RUNNING HEAD: Bowling loads and injury risk in fast bowlers

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

Abstract

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

Design: Prospective cohort study.

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

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

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

Key words: External load, ACWR, risk factor

Introduction

Cricket is one of the most popular sports in the UK, having nearly two hundred thousand adult participants[1]. There are a total of 18 professional, first-class county cricket (FCCC) clubs in England and Wales and they take part in three national competitions; a four-day competition (two batting innings per team) and two one-day, limited over competitions (50- and 20-over formats). Research within cricket has repeatedly found that fast bowlers have the highest injury rates of the four player roles (slow bowler, batsmen, wicket-keeper) and that bowling loads are an important risk factor in the pathway to injury.[2] Efforts to reduce injury rates in this population have led to investigations of the influence of bowling volumes and bowling session frequency on injury risk.[3] Several authors have reported both high and low bowling loads to be associated with increased injury,[4, 5] and recommendations for 'safe' fast bowling volumes/frequencies have been proposed.[6]

Following on from these initial load-injury investigations in cricket, the ratio of acute (one-week) to chronic (four-week rolling average) loads have been modelled against injury risk, with this metric termed the 'acute-to-chronic workload ratio' (ACWR).[7] Fast bowlers with an ACWR of more than 200% had a relative risk of 3.3 in comparison to fast bowlers with an ACWR between 50-99%.[7] Several subsequent studies have explored the association between the ACWR metric and injury risk within cricket,[2] as well as other sporting populations.[8] This work has led to the recommendation that practitioners should aim to maintain the ACWR within a range of approximately 0.8–1.3 to minimise injury risk.[9] However, the level of evidence supporting the ACWR as a risk factor for injury is poor,[10, 11] no study has demonstrated reduced injury risk following an altered ACWR in a causal manner, and there has been considerable debate concerning appropriate calculation methods. For instance, rolling averages have been used to compute the acute and chronic periods of the ACWR in the majority of studies, but these fail to account for the decaying nature of 'fitness' and 'fatigue'.[12] That is, loads undertaken seven days ago will have less of an influence on an athlete's current fatigue status than an equivalent load undertaken one day ago, whilst fitness effects will also decay over time.[13] Exponentially-weighted moving averages (EWMA) have been proposed as a solution,[14] and have indeed demonstrated greater sensitivity with respect to injury risk in a cohort of elite Australian football players.[15] There has also been debate regarding the arbitrary length of chosen acute and chronic periods,[16] and the potential for spurious correlations caused by mathematical coupling when calculating the ACWR.[17] Overall, the ACWR may represent an inaccurate scaling index for an unnecessary normalisation process.[18]

More recently, a novel 'differential load' metric, representing the smoothed rate of change in load from one week to the next, was proposed by Lazarus et al.,[19] and was shown to be associated with team performance in elite Australian football. Week-to-week changes in load have previously been associated with injury risk in team sport athletes[20]; the exponentially-weighted smoothing of this metric helps to account for the decaying nature of 'fitness' and 'fatigue' and helps to reduce 'noise' when using daily load data. This metric may be valuable in capturing 'spikes' in acute loads, whilst mitigating methodological issues associated with the use of ACWR. Therefore, the purpose of the present study was to identify the optimal ACWR calculation method within FCCC fast bowlers, and to investigate the utility of 'differential load' as a potential alternative metric for injury risk management in this setting.

Methods

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

An injury was defined as any fast bowling related injury that resulted in the player being considered unavailable for cricket match selection, regardless of whether there was a match or training scheduled on that date, or, during a match, caused a player to be unable to bat, bowl, or keep wicket when required by either the rules or the team's captain.[22] It was left to the team physiotherapist's discretion as to whether the injury sustained was fast bowling related.

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

In order to select the most parsimonious set of training load measures, whilst still retaining the variation and unique components within the data, a variable selection procedure was undertaken using the *AICcmodavg* package.[23] The training load measure with the lowest Akaike Information Criteria (AICc) score was selected as the representative measure for each of the following components; 'chronic load', 'acute load', and 'change in load'.[24] The best-fitting ACWR and differential load measures were chosen for the 'change in load' component to enable direct comparison between these measures. The selected training load measures were then included in multivariable analyses to identify the overall best-fitting model, as determined by the *GLMERSelect* stepwise selection procedure.[25] Polynomial and interaction terms were evaluated in this process. The best-fitting ACWR and differential load measures were compared via the area under the curve (AUC) achieved when modelled on an independent (holdout) test dataset (25% of original dataset).

All estimations were made using *R* (version 3.6.0, R Foundation for Statistical Computing, Vienna, Austria). A generalized linear mixed-effects model (GLMM) with complementary log-log link function was used to model the association between the training load measures (as determined by the aforementioned variable selection process) and injury risk. This model was implemented via the *lmer* package.[26] Fixed effects in this model were the intercept and the training load measures, with the square of the training measure included to estimate the mean quadratic. Player identity was included as a random effect. Predictor variables were evaluated as the change in risk associated with a 2SD increase in the predictor variable.[19] The smallest important increase in injury risk was a relative risk (RR) of 1.11, and the smallest important decrease in risk was 0.90.[27] 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*.[19] The data is presented as means and 90% confidence intervals (CI) with injury likelihoods estimated at typically very low (-2SD), low (-1SD), mean, high (+1SD), and very high (+2SD) values of each predictor.[19]

Results

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

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

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

Figure 1 here

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

Figure 2 here

Discussion

The purpose of this study was to identify the optimal ACWR calculation method within FCCC fast bowlers, and to investigate the utility of ‘differential load’ as a potential alternative metric for injury risk mitigation in this setting. An exponentially-weighted 9:21-day ACWR was shown to be the best-fitting ACWR measure. However, the 7-d differential load metric produced a substantially better model fit and was selected for inclusion in the multivariable model alongside 42-d chronic load and 9-d acute load. A 2SD increase in 7-day differential load and 42-day chronic load was associated with a substantial increase in injury risk. A non-linear effect was evident for 9-day acute load, such that very low acute load values were associated with substantially higher injury risk versus moderate and high acute loads. Overall, these data support previous work recommending that chronic bowling load be systematically progressed, and then maintained at moderate-high levels (~21-28 overs/week).

The differential load measure explored in the current study displayed a significant and meaningful association with injury risk, such that a 2SD increase in 7-day differential load (22 overs/week) was associated with a ~2.5 time's higher risk of injury. That is, a sustained increase in bowling workload over the past seven days, compared to the preceding week, of 22 overs/week was associated with a substantial increase in injury risk. The differential load measure may therefore be used to capture 'spikes' in acute loads that potentially reduce "injury resiliency". Notably, the differential load measure can capture these acute spikes in load without the need to normalise for chronic load via a potentially inaccurate scaling index[18] and whilst avoiding 'coupling' issues associated with the ACWR.[17] The multivariable model included a measure of both 42-day chronic and 9-day acute bowling load, and thus controlled for these unique components.[24] Together, these findings suggest that very high chronic bowling loads, large week-to-week increases in bowling loads, and bowling after a period of de-loading (low 9-day acute load) all independently increase risk of injury in fast bowlers. These metrics may each relate to specific injury types (e.g., tendon versus bone stress injuries).[5] However, this could not be addressed in the current study given the number of injuries included in the model, but this concept warrants further investigation in future studies. Overall, these data support previous work recommending that chronic bowling volume be systematically progressed and then maintained at moderate-high levels (approximately 21-28 overs/week), to best manage injury risk.[2, 5, 28]

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

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

There were several limitations associated with the present study. Firstly, the number of competitive effort balls bowled was the only workload measured. It is recognised that injuries are a multifactorial occurrence[6] and previous studies have found that internal loads may have a greater association with injury risk in cricket.[7] However, although other training could influence injury risk, it was difficult to accurately quantify in this multi-team setting and was therefore omitted. Future research should aim to incorporate measures of other sources of training load (e.g., resistance training, conditioning, batting, fielding, and travel) for elite fast-bowlers, alongside objective measures of bowling volumes and intensity. Injury occurrences were recorded by the corresponding team physiotherapist and required their discretion as to whether injuries sustained had qualified as a bowling-related injury or not. This not only relies on the judgement of others, but conjecture may have taken place in identifying truly bowling-related injuries. For example, it may have been difficult to determine if an injury sustained while batting or fielding after finishing a bowling session may have been caused by fatigue induced from bowling. However, the injury prevalence rates of approximately 15% were comparable to other studies of first-class cricket fast bowlers,[29] suggesting the determination of a bowling injury was appropriate. Finally, the potential for there to be a 'lag period' between high bowling loads and injury occurrence was not accounted for in the present study.[30]

Conclusion

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

Practical implications

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

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References

1. Sport England. Active People Survey 7. http://www.sportengland.org/media/226699/1x30_sport_16-factsheet_APS7_final.pdf.

2. Warren A, Williams S, McCaig S, Trewartha G. High acute: chronic workloads are associated with injury in England & Wales Cricket Board Development Programme fast bowlers. *J. Sci. Med. Sport.* 2018; 21(1):40-45.

3. Kountouris A, Sims K, Beakley D, et al. MRI bone marrow oedema precedes lumbar bone stress injury diagnosis in junior elite cricket fast bowlers. *Br. J. Sports Med.* 2018:bjsports-2017-097930.

4. Alway P, Brooke-Wavell K, Langley B, King M, Peirce N. Incidence and prevalence of lumbar stress fracture in English County Cricket fast bowlers, association with bowling workload and seasonal variation. *BMJ Open Sport & Exercise Medicine.* 2019; 5(1):e000529.

5. Orchard JW, Blanch P, Paoloni J, et al. Cricket fast bowling workload patterns as risk factors for tendon, muscle, bone and joint injuries. *Br. J. Sports Med.* 2015; 49(16):1064-1068.

6. Dennis R, Farhart R, Goumas C, Orchard J. Bowling workload and the risk of injury in elite cricket fast bowlers. *J. Sci. Med. Sport.* 2003; 6(3):359-367.

7. Hulin BT, Gabbett TJ, Blanch P, Chapman P, Bailey D, Orchard JW. Spikes in acute workload are associated with increased injury risk in elite cricket fast bowlers. *Br. J. Sports Med.* 2014; 48(8):708-712.

8. Griffin A, Kenny IC, Comyns TM, Lyons M. The association between the acute: chronic workload ratio and injury and its application in team sports: A systematic review. *Sports Med.* 2019:1-20.

9. Gabbett TJ. The training-injury prevention paradox: Should athletes be training smarter and harder? *Br. J. Sports Med.* 2016; 50(5):273-280.

10. Coyne JO, Haff GG, Coutts AJ, Newton RU, Nimphius S. The current state of subjective training load monitoring—A practical perspective and call to action. *Sports Medicine - Open.* 2018; 4(1):58.

11. Impellizzeri F, Wookcock S, McCall A, Ward P, Coutts AJ. The acute-chronic workload ratio-injury figure and its 'sweet spot'are flawed. 2019.

12. Menaspà P. Are rolling averages a good way to assess training load for injury prevention? *Br. J. Sports Med.* 2016.

13. Hawley JA. Adaptations of skeletal muscle to prolonged, intense endurance training. *Clin. Exp. Pharmacol. Physiol.* 2002; 29(3):218-222.

14. Williams S, West S, Cross MJ, Stokes KA. Better way to determine the acute: chronic workload ratio? *Br. J. Sports Med.* 2017; 51(3):209-210.

15. Murray NB, Gabbett TJ, Townshend AD, Blanch P. Calculating acute: chronic workload ratios using exponentially weighted moving averages provides a more sensitive indicator of injury likelihood than rolling averages. *Br. J. Sports Med.* 2016; 51:749-754.

16. Carey DL, Blanch P, Ong K-L, Crossley KM, Crow J, Morris ME. Training loads and injury risk in Australian football—differing acute: chronic workload ratios influence match injury risk. *Br. J. Sports Med.* 2016:bjsports-2016-096309.

17. Lolli L, Batterham AM, Hawkins R, et al. Mathematical coupling causes spurious correlation within the conventional acute-to-chronic workload ratio calculations. *Br. J. Sports Med.* 2017.

18. Lolli L, Batterham AM, Hawkins R, et al. The acute-to-chronic workload ratio: an inaccurate scaling index for an unnecessary normalisation process? *Br. J. Sports Med.* 2018.

19. Lazarus BH, Stewart AM, White KM, et al. Proposal of a global training load measure predicting match performance in an elite team sport. *Frontiers in Physiology.* 2017; 8:930.

20. Rogalski B, Dawson B, Heasman J, Gabbett TJ. Training and game loads and injury risk in elite Australian footballers. *J. Sci. Med. Sport.* 2013; 16(6):499-503.

21. Orchard J, Newman D, Stretch R, Frost W, Mansingh A, Lelpus A. Methods for injury surveillance in international cricket. *South African Journal of Sports Medicine.* 2005; 17(2):18-28.

22. Orchard JW, Ranson C, Olivier B, et al. International consensus statement on injury surveillance in cricket: a 2016 update. *Br. J. Sports Med.* 2016; 50(20):1245-1251.

23. Mazerolle MJ, Mazerolle MMJ. Package 'AICcmodavg'. *R package.* 2017.

24. Williams S, Trewartha G, Cross M, Kemp S, Stokes K. Monitoring what matters: A systematic process for selecting training-load measures. *International Journal of Sports Physiology and Performance.* 2017; 12(S2):101-106.

25. Newbold T. StatisticalModels. https://rdrr.io/github/timnewbold/StatisticalModels/man/GLMERSelect.html.

26. Bates D, Maechler M, Dai B. Fitting Linear Mixed-Effects Models Using lme4. *Journal of Statistical Software.* 2015; 67:1-48.

27. Hopkins WG. Linear models and effect magnitudes for research, clinical and practical applications. *Sportscience.* 2010; 14:49-57.

28. Ahmun R, McGraig S, Tallent J, Williams S, Gabbett T. Association of Daily Workload, Wellness, Injury and Illness during Tours in International Cricketers. *International Journal of Sports Physiology and Performance.* 2018.

29. Orchard J, James T, Kountouris A, Portus M. Changes to injury profile (and recommended cricket injury definitions) based on the increased frequency of Twenty20 cricket matches. *Open access journal of sports medicine.* 2010; 1:63.

30. Orchard JW, James T, Portus M, Kountouris A, Dennis R. Fast bowlers in cricket demonstrate up to 3-to 4-week delay between high workloads and increased risk of injury. *Am. J. Sports Med.* 2009; 37(6):1186-1192.

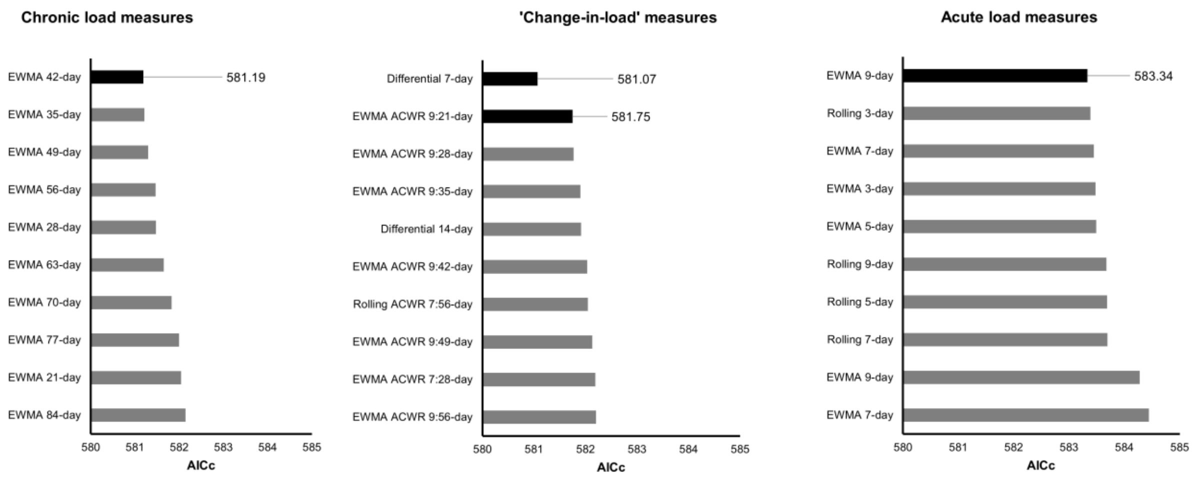

Figure 1: AICc values for each predictor within the ‘chronic load’, ‘change-in-load’ and ‘acute load’ components.

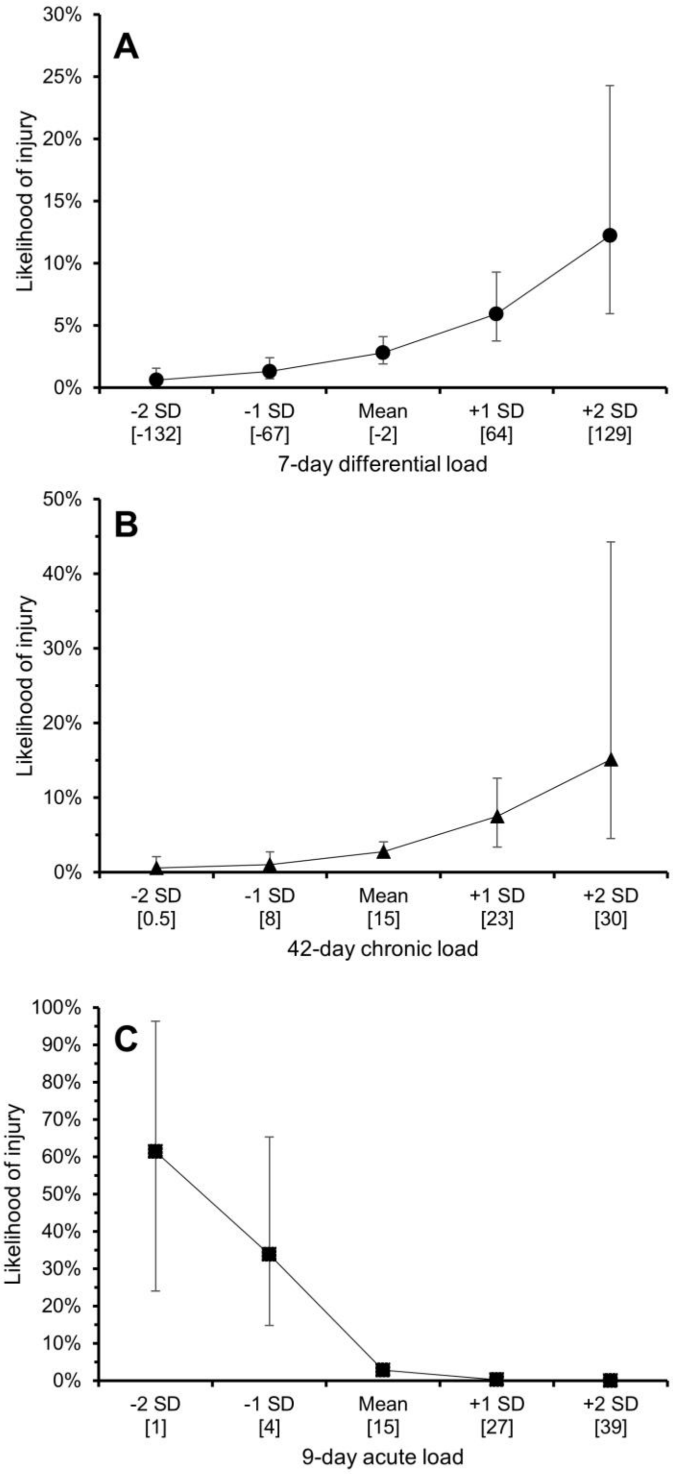

Figure 2: Predicted injury likelihood and 90% confidence intervals estimated at typically very low (-2SD), low (-1SD), mean, high (+1SD), and very high (+2SD) values of (A) 7-d differential load, (B) 42-d chronic load, and (C) 9-d acute load. Values in square brackets represent daily balls bowled.