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1 RUNNING HEAD: Bowling loads and injury risk in fast bowlers

2

3 **Bowling loads and injury risk in male first class county cricket: Is ‘differential load’ an**
4 **alternative to the acute-to-chronic workload ratio?**

5 **Abstract**

6 **Objectives:** Methodological concerns relating to acute-to-chronic workload ratios (ACWR) have been
7 raised. This study aimed to assess the relationship between an alternative predictor variable named
8 ‘differential load’, representing the smoothed week-to-week rate change in load, and injury risk in first
9 class county cricket (FCCC) fast bowlers.

10 **Design:** Prospective cohort study.

11 **Methods:** Bowling loads and injuries were recorded for 49 professional male fast bowlers from six
12 FCCC teams. A range of differential loads and ACWRs were calculated and subjected to a variable
13 selection procedure.

14 **Results:** Exponentially-weighted 7-day differential load, 9:21-day ACWR, 42-day chronic load, and 9-
15 day acute load were the best-fitting predictor variables in their respective categories. From these, a
16 generalized linear mixed-effects model combining 7-day differential load, 42-day chronic load, and 9-
17 day acute load provided the best model fit. A two-standard deviation (2SD) increase in 7-day differential
18 load (22 overs) was associated with a substantial increase in injury risk (risk ratio [RR] = 2.47, 90% CI:
19 1.27-4.80, *most likely harmful*), and a 2SD increase in 42-day chronic load (17.5 overs/week) was
20 associated with a *most likely harmful* increase in injury risk (RR = 6.77, 90% CI: 2.15-21.33). For 9-
21 day acute load, very low values (≤ 1 over/week) were associated with a *most likely* higher risk of injury
22 versus moderate (17.5 overs/week; RR: 15.50, 90% CI: 6.19-38.79) and very high 9-day acute loads
23 (45.5 overs/week; RR: 133.33, 90% CI: 25.26-703.81).

24 **Conclusions:** Differential loads may be used to identify potentially harmful spikes in load, whilst
25 mitigating methodological issues associated with ACWRs.

26 Key words: External load, ACWR, risk factor

27 **Introduction**

28 Cricket is one of the most popular sports in the UK, having nearly two hundred thousand adult
29 participants¹. There are a total of 18 professional, first-class county cricket (FCCC) clubs in England
30 and Wales and they take part in three national competitions; a four-day competition (two batting innings
31 per team) and two one-day, limited over competitions (50- and 20-over formats). Research within
32 cricket has repeatedly found that fast bowlers have the highest injury rates of the four player roles (slow
33 bowler, batsmen, wicket-keeper) and that bowling loads are an important risk factor in the pathway to
34 injury.² Efforts to reduce injury rates in this population have led to investigations of the influence of
35 bowling volumes and bowling session frequency on injury risk.³ Several authors have reported both
36 high and low bowling loads to be associated with increased injury,^{4,5} and recommendations for ‘safe’
37 fast bowling volumes/frequencies have been proposed.⁶

38 Following on from these initial load-injury investigations in cricket, the ratio of acute (one-week) to
39 chronic (four-week rolling average) loads have been modelled against injury risk, with this metric
40 termed the ‘acute-to-chronic workload ratio’ (ACWR).⁷ Fast bowlers with an ACWR of more than
41 200% had a relative risk of 3.3 in comparison to fast bowlers with an ACWR between 50-99%.⁷ Several
42 subsequent studies have explored the association between the ACWR metric and injury risk within
43 cricket,² as well as other sporting populations.⁸ This work has led to the recommendation that
44 practitioners should aim to maintain the ACWR within a range of approximately 0.8–1.3 to minimise
45 injury risk.⁹ However, the level of evidence supporting the ACWR as a risk factor for injury is poor,¹⁰
46 ¹¹ no study has demonstrated reduced injury risk following an altered ACWR in a causal manner, and
47 there has been considerable debate concerning appropriate calculation methods. For instance, rolling
48 averages have been used to compute the acute and chronic periods of the ACWR in the majority of
49 studies, but these fail to account for the decaying nature of ‘fitness’ and ‘fatigue’.¹² That is, loads
50 undertaken seven days ago will have less of an influence on an athlete’s current fatigue status than an
51 equivalent load undertaken one day ago, whilst fitness effects will also decay over time.¹³
52 Exponentially-weighted moving averages (EWMA) have been proposed as a solution,¹⁴ and have

53 indeed demonstrated greater sensitivity with respect to injury risk in a cohort of elite Australian
54 football players.¹⁵ There has also been debate regarding the arbitrary length of chosen acute and chronic
55 periods,¹⁶ and the potential for spurious correlations caused by mathematical coupling when calculating
56 the ACWR.¹⁷ Overall, the ACWR may represent an inaccurate scaling index for an unnecessary
57 normalisation process.¹⁸

58 More recently, a novel ‘differential load’ metric, representing the smoothed rate of change in load from
59 one week to the next, was proposed by Lazarus et al.,¹⁹ and was shown to be associated with team
60 performance in elite Australian football. Week-to-week changes in load have previously been associated
61 with injury risk in team sport athletes²⁰; the exponentially-weighted smoothing of this metric helps to
62 account for the decaying nature of ‘fitness’ and ‘fatigue’ and helps to reduce ‘noise’ when using daily
63 load data. This metric may be valuable in capturing ‘spikes’ in acute loads, whilst mitigating
64 methodological issues associated with the use of ACWR. Therefore, the purpose of the present study
65 was to identify the optimal ACWR calculation method within FCCC fast bowlers, and to investigate
66 the utility of ‘differential load’ as a potential alternative metric for injury risk management in this
67 setting.

68 **Methods**

69 A cohort of 49 adult professional male fast bowlers (mean age of 27 ± 5 years) from six FCCC Clubs
70 participated in this study. Ethical approval for the project was granted by Cardiff Metropolitan
71 University and each participant provided written informed consent. For the purposes of the study, a fast
72 bowler was defined as someone to whom the wicketkeeper usually stands back from the stumps to
73 receive the ball.²¹ Bowling loads and injury data collected over a full season (6 months) of FCCC were
74 retrospectively analysed.

75 An injury was defined as any fast bowling related injury that resulted in the player being considered
76 unavailable for cricket match selection, regardless of whether there was a match or training scheduled
77 on that date, or, during a match, caused a player to be unable to bat, bowl, or keep wicket when required

78 by either the rules or the team's captain.²² It was left to the team physiotherapist's discretion as to
79 whether the injury sustained was fast bowling related.

80 Daily load data (number of balls bowled, with six balls bowled equating to one 'over') was collected
81 using a standardised data collection form by the physiotherapist of each participating FCCC Club.
82 Warm-up deliveries prior to the start of a game or in a training session were not included. This insured
83 that only competitive effort bowling data was recorded. Average loads on each day were calculated for
84 a range of 'acute' (3→9 d, in 2 day increments) and 'chronic' (14→84 d, in 7 d increments) periods,
85 using both rolling and exponentially-weighted (smoothed) averaging approaches.¹⁴ A range of acute and
86 chronic time windows were explored in order to find the optimal choice for this sport,¹⁶ with previous
87 research suggesting longer chronic time windows may be most relevant in cricket fast bowlers.⁵ The
88 smoothed load for each day was calculated as $\lambda \times (\text{the previous day's load}) + (1 - \lambda) \times (\text{the smoothed}$
89 $\text{load up to that point})$. Smoothed loads were initiated using the mean of the first seven days of load data
90 for each bowler. Rolling average ACWR on each day was calculated by dividing each acute rolling
91 average load by each chronic rolling average load. Similarly, smoothed ACWR on each day was
92 calculated by dividing each acute smoothed load by each of the chronic smoothed loads. A differential
93 load measure was also calculated, as proposed by Lazarus et al.¹⁹ Differential load represented the
94 smoothed rate of change in load from one week to the next. For this, the previous day's load in the
95 above formula was replaced with the change in total load between the current and previous week.
96 Smoothed differential loads with time constants of 7, 14, 21, and 28 days were generated. The fast
97 bowler's load metrics on a given day represented their load prior to any training/competition performed
98 on that day. As such, the loads undertaken on the day of an injury did not contribute to the load metrics
99 associated with that given injury.

100 In order to select the most parsimonious set of training load measures, whilst still retaining the variation
101 and unique components within the data, a variable selection procedure was undertaken using the
102 *AICcmodavg* package.²³ The training load measure with the lowest Akaike Information Criteria (AICc)
103 score was selected as the representative measure for each of the following components; 'chronic load',

104 'acute load', and 'change in load'.²⁴ The best-fitting ACWR and differential load measures were chosen
105 for the 'change in load' component to enable direct comparison between these measures. The selected
106 training load measures were then included in multivariable analyses to identify the overall best-fitting
107 model, as determined by the *GLMERSelect* stepwise selection procedure.²⁵ Polynomial and interaction
108 terms were evaluated in this process. The best-fitting ACWR and differential load measures were
109 compared via the area under the curve (AUC) achieved when modelled on an independent (holdout)
110 test dataset (25% of original dataset).

111 All estimations were made using *R* (version 3.6.0, R Foundation for Statistical Computing, Vienna,
112 Austria). A generalized linear mixed-effects model (GLMM) with complementary log-log link function
113 was used to model the association between the training load measures (as determined by the
114 aforementioned variable selection process) and injury risk. This model was implemented via the *lmer*
115 package.²⁶ Fixed effects in this model were the intercept and the training load measures, with the square
116 of the training measure included to estimate the mean quadratic. Player identity was included as a
117 random effect. Predictor variables were evaluated as the change in risk associated with a 2SD increase
118 in the predictor variable.¹⁹ The smallest important increase in injury risk was a relative risk (RR) of
119 1.11, and the smallest important decrease in risk was 0.90.²⁷ An effect was deemed '*unclear*' if the
120 chance that the true value was beneficial was >25%, with odds of benefit relative to odds of harm (odds
121 ratio) of <66. Otherwise, the effect was deemed clear, and was qualified with a probabilistic term using
122 the following scale: <0.5%, *most unlikely*; 0.5-5%, *very unlikely*; 5-25%, *unlikely*; 25-75%, *possible*;
123 75-95%, *likely*; 95-99.5%, *very likely*; >99.5%, *most likely*.¹⁹ The data is presented as means and 90%
124 confidence intervals (CI) with injury likelihoods estimated at typically very low (-2SD), low (-1SD),
125 mean, high (+1SD), and very high (+2SD) values of each predictor.¹⁹

126 **Results**

127 A total of 9240 player days exposure were included in the study of which bowling related injuries
128 accounted for 1351 days-lost. Sixty-nine bowling-related injuries were sustained in a total of 40 (73%)

129 players with 15 (27%) remaining injury free. Injury incidence was 7.5 per 1000 days and injury
130 prevalence was 14.6%.

131 The best-fitting ‘chronic load’, ‘acute load’, and ‘change in load’ measures were smoothed 42-d load,
132 smoothed 9-d load, 7-d differential load, and smoothed 9:21-d ACWR, respectively (Figure 1). From
133 these, a model combining 7-day differential load, smoothed 42-day chronic load, and a quadratic term
134 for smoothed 9-d acute load term, provided the best overall model fit. The model utilising 7-day
135 differential load produced a higher AUC on the independent test dataset (AUC: 69.5) versus the
136 equivalent model with 9:21 d ACWR as the ‘change-in-load’ metric (AUC: 61.3).

137 **Figure 1 here**

138 A 2SD increase in 7-day differential load (22 overs) was associated with a substantial increase in injury
139 risk (risk ratio [RR] = 2.47, 90% CI: 1.27-4.80, *most likely harmful*, $P=0.02$). A 2SD increase in 42-day
140 chronic load (17.5 overs/week) was associated with a *most likely harmful* increase in injury risk (RR =
141 6.77, 90% CI: 2.15-21.33, $P=0.006$). For 9-day acute load, a non-linear effect was present, such that
142 very low values (≤ 1 over/week) were associated with a *most likely* higher risk of injury versus moderate
143 (17.5 overs/week; RR: 15.50, 90% CI: 6.19-38.79, $P<0.001$) and very high 9-day acute loads (45.5
144 overs/week; RR: 133.33, 90% CI: 25.26-703.81, $P<0.001$) (Figure 1).

145 **Figure 2 here**

146

147

148

149 **Discussion**

150 The purpose of this study was to identify the optimal ACWR calculation method within FCCC fast
151 bowlers, and to investigate the utility of ‘differential load’ as a potential alternative metric for injury

152 risk mitigation in this setting. An exponentially-weighted 9:21-day ACWR was shown to be the best-
153 fitting ACWR measure. However, the 7-d differential load metric produced a substantially better model
154 fit and was selected for inclusion in the multivariable model alongside 42-d chronic load and 9-d acute
155 load. A 2SD increase in 7-day differential load and 42-day chronic load was associated with a substantial
156 increase in injury risk. A non-linear effect was evident for 9-day acute load, such that very low acute
157 load values were associated with substantially higher injury risk versus moderate and high acute loads.
158 Overall, these data support previous work recommending that chronic bowling load be systematically
159 progressed, and then maintained at moderate-high levels (~21-28 overs/week).

160 The differential load measure explored in the current study displayed a significant and meaningful
161 association with injury risk, such that a 2SD increase in 7-day differential load (22 overs/week) was
162 associated with a ~2.5 time's higher risk of injury. That is, a sustained increase in bowling workload
163 over the past seven days, compared to the preceding week, of 22 overs/week was associated with a
164 substantial increase in injury risk. The differential load measure may therefore be used to capture
165 'spikes' in acute loads that potentially reduce "injury resiliency". Notably, the differential load measure
166 can capture these acute spikes in load without the need to normalise for chronic load via a potentially
167 inaccurate scaling index¹⁸ and whilst avoiding 'coupling' issues associated with the ACWR.¹⁷ The
168 multivariable model included a measure of both 42-day chronic and 9-day acute bowling load, and thus
169 controlled for these unique components.²⁴ Together, these findings suggest that very high chronic
170 bowling loads, large week-to-week increases in bowling loads, and bowling after a period of de-loading
171 (low 9-day acute load) all independently increase risk of injury in fast bowlers. These metrics may each
172 relate to specific injury types (e.g., tendon versus bone stress injuries).⁵ However, this could not be
173 addressed in the current study given the number of injuries included in the model, but this concept
174 warrants further investigation in future studies. Overall, these data support previous work
175 recommending that chronic bowling volume be systematically progressed and then maintained at
176 moderate-high levels (approximately 21-28 overs/week), to best manage injury risk.^{2, 5, 28}

177 In this setting, the EWMA approach produced the best-fitting ACWR measure for injury relationships,
178 with time constants of 9- and 21-days used for the acute and chronic components, respectively. This
179 finding is in line with existing work demonstrating the EWMA to be more sensitive to injury risk than
180 the rolling average approach in elite Australian football players,¹⁵ likely due to its ability to account for
181 the decaying nature of fitness and fatigue effects over time.¹⁴ As a simplified example, a short-term
182 ‘spike’ in bowling load towards the end of a training week, prior to a competitive match, may reduce
183 “injury resiliency” and thus increase a bowler’s likelihood of injury during that match (e.g., via reduced
184 tissue capacity/compliance). However, if the equivalent load spike were undertaken earlier in the
185 training week, the associated fatigue effects would dissipate to a larger degree by the time of the
186 competitive fixture, and thus the change in injury risk may be attenuated. The EWMA approach can
187 capture variations in how loads are accumulated more effectively than rolling averages, which may
188 explain its increased sensitivity to injury.¹⁵

189 Acute and chronic parameters of 9- and 21-days, respectively, were found to be optimal in this study,
190 as opposed to the more commonly used 7- and 28-day values.⁹ The structure of the First Class County
191 Cricket season is such that a 9-day acute load period may better capture the accumulation of fatigue
192 associated with bowling during consecutive 4-day and/or one-day fixtures. Similarly, the 21-day chronic
193 load period may reflect the structure of fixture ‘blocks’ within the sport, alongside typical player
194 management strategies. This finding endorses the suggestion of Carey et al.¹⁶ that teams wishing to use
195 ACWRs should model their own data so that they may identify which ratio is most appropriate for them.

196 There were several limitations associated with the present study. Firstly, the number of competitive
197 effort balls bowled was the only workload measured. It is recognised that injuries are a multifactorial
198 occurrence⁶ and previous studies have found that internal loads may have a greater association with
199 injury risk in cricket.⁷ However, although other training could influence injury risk, it was difficult to
200 accurately quantify in this multi-team setting and was therefore omitted. Future research should aim to
201 incorporate measures of other sources of training load (e.g., resistance training, conditioning, batting,
202 fielding, and travel) for elite fast-bowlers, alongside objective measures of bowling volumes and

203 intensity. Injury occurrences were recorded by the corresponding team physiotherapist and required
204 their discretion as to whether injuries sustained had qualified as a bowling-related injury or not. This
205 not only relies on the judgement of others, but conjecture may have taken place in identifying truly
206 bowling-related injuries. For example, it may have been difficult to determine if an injury sustained
207 while batting or fielding after finishing a bowling session may have been caused by fatigue induced
208 from bowling. However, the injury prevalence rates of approximately 15% were comparable to other
209 studies of first-class cricket fast bowlers,²⁹ suggesting the determination of a bowling injury was
210 appropriate. Finally, the potential for there to be a 'lag period' between high bowling loads and injury
211 occurrence was not accounted for in the present study.³⁰

212 **Conclusion**

213 Differential loads may be used to identify harmful spikes in load, whilst mitigating methodological
214 issues associated with the use of ACWR. This study supports previous work recommending that chronic
215 bowling volume be systematically progressed, and then maintained at moderate-high levels, to best
216 manage injury risk. Specifically, prolonged periods of high bowling loads (high 42-day chronic loads)
217 and large week-to-week increases in load (differential load) should be avoided. Yet, bowling after a
218 period of unloading (resulting in a low 9-day acute load) was also found to be associated with increased
219 risk of injury, and so (42-d) chronic bowling loads should be progressively increased and then
220 maintained at moderate-high (~21-28 overs/week) levels to attenuate injury risk. Future research should
221 seek to determine the role of differential loads in the causal pathway of injury.

222 **Practical implications**

- 223 • Differential loads should be monitored in fast bowlers to help avoid week-to-week changes in
224 bowling loads that increase injury risk.
- 225 • Chronic bowling loads should be progressively increased and then maintained at moderate-high
226 (~21-28 overs/week) levels to attenuate injury risk.
- 227 • Special attention should also be paid to bowlers returning from a period of unloading (resulting
228 in a low 9-day acute load).

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300 **Figure descriptions:**

301 Figure 1: AICc values for each predictor within the ‘chronic load’, ‘change-in-load’ and ‘acute load’
302 components.

303

304 Figure 2: Predicted injury likelihood and 90% confidence intervals estimated at typically very low
305 (-2SD), low (-1SD), mean, high (+1SD), and very high (+2SD) values of (A) 7-d differential load, (B)
306 42-d chronic load, and (C) 9-d acute load. Values in square brackets represent daily balls bowled.