[CLINICAL COMMENTARY]

FRANCO M. IMPELLIZZERI, PhD[1] • **PATRICK WARD,** PhD[1]
AARON J. COUTTS, PhD[1] • **LUKE BORNN,** PhD[2] • **ALAN MCCALL,** PhD[1,3]

Training Load and Injury Part 2: Questionable Research Practices Hijack the Truth and Mislead Well-Intentioned Clinicians

> *"We must be careful not to believe things simply because we want them to be true; no one can fool you as easily as you can fool yourself."*
>
> *— Richard Feynman*

BACKGROUND: In this clinical commentary, we highlight issues related to conceptual foundations and methods used in training load and injury research. We focus on sources of degrees of freedom that can favor questionable research practices such as *P* hacking and hypothesizing after the results are known, which can undermine the trustworthiness of research findings.

CLINICAL QUESTION: Is the methodological rigor of studies in the training load and injury field sufficient to inform training-related decisions in clinical practice?

KEY FINDINGS: The absence of a clear conceptual framework, causal structure, and reliable methods can promote questionable research practices, selective reporting, and confirmation bias. The fact that well-accepted training principles (eg, overload progression) are in line with some study findings may simply be a consequence of confirmation bias, resulting from cherry picking and emphasizing results that align with popular beliefs. Identifying evidence-based practical applications, grounded in high-quality research, is not currently possible. The strongest recommendation we can make for the clinician is grounded in common sense: "Do not train too much, too soon"—not because it has been confirmed by studies, but because it reflects accepted generic training principles.

CLINICAL APPLICATION: The training load and injury research field has fundamental conceptual and methodological weaknesses. Therefore, making decisions about planning and modifying training programs for injury reduction in clinical practice, based on available studies, is premature. Clinicians should continue to rely on best practice, experience, and well-known training principles, and consider the potential influence of contextual factors when planning and monitoring training loads. *J Orthop Sports Phys Ther 2020;50(10):577-584. Epub 1 Aug 2020. doi:10.2519/jospt.2020.9211*

KEY WORDS: *conceptual model, injury, research methods, risk of bias, training load*

It is tempting to believe a theory when it appears reasonable and fits with one's beliefs. For example, the theory that training "too much" or "too little," or "too much, too soon," might cause sports injury seems biologically plausible and aligns well with training dogma. Common beliefs about how training load affects the chances of the athlete getting injured have been strongly shaped by a combination of old and deeply held training principles, best practice, and common sense. Progressive overload and the "danger" of excessive training (overtraining or nonfunctional overreaching) are well-recognized training principles. The idea that excessive training can increase injury risk can be traced back to the early 1990s.[43]

Popular beliefs about training load and injury obfuscate important concepts and methodological issues. Unfortunately, these issues have not been well accounted for in previous research. Our concern is that the training load and injury research field is dominated by well-intentioned, yet potentially misleading, recommendations for clinical practice.

Collecting injury and training load data is now considered best practice in sport.[14] An unfortunate consequence of such a data-rich environment is that researchers studying the relationship between training load and injury may retrospectively select from a convenient sample of available data rather than develop clear and well-defined research questions before collecting data. There are many

[1]Human Performance Research Centre, Faculty of Health, University of Technology Sydney, Moore Park, Australia. [2]Strategy and Analytics, Sacramento Kings, Sacramento, CA. [3]Arsenal Performance and Research Team, Arsenal Football Club, London, United Kingdom. No funding support has been obtained for the present manuscript. The authors certify that they have no affiliations with or financial involvement in any organization or entity with a direct financial interest in the subject matter or materials discussed in the article. Address correspondence to Professor Franco M. Impellizzeri, Human Performance Research Centre, Faculty of Health, University of Technology Sydney, Driver Avenue, Moore Park, NSW 2021 Australia. E-mail: Franco.Impellizzeri@uts.edu.au

studies reporting associations between training load and injury. The problem is, without a clear conceptual framework, it is easier for confirmation bias or selective reporting to creep in and hijack the truth.

Clinicians are exposed to an ocean of information. One challenge for clinicians is to unravel the "signal" from the "noise" and identify relevant findings that can be confidently applied in practice. Most clinicians do not possess the ability to identify studies at high risk of bias, as this requires in-depth research methods training. The aims of our clinical commentary are to (1) help clinicians identify some of the methodological weaknesses in training load and injury studies, and (2) demonstrate why clinicians should exercise caution when applying findings from these studies to their practice.

CLINICAL QUESTION

Is the methodological rigor of studies investigating relationships between training load and injury sufficient to inform training load–related decisions in clinical practice? We have highlighted why it is important to critically examine the strength of evidence supporting the claims made in several training load and injury studies.[36] In this clinical commentary, we focus on sources of degrees of freedom that can favor questionable research practices (including *P* hacking and hypothesizing after the results are known [HARKing]) that can impact the trustworthiness of research findings and the application of training load metrics in clinical practice.

A Robust Conceptual Framework: The First Step in Designing Quality Research to Help Clinicians and Athletes

Developing a conceptual framework is an essential early step when designing research to inform clinical practice. If properly developed, a conceptual framework can guide researchers' hypotheses and specific research questions, and provide a frame for analyzing data and interpreting the results.[34,53] The practice of HARKing is a bit like doing research in reverse. When (well-intentioned) researchers do not develop a clear conceptual framework before collecting research data, they risk fashioning a hypothesis to suit their research results, and the temptation to conduct (unplanned) analyses until they find something "significant" (*P* hacking).

There have been attempts within the training load and injury field to provide generic concept maps and models.[61] These can help clinicians understand the multifactorial nature of injuries and contextual factors that influence injury, but they lack detail to define precise research questions and/or select specific training load metrics. This necessitates the use of a plausible biological and physiological rationale to select specific training load measures of exposure as potential prognostic factors for certain injuries. The conceptual framework proposed by Bertelsen et al[6] is the most appropriate model of the causes of running-related injury (**FIGURE 1**).[40] While one can argue the suitability of specific proxy measures (eg, the use of ratios or 7- and 28-day cumulative loads), we applaud the authors for transparently presenting their research assumptions, and encourage researchers to consider using the framework[6] as a starting point for new projects.[41]

Conceptual frameworks must be verified (or disproven) through specific study of the hypothesized relationships between variables in the framework. If the hypotheses are confirmed by original studies, the model can be accepted as a reasonable explanation of the relationships. If the hypotheses are not confirmed, the researchers must go back to the drawing board and rethink their hypotheses. Research must challenge the assumptions and logic inherent to the framework to test its strength. Without a conceptual framework and predefined hypothesis about the relationship between variables, there is a risk of confirmation bias, as the researchers may attempt to assign meaning to results.

Without understanding and testing underlying etiology using a framework, it is impossible—irrespective of statistical approach—to accurately interpret research results. A satirical study in American football[54] illustrated that the risk of concussion was linked to the team logo: teams with animal logos were protected from concussion. Should teams consider changing their logos or implementing "protective" animal stickers on their equipment to reduce concussion risk?

We expect most clinicians would agree that changing a logo is unlikely to change concussion risk. This article illustrates how, in the absence of a strong physiological rationale (ie, framework), coincidental links may be misconstrued as clinical (or practical) recommendations. Our concern is that in the absence of an established conceptual framework, the link between training load and sports injury might be misleading clinicians in sports science and medicine practice.

A Fishing Expedition: *P* Hacking

Many studies have reported associations between training load and sports injuries. However, the results are inconsistent and often confusing.[17] We summarized the results (odds ratio, relative risk, and injury risk) of studies in soccer that calculated the acute-chronic workload ratio (ACWR) from in-season session rating of perceived exertion (sRPE) or global positioning system (GPS) measures for noncontact injuries (**FIGURES 2** and **3**). Some studies have reported a relationship between high ACWR and injury, some have reported a relationship between low ACWR and injury, and others have reported no relationship between ACWR and injury.

Using sRPE, 3 studies[19,45,46] reported increased injury risk when the ACWR was high (**FIGURE 2**).[4] In 1 study,[38] the results were the opposite: a lower injury risk when the ACWR was high (**FIGURE 2**). In another study,[16] there was no relationship between ACWR and injury for 8 of 9 comparisons. For GPS-derived measures (**FIGURE 3**), in 1 study there was no relationship between ACWR and injury risk in 4 of 5 comparisons,[10] elevated injury risk at a high ACWR for total distance and accelerations but not for high-speed distance and decelerations,[9] and higher odds ratios for high-speed running but not for accelerations and decelerations.[38] Confused? It is difficult to reconcile the inconsistencies to a cogent statement about the relationship between training load and injury. And these inconsistencies are not limited to studies on soccer or using the ACWR metric.

When one considers all of the relationships between all of the variables in all of the studies, what stands out is that some results might have been emphasized and others received little (or no) discussion—in research methods, this is referred to as selective reporting bias. The researcher emphasizes the results that fit with his or her preconceptions or the common beliefs about training load, for example, emphasizing 3 studies that supported a protective effect of a moderate ACWR and omitting other studies that did not show the same trend.[21] Selective reporting (and discussion) of study findings misleads clinicians and researchers.

Inconsistency between and within studies in the training load and injury field is often justified by the multifactorial nature of injury etiology. While this is true and models accounting for this complexity have been proposed,[8,32,33] the multifactorial nature of injury cannot be used as an excuse to ignore inconsistency. Instead, the complexity must be overcome with robust studies. A small number of training load metrics cannot adequately explain injury risk in sport.

According to the Grading of Recommendations Assessment, Development and Evaluation (GRADE) guidelines, inconsistency in the results of similar studies is grounds to downgrade the credibility of evidence.[22] We recommend that researchers and practitioners examine all the results of the studies, avoiding or recognizing selective discussion. Be on alert for implausible and inconsistent findings (also called unexpected associations), which may suggest associations due to chance, misclassification of the predictor, selection bias, mixing of effects (confounding), intervention effects, and heterogeneity.[52]

The Decisions Researchers Make Affect the Likelihood of HARKing and *P* Hacking: Threats to the Credibility of Results in the Training Load and Injury Field

We believe the training load and injury field to be at high risk of "data fishing"—where researchers go searching (consciously or unconsciously) for answers in the data to confirm a relationship between training load and injury. Clinicians trying to apply research findings in practice may not be aware of all the choices researchers must make when conducting a study, and how each choice might influence the results.

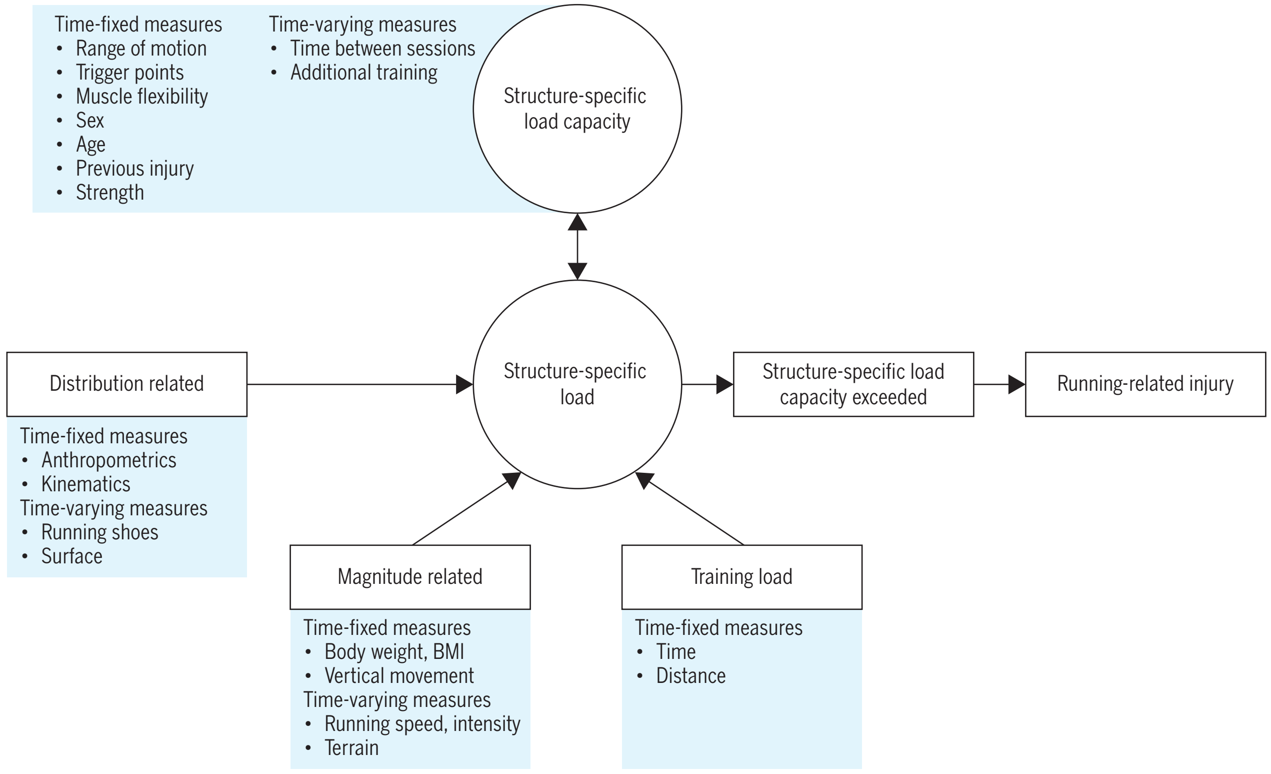

FIGURE 1. Simplified directed acyclic graph–inspired approach[6,40] to visualize the causal relationship between structure-specific load and running-related injury. Abbreviation: BMI, body mass index. Modified with permission from Bertelsen et al.[6]

Sometimes, the choices researchers make might lead to false discoveries that favor their beliefs (confirmation bias). In this section, we highlight 8 methods issues (choices to be made by the researcher) that can increase the risk of *P* hacking and HARKing ("data fishing").

Measures of Exposure and Ratios In the absence of a strong a priori conceptual framework, researchers are free to select the training load metric(s) they wish to include in a statistical model after the data are collected. Because there are so many different measures of training load (exposure),[35] different researchers might make different choices. How does one interpret different results and different metrics, especially when there is a high chance of false discoveries? Different training load metrics may also have different relationships to injury risk.[9,10,38]

Common measures of exposure (eg, acute and chronic training loads and their ratio) lack conceptual and computational validity.[37,55] Ratio measures of training load are common in the training load and injury field. However, the dangers of using ratios (as a normalization method or dependent/independent variables) have previously been described, and the pitfalls well documented.[3,15,57] When clinicians and researchers ignore warnings about using ratios as the main training load measure, they risk falsely concluding that the quantity of training load causes injury.

Training Load Measures Measures of exposure are calculated using various training load metrics. However, training load can be assessed using different methods and devices, which further complicates the selection of suitable measures. Again, a conceptual framework should guide selecting appropriate training load measures. Although studies have used sRPE, GPS, and inertial sensors, each of these measures different training load constructs.[9,10] Therefore, combining injury rates from different sports and training load measures[7] is inappropriate.

Time Windows Without a conceptual framework, it is not possible to justify or determine appropriate time windows within which to measure acute and chronic loads. The original Banister model cannot and should not be used to derive these time windows, because the time decays used in the model are conceptually very different from weekly average training load. The solution to trial several windows concurrently (to find the best model)[11] is prone to bias, multiple testing concerns, and overfitting.

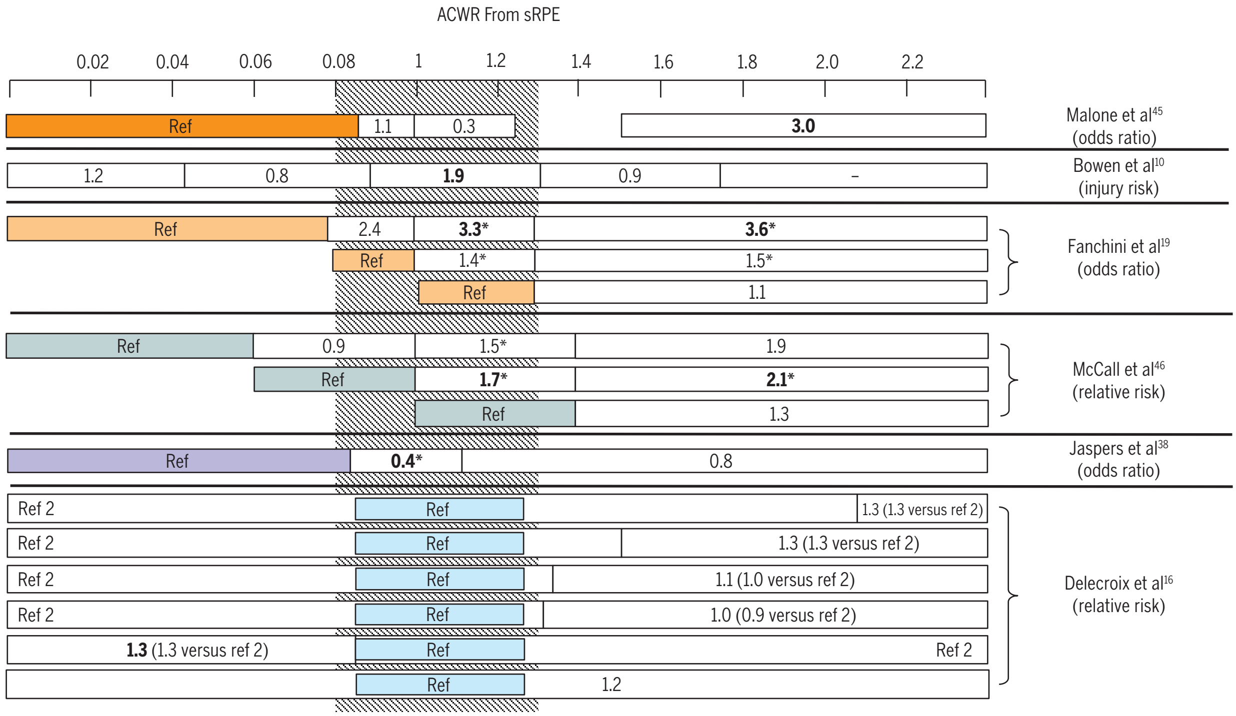

FIGURE 2. Graphical representation of results from studies examining the association between ACWR, calculated using the sRPE, and injuries in soccer. The rectangular boxes represent the ACWR categories used in the studies. When there is no rectangle, that category range was not used or reported in the results. Boxes with "ref" and "ref 2" indicate the reference category used in the statistical analysis. The reference categories are shown, with the exception of Bowen et al,[10] where we reported what they defined as injury risks from their tables (the values reported are injury rates). The studies by Ehrmann et al[18] and Watson et al[59] were excluded from **FIGURES 2** and **3** because they did not use categories. The numbers inside the rectangular boxes refer to the injury risk or rate (ie, relative risk, odds ratio) reported in the studies. The gray-shaded area represents the ACWR range (0.8-1.3) that is claimed to correspond to a sweet spot (lower injury risk or rate). Numbers in boxes in boldface represent measures of association not overlapping 1. *Likely or very likely association, based on magnitude-based inference. Abbreviations: ACWR, acute-chronic workload ratio; ref, reference; sRPE, session rating of perceived exertion.

Time Lags Typical time lags between injury registration and the acute or chronic load typically range from a few days to 1 week (subsequent-week injuries),[11,29,31,39] but longer lags have been used.[39,58] There is no reason to expect that the training completed on the day or days before an injury would not affect injury risk. Researchers do not usually explain why they chose a particular time lag over another time lag, raising suspicion of *P* hacking.

Discretization and Reference Category Most studies lump training load measures and ratios into categories (**FIGURES 2** and **3**). Such an approach has serious limitations,[1,5,12] including that the number of categories can influence the results and subsequent interpretation. Using categories exacerbates the risks and consequences of sparse-data bias (some categories have many data points and some categories have very few data points). Results from studies using different categories and references should not be compared.

Statistical Analysis Most studies examining the association between training load and injury have used inadequate statistical analyses,[48,60] including approaches that cannot account for time-varying variables, recurrent events, or repeated measures.[29-31] The challenges and solutions for more appropriate analysis have been provided, but are rarely followed.[2,48,49,51] This is a problem, because inappropriate analysis can produce unreliable and biased results.[56]

Missing Data Missing training load data are common and sometimes unavoidable. Most studies in the training load and injury field do not describe how missing data were handled. For example, were data imputed? What were the assumptions the researchers made about the missing data?[24,56] Imputation can have an effect on the results. Sensitivity analyses should be performed to show the effects of the methods, as recommended by international guidelines.[13]

Injury Definitions The injury definition a researcher chooses is important. Some definitions are very broad (eg, all complaints); others are narrow (eg, serious, noncontact, time-loss injuries). When researchers do not provide an appropriate rationale, grounded in a solid theoretical framework and etiology model, to justify their choice, it is difficult for readers to interpret results and compare studies.[23]

Correlation Does Not Equal Causation

The dominant narrative of the training load and injury field is that by manipulating training load, one can alter the probability of future injuries. However, this assumes a cause-and-effect rela-

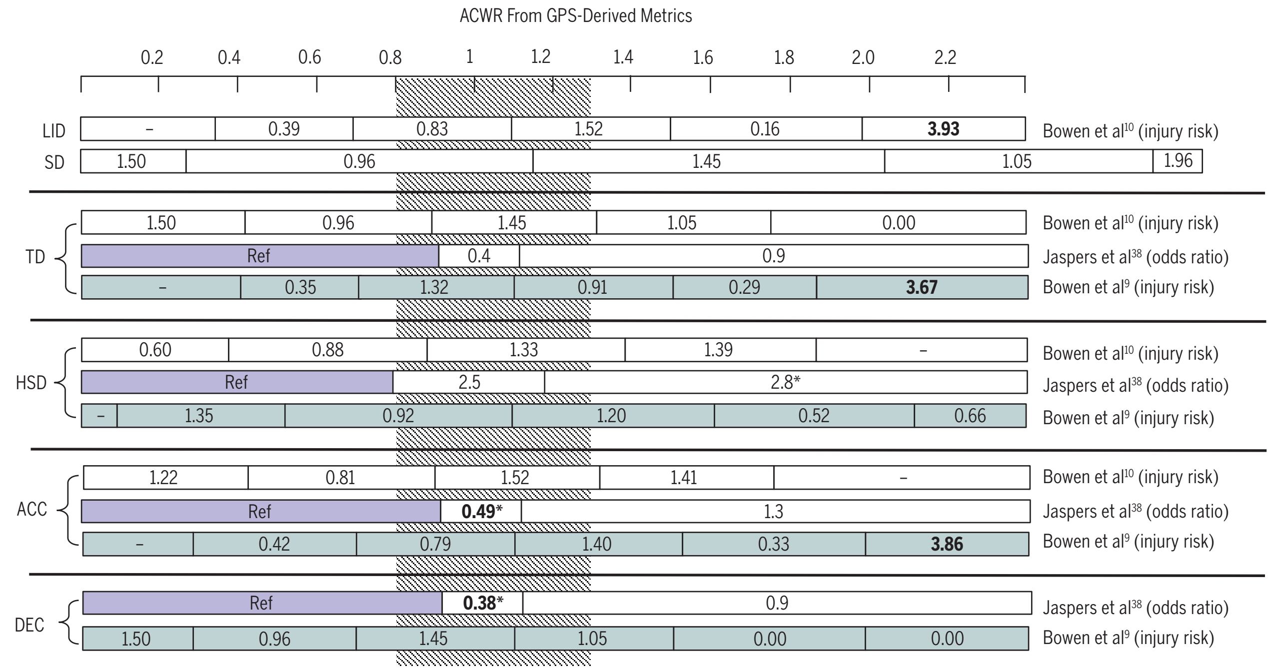

FIGURE 3. Graphical representation of results from studies examining the association between ACWR, calculated using a GPS, and injuries in soccer. The rectangular boxes represent the ACWR categories used in the studies. When there is no rectangle, that category range was not used or reported in the results. Boxes with "ref" indicate the reference category used in the statistical analysis. The reference categories are shown, with the exception of Bowen et al,[9,10] where we reported what they defined as injury risks from their tables (the values reported are injury rates). The studies by Ehrmann et al[18] and Watson et al[59] were excluded from **FIGURES 2** and **3** because they did not use categories. The numbers inside the rectangular boxes refer to the injury risk or rate (ie, relative risk, odds ratio) reported in the studies. The gray-shaded area represents the ACWR range (0.8-1.3) that is claimed to correspond to a sweet spot (lower injury risk or rate). Numbers in boxes in boldface represent measures of association not overlapping 1. *Likely or very likely association, based on magnitude-based inference. Abbreviations: ACC, accelerations; ACWR, acute-chronic workload ratio; DEC, decelerations; GPS, global positioning system; HSD, high-speed distance; LID, low-intensity distance; ref, reference; SD, sprint distance; TD, total distance.

tionship (changing training load causes an injury to occur or not to occur) that has never been examined using appropriate methods required to make causal inferences.[20,26,50,51]

Although the field acknowledged that association is not prediction[19,25,28,47] (associations between training load metrics and injury do not automatically imply that training load metrics can predict injury occurrence), it is important to recognize that neither associations nor predictors can be automatically used to make causal inferences if this was not the original aim.[27] Associations can be descriptive, predictive, or used to estimate causal effects. However, if no causal relationship has been estimated, any practical applications regarding the manipulation of the prognostic factor/predictor to alter the probability of an event are an overinterpretation and a speculation (and should be declared as such).

TABLE List of the Most Common Variations and Combinations of Features and Outcomes Used in Training Load and Injury Research

Features	Outcomes (injuries)
Chronic load 1 wk, 2 wk, 3 wk, 4 wk, *k* d/wk[a]	Definitions Match loss, match and training time loss, complaints but no time loss, modified training
Acute load 1 wk, *k* d[a]	Injury types Contact, noncontact, both contact and noncontact
Acute load calculation in relation to the injury day Load in the same week of the injury, load starting the day before the injury, load starting the day of the injury, load starting the week preceding the injury	Collection Self-reported, medical staff
Training load variation metrics 1 wk (acute)-4 wk (chronic): ACWR, *k* days or weeks acute-*k* days or weeks chronic,[a] week-to-week variation (relative), week-to-week variation (absolute), monotony, strain	Location Lower body, both lower and upper body
Computations Rolling average, accumulated (sum), exponentially weighted moving average, coupled (week 1/week 1 to week 4), uncoupled (week 1/week 2 to week 5)	
Categories 2 (median split), 3 (low, moderate, high), 4 (low, moderate-low, moderate-high, high), 5 (very low, low, moderate, high, very high), 6 (very low, low, low-moderate, moderate-high, high, very high), 7 (very low, low, low-moderate, moderate, moderate-high, high, very high), >7	
Reference categories 1 of the categories (lower, middle, higher), all of the above	
Category determination *z* score, absolute, percentile, arbitrary cut point (eg, 0.5, 0.75, 1.0, etc)	
Combinations Acute only, chronic only, variations only, low chronic versus ACWR/weekly changes, high chronic versus ACWR/weekly changes	
Training load indicators Session RPE (global), session RPE on leg, balls bowled, total distance, low-intensity running distance,[b] moderate-intensity running distance,[b] high-speed running distance,[b] very high–speed running distance,[b] sprinting,[b] accelerations,[b] decelerations,[b] player load, distance load	

Abbreviations: ACWR, acute-chronic workload ratio; RPE, rating of perceived exertion.

[a] *Various combinations.*

[b] *Various cutoff values.*

Changing a risk factor like a training load metric, if the metric does not have a causal relationship to the outcome or event, cannot modify the risk of an event occurring. Clinicians should be aware that, regardless of the methodological approach, if a study does not explicitly estimate causal effects (using appropriate methods), it is difficult to know whether changing training load causes injury. Ultimately, it should not be claimed that the intervention is "evidence based," as is often stated.

SUMMARY

As published research in the training load and injury field has proliferated, clinicians may be lulled into a false sense of security and, accepting that training "too much, too soon" causes injuries, may diligently adopt new training load metrics in the hope of reducing injury risk. However, when one looks carefully at the methodological limitations and inconsistencies in previous research, evidence supporting these beliefs is not as strong as one might expect (**TABLE**).

Recommendations for Clinical Practice

Given the research limitations, we encourage clinicians to follow well-established training principles.[42,44] One key principle is load progression. While some might believe that the current influx of studies has increased the attention to "correct handling" of training load, this seems to be another bias. The overload progression concept has been well known among coaches, fitness trainers, and sport scientists for at least the past half-century (training and periodization principles), but we concede that this may not be the case for clinicians who may not be as familiar with athletic training methods. Stronger multidisciplinary collaboration may help when making decisions about future training. We recommend that clinicians work together with the various support staff of athletes/teams to share specific knowledge and expertise.

When reading research in the training load and injury field, be on the lookout for inconsistent results ("consistent" associations in different directions do not constitute a consistent finding) and different analysis methods that are not well justified (eg, computational manipulations of the same prognostic factors, data trimming, categorizations, etc). Consider whether the results make sense in the practical context. For example, immediately after a recovery or a tapering week, would one expect athletes to be at higher risk of injuries? All of these could be signs that something is wrong and suggest caution when applying the results to clinical practice. ◉

STUDY DETAILS

AUTHOR CONTRIBUTIONS: All authors contributed substantially to the conception of the work (in full or some sections), interpretation of published data, drafting the work or revising it critically for important intellectual content, and giving final approval of the version to be submitted and published.

DATA SHARING: No original data were used for the commentary.

PATIENT AND PUBLIC INVOLVEMENT: No patients or athletes were involved in this paper.

REFERENCES

1. Altman DG, Royston P. The cost of dichotomising continuous variables. *BMJ*. 2006;332:1080. https://doi.org/10.1136/bmj.332.7549.1080
2. Amorim LD, Cai J. Modelling recurrent events: a tutorial for analysis in epidemiology. *Int J Epidemiol*. 2015;44:324-333. https://doi.org/10.1093/ije/dyu222
3. Atkinson G, Batterham AM. The use of ratios and percentage changes in sports medicine: time for a rethink? *Int J Sports Med*. 2012;33:505-506. https://doi.org/10.1055/s-0032-1316355
4. Batterham AM, Hopkins WG. Making meaningful inferences about magnitudes. *Int J Sports Physiol Perform*. 2006;1:50-57. https://doi.org/10.1123/ijspp.1.1.50
5. Bennette C, Vickers A. Against quantiles: categorization of continuous variables in epidemiologic research, and its discontents. *BMC Med Res Methodol*. 2012;12:21. https://doi.org/10.1186/1471-2288-12-21
6. Bertelsen ML, Hulme A, Petersen J, et al. A framework for the etiology of running-related injuries. *Scand J Med Sci Sports*. 2017;27:1170-1180. https://doi.org/10.1111/sms.12883
7. Blanch P, Gabbett TJ. Has the athlete trained enough to return to play safely? The acute:chronic workload ratio permits clinicians to quantify a player's risk of subsequent injury. *Br J Sports Med*. 2016;50:471-475. https://doi.org/10.1136/bjsports-2015-095445
8. Bolling C, van Mechelen W, Pasman HR, Verhagen E. Context matters: revisiting the first step of the 'sequence of prevention' of sports injuries. *Sports Med*. 2018;48:2227-2234. https://doi.org/10.1007/s40279-018-0953-x
9. Bowen L, Gross AS, Gimpel M, Bruce-Low S, Li FX. Spikes in acute:chronic workload ratio (ACWR) associated with a 5-7 times greater injury rate in English Premier League football players: a comprehensive 3-year study. *Br J Sports Med*. 2020;54:731-738. https://doi.org/10.1136/bjsports-2018-099422
10. Bowen L, Gross AS, Gimpel M, Li FX. Accumulated workloads and the acute:chronic workload ratio relate to injury risk in elite youth football players. *Br J Sports Med*. 2017;51:452-459. https://doi.org/10.1136/bjsports-2015-095820
11. Carey DL, Blanch P, Ong KL, 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*. 2017;51:1215-1220. https://doi.org/10.1136/bjsports-2016-096309
12. Carey DL, Crossley KM, Whiteley R, et al. Modeling training loads and injuries: the dangers of discretization. *Med Sci Sports Exerc*. 2018;50:2267-2276. https://doi.org/10.1249/MSS.0000000000001685
13. Collins GS, Reitsma JB, Altman DG, Moons KG. Transparent Reporting of a multivariable prediction model for Individual Prognosis Or Diagnosis (TRIPOD): the TRIPOD statement. *J Clin Epidemiol*. 2015;68:134-143. https://doi.org/10.1016/j.jclinepi.2014.11.010
14. Coutts AJ, Crowcroft S, Kempton T. Developing athlete monitoring systems: theoretical basis and practical applications. In: Kellmann M, Beckmann J, eds. *Sport, Recovery and Performance: Interdisciplinary Insights*. Abingdon, UK: Routledge; 2018:ch 2.
15. Curran-Everett D. Explorations in statistics: the analysis of ratios and normalized data. *Adv Physiol Educ*. 2013;37:213-219. https://doi.org/10.1152/advan.00053.2013
16. Delecroix B, McCall A, Dawson B, Berthoin S, Dupont G. Workload and non-contact injury incidence in elite football players competing in European leagues. *Eur J Sport Sci*. 2018;18:1280-1287. https://doi.org/10.1080/17461391.2018.1477994
17. Eckard TG, Padua DA, Hearn DW, Pexa BS, Frank BS. The relationship between training load and injury in athletes: a systematic review. *Sports Med*. 2018;48:1929-1961. https://doi.org/10.1007/s40279-018-0951-z
18. Ehrmann FE, Duncan CS, Sindhusake D, Franzsen WN, Greene DA. GPS and injury prevention in professional soccer. *J Strength Cond Res*. 2016;30:360-367. https://doi.org/10.1519/JSC.0000000000001093
19. Fanchini M, Rampinini E, Riggio M, Coutts AJ, Pecci C, McCall A. Despite association, the acute:chronic work load ratio does not predict non-contact injury in elite footballers. *Sci Med Football*. 2018;2:108-114. https://doi.org/10.1080/24733938.2018.1429014
20. Greenland S, Brumback B. An overview of relations among causal modelling methods. *Int J Epidemiol*. 2002;31:1030-1037. https://doi.org/10.1093/ije/31.5.1030
21. 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*. 2020;50:561-580. https://doi.org/10.1007/s40279-019-01218-2
22. Guyatt GH, Oxman AD, Vist GE, et al. GRADE: an emerging consensus on rating quality of evidence and strength of recommendations. *BMJ*. 2008;336:924-926. https://doi.org/10.1136/bmj.39489.470347.AD
23. Hamilton GM, Meeuwisse WH, Emery CA, Shrier I. Examining the effect of the injury definition on risk factor analysis in circus artists. *Scand J Med Sci Sports*. 2012;22:330-334. https://doi.org/10.1111/j.1600-0838.2010.01245.x
24. Harel O, Mitchell EM, Perkins NJ, et al. Multiple imputation for incomplete data in epidemiologic studies. *Am J Epidemiol*. 2018;187:576-584. https://doi.org/10.1093/aje/kwx349
25. Hernán MA, Hsu J, Healy B. A second chance to get causal inference right: a classification of data science tasks. *CHANCE*. 2019;32:42-49. https://doi.org/10.1080/09332480.2019.1579578
26. Hernán MA, Robins JM. Estimating causal effects from epidemiological data. *J Epidemiol Community Health*. 2006;60:578-586. https://doi.org/10.1136/jech.2004.029496
27. Hjerrild M, Videbaek S, Theisen D, Malisoux L, Nielsen RO. How (not) to interpret a non-causal association in sports injury science. *Phys Ther Sport*. 2018;32:121-125. https://doi.org/10.1016/j.ptsp.2018.05.009
28. Hulin BT, Gabbett TJ. Indeed association does not equal prediction: the never-ending search for the perfect acute:chronic workload ratio. *Br J Sports Med*. 2019;53:144-145. https://doi.org/10.1136/bjsports-2018-099448
29. 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;48:708-712. https://doi.org/10.1136/bjsports-2013-092524
30. Hulin BT, Gabbett TJ, Caputi P, Lawson DW, Sampson JA. Low chronic workload and the acute:chronic workload ratio are more predictive of injury than between-match recovery time: a two-season prospective cohort study

in elite rugby league players. *Br J Sports Med*. 2016;50:1008-1012. https://doi.org/10.1136/bjsports-2015-095364

31. Hulin BT, Gabbett TJ, Lawson DW, Caputi P, Sampson JA. The acute:chronic workload ratio predicts injury: high chronic workload may decrease injury risk in elite rugby league players. *Br J Sports Med*. 2016;50:231-236. https://doi.org/10.1136/bjsports-2015-094817
32. Hulme A, Finch CF. From monocausality to systems thinking: a complementary and alternative conceptual approach for better understanding the development and prevention of sports injury. *Inj Epidemiol*. 2015;2:31. https://doi.org/10.1186/s40621-015-0064-1
33. Hulme A, Thompson J, Nielsen RO, Read GJM, Salmon PM. Towards a complex systems approach in sports injury research: simulating running-related injury development with agent-based modelling. *Br J Sports Med*. 2019;53:560-569. https://doi.org/10.1136/bjsports-2017-098871
34. Imenda S. Is there a conceptual difference between theoretical and conceptual frameworks? *J Soc Sci*. 2014;38:185-195. https://doi.org/10.1080/09718923.2014.11893249
35. Impellizzeri FM, Marcora SM, Coutts AJ. Internal and external training load: 15 years on. *Int J Sports Physiol Perform*. 2019;14:270-273. https://doi.org/10.1123/ijspp.2018-0935
36. Impellizzeri FM, Ward P, Coutts AJ, Bornn L, McCall A. Training load and injury part 1: the devil is in the detail—challenges to applying the current research in the training load and injury field. *J Orthop Sports Phys Ther*. 2020;50:574-576. https://doi.org/10.2519/jospt.2020.9675
37. Impellizzeri FM, Woodcock S, McCall A, Ward P, Coutts AJ. The acute-chronic workload ratio-injury figure and its 'sweet spot' are flawed [letter] [preprint]. *SportRxiv*. 2019. Available at: https://doi.org/10.31236/osf.io/gs8yu
38. Jaspers A, Kuyvenhoven JP, Staes F, Frencken WGP, Helsen WF, Brink MS. Examination of the external and internal load indicators' association with overuse injuries in professional soccer players. *J Sci Med Sport*. 2018;21:579-585. https://doi.org/10.1016/j.jsams.2017.10.005
39. Johnston R, Cahalan R, Bonnett L, et al. Training load and baseline characteristics associated with new injury/pain within an endurance sporting population: a prospective study. *Int J Sports Physiol Perform*. 2019;14:590-597. https://doi.org/10.1123/ijspp.2018-0644
40. Jungmalm J, Grau S, Desai P, Karlsson J, Nielsen RØ. Study protocol of a 52-week Prospective Running INjury study in Gothenburg (SPRING). *BMJ Open Sport Exerc Med*. 2018;4:e000394. https://doi.org/10.1136/bmjsem-2018-000394
41. Kalkhoven JT, Watsford ML, Impellizzeri FM. A conceptual model and detailed framework for stress-related, strain-related, and overuse athletic injury. *J Sci Med Sport*. 2020;23:726-734. https://doi.org/10.1016/j.jsams.2020.02.002
42. Kasper K. Sports training principles. *Curr Sports Med Rep*. 2019;18:95-96. https://doi.org/10.1249/JSR.0000000000000576
43. Kibler WB, Chandler TJ, Stracener ES. Musculoskeletal adaptations and injuries due to overtraining. *Exerc Sport Sci Rev*. 1992;20:99-126.
44. Kraemer WJ, Duncan ND, Volek JS. Resistance training and elite athletes: adaptations and program considerations. *J Orthop Sports Phys Ther*. 1998;28:110-119. https://doi.org/10.2519/jospt.1998.28.2.110
45. Malone S, Owen A, Newton M, Mendes B, Collins KD, Gabbett TJ. The acute:chonic [sic] workload ratio in relation to injury risk in professional soccer. *J Sci Med Sport*. 2017;20:561-565. https://doi.org/10.1016/j.jsams.2016.10.014
46. McCall A, Dupont G, Ekstrand J. Internal workload and non-contact injury: a one-season study of five teams from the UEFA Elite Club Injury Study. *Br J Sports Med*. 2018;52:1517-1522. https://doi.org/10.1136/bjsports-2017-098473
47. McCall A, Fanchini M, Coutts AJ. Prediction: the modern-day sport-science and sports-medicine "quest for the holy grail". *Int J Sports Physiol Perform*. 2017;12:704-706. https://doi.org/10.1123/ijspp.2017-0137
48. Nielsen RO, Bertelsen ML, Ramskov D, et al. Time-to-event analysis for sports injury research part 1: time-varying exposures. *Br J Sports Med*. 2019;53:61-68. https://doi.org/10.1136/bjsports-2018-099408
49. Nielsen RO, Bertelsen ML, Ramskov D, et al. Time-to-event analysis for sports injury research part 2: time-varying outcomes. *Br J Sports Med*. 2019;53:70-78. https://doi.org/10.1136/bjsports-2018-100000
50. Pearl J. *Causality: Models, Reasoning, and Inference*. 2nd ed. New York, NY: Cambridge University Press; 2009.
51. Rothman KJ, Greenland S, Lash TL. *Modern Epidemiology*. 3rd ed. Philadelphia, PA: Wolters Kluwer Health/Lippincott Williams & Wilkins; 2008.
52. Schuit E, Groenwold RH, Harrell FE, Jr., et al. Unexpected predictor–outcome associations in clinical prediction research: causes and solutions. *CMAJ*. 2013;185:E499-E505. https://doi.org/10.1503/cmaj.120812
53. Shrier I, Platt RW. Reducing bias through directed acyclic graphs. *BMC Med Res Methodol*. 2008;8:70. https://doi.org/10.1186/1471-2288-8-70
54. Smoliga JM, Zavorsky GS. Team logo predicts concussion risk: lessons in protecting a vulnerable sports community from misconceived, but highly publicized epidemiologic research. *Epidemiology*. 2017;28:753-757. https://doi.org/10.1097/EDE.0000000000000694
55. Soligard T, Schwellnus M, Alonso JM, et al. How much is too much? (Part 1) International Olympic Committee consensus statement on load in sport and risk of injury. *Br J Sports Med*. 2016;50:1030-1041. https://doi.org/10.1136/bjsports-2016-096581
56. Sterne JA, White IR, Carlin JB, et al. Multiple imputation for missing data in epidemiological and clinical research: potential and pitfalls. *BMJ*. 2009;338:b2393. https://doi.org/10.1136/bmj.b2393
57. Tanner JM. Fallacy of per-weight and per-surface area standards, and their relation to spurious correlation. *J Appl Physiol*. 1949;2:1-15. https://doi.org/10.1152/jappl.1949.2.1.1
58. 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;21:40-45. https://doi.org/10.1016/j.jsams.2017.07.009
59. Watson A, Brickson S, Brooks A, Dunn W. Subjective well-being and training load predict in-season injury and illness risk in female youth soccer players. *Br J Sports Med*. 2017;51:194-199. https://doi.org/10.1136/bjsports-2016-096584
60. Windt J, Ardern CL, Gabbett TJ, et al. Getting the most out of intensive longitudinal data: a methodological review of workload–injury studies. *BMJ Open*. 2018;8:e022626. https://doi.org/10.1136/bmjopen-2018-022626
61. Windt J, Gabbett TJ. How do training and competition workloads relate to injury? The workload–injury aetiology model. *Br J Sports Med*. 2017;51:428-435. https://doi.org/10.1136/bjsports-2016-096040

@ **MORE INFORMATION**
WWW.JOSPT.ORG