACWR model may be refined to increase sensitivity, the basic concept of building chronic workloads to prepare players to tolerate acute workloads will remain the same. Similarly, the ACWR should not be considered in isolation, but rather in context with acute and chronic workloads. Future work should attempt to quantify the direct (ie, medical expenses, financial loss) and indirect (ie, missed training and competition, etc) costs of workload-related (ie, spikes in workload) injuries and/or the longitudinal effects of controlled training loads on injury rates, as this may provide greater insight than continued risk factor analysis.

What are the findings?

- The exponentially weighted moving averages (EWMA) model is more sensitive to detect increases in injury risk at higher acute:chronic workload ratio (ACWR) ranges during the preseason and in-season periods.
- The EWMA model may be better suited to modelling workloads and injury risk than the rolling averages ACWR model.
- Irrespective of the ACWR model used, large spikes in acute workload are significantly associated with an increase in injury risk.

How might it impact on clinical practice in the future?

- Sharp spikes in workload for multiple variables should be avoided, as they are associated with an increase in injury risk.
- The rolling averages model is evidence-based and supported by the available literature to quantify injury risk; however, the exponentially weighted moving averages model to calculate acute:chronic workload ratio (ACWR) has greater sensitivity for detecting increases in injury risk at higher ACWR ranges and therefore should be used to model workloads and injury risk.
- Providing more evidence around different methods of ACWR calculation and injury risk will enable practitioners involved in the physical preparation of elite players to systematically and 'safely' prescribe high training loads to enhance the physical qualities required to both compete and succeed at the highest level of their chosen sport while minimising the risk of workload-related injury.

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Contributors NBM was primarily responsible for the collection and analysis of the study data. All authors were responsible for the study concept and design, and contributed to the writing and critical revision of the manuscript.

Competing interests None declared.

Ethics approval Approval was granted by the Australian Catholic University Human Research Ethics Committee.

Provenance and peer review Not commissioned; externally peer reviewed.

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