MAX R. PAQUETTE, PhD[1] • **CHRISTOPHER NAPIER**, PT, PhD[2,3]
RICHARD W. WILLY, PT, PhD[4] • **TRENT STELLINGWERFF**, PhD[5]

Moving Beyond Weekly "Distance": Optimizing Quantification of Training Load in Runners

> *"How do they know the load limits on bridges? They drive bigger and bigger trucks over until it breaks, then they weigh the last truck and rebuild the bridge."*
>
> *— Bill Watterson, Calvin and Hobbes*

BACKGROUND: Quantifying total running distance is valuable, as it comprises some aspects of the mechanical/neuromuscular, cardiovascular, and perceptual/psychological loads that contribute to training stress and is partially predictive of distance-running success. However, running distance is only one aspect contributing to training stress.

CLINICAL QUESTION: The purpose of this commentary is to highlight (1) problems with only using running distance to quantify running training and training stress, (2) the importance of alternative approaches to quantify and monitor training stress, (3) moderating factors (effect-measure modifiers) of training loads, and (4) the challenges of monitoring training stress to assess injury risks.

KEY RESULTS: Training stress is influenced by external (ie, application of mechanical load) and internal (ie, physiological/psychological effort) training load factors. In running, some commonly used external load factors include volume and pace, while physiological internal load factors include session rating of perceived exertion, heart rate, or blood lactate level. Running distance alone might vastly obscure the cumulative training stress on different training days and, ultimately, misrepresent overall training stress. With emerging and novel wearable technology that quantifies external load metrics beyond volume or pace, the future of training monitoring should have an ever-increasing emphasis on biomechanical external load metrics, coupled with internal (ie, physiological/psychological) load metrics.

CLINICAL APPLICATION: It may be difficult to change the running culture's obsession with weekly distance, but advanced and emerging methods to quantify running training discussed in this commentary will, with research confirmation, improve training monitoring and injury risk stratification.

J Orthop Sports Phys Ther 2020;50(10):564-569. Epub 1 Aug 2020. doi:10.2519/jospt.2020.9533

KEY WORDS: *adaptations, biomechanics, monitoring, physiology, runners*

Anyone who has spent time around distance runners has inevitably, and repeatedly, heard the question, "How many miles do you run per week?" with "high-mileage" weeks typically considered as a measure of success. The ability to easily and accurately quantify running distance via the widespread adoption of global positioning system technology has only solidified the long-term "mileage love affair" of runners and coaches. Running distance is typically the only collected training metric. Quantifying total running distance is valuable, as it comprises some aspects of the mechanical/neuromuscular, cardiovascular, and perceptual/psychological loads that contribute to training stress and is partially predictive of distance-running success.[8,40] However, running distance is only one aspect contributing to training stress. In this commentary, we aim to address 4 issues:

1. Why solely relying on running distance to quantify running training load is a problem
2. Alternative approaches to quantifying and monitoring training load
3. Moderating factors (effect-measure modifiers) of training load
4. The challenge for coaches, clinicians, and runners of how best to monitor training load and its implications for performance and injury risk

Why Relying on Distance Alone to Quantify and Monitor Training in Runners Is a Problem

Runners and coaches have historically only relied on weekly distance to quantify and monitor running training. However, it is increasingly evident that running distance should not be the sole training metric, as it can often misrepresent

[1]School of Hea[illegible]udies, University of Memphis, Memphis, TN. [2]Menrva Research Group, Schools of Mechatronic Systems Engineering and Engineering Science, Simon Fraser University, Surrey, Canada. [3]Department of Physical Therapy, University of British Columbia, Vancouver, Canada. [4]School of Physical Therapy and Rehabilitation Science, University of Montana, Missoula, MT. [5]Canadian Sport Institute Pacific, Victoria, Canada. The authors certify that they have no affiliations with or financial in[illegible]ent in any organization or entity with a direct financial interest in the subject matter [illegible]erials discussed in the article. Address correspondence to Dr Max R. Paquette, Sc[illegible]ool [illegible] Health Studies, University of Memphis, 171b Elma Roane Fieldhouse, Memphis, TN 38[illegible]-mail: mrpqette@memphis.edu

and significantly underestimate training stress and resulting adaptation, and other critical factors contributing to the overall training stress in other endurance sports are rarely considered in runners.[33,39] In any sport, training stress[2,7,19] is influenced by both external (ie, application of mechanical load) and internal (ie, physiological/psychological responses to the external load) load factors.[23] Unfortunately, many training-related terms are poorly defined and/or used inappropriately in the lay and scientific literature alike. Therefore, **TABLE 1** provides definitions of training-related terms used throughout this commentary.

In running, some commonly used external load factors include volume, in distance or minutes, and pace, while internal load factors include session rating of perceived exertion (sRPE), heart rate, or blood lactate level. Here it is important to differentiate the term "internal physiological load," which is more common in applied sport sciences and physiology, from "internal tissue (or mechanical) load," which is more commonly used by biomechanists and physical therapists (eg, force, stress, strain, and stiffness). For example, the same 10 km of running distance can result in approximately 14% more foot strikes per session and approximately 6% greater accumulated peak vertical ground reaction forces when fatigued versus fresh (**TABLE 2**). This increase in external load, despite the same running distance, and on a day when the runner/coach might actually be seeking lower training stress, can accumulate into real differences in the training stress experienced by the runner.[33] Similarly, prescribing a workout based solely on running pace, for example, 4:30 min/km, can also be a misleading measure of training stress, as individual variability, based primarily on sRPE or fatigue, can result in (1) different internal load responses and (2) variable training stress and long-term training adaptations.[33] Furthermore, it appears difficult to estimate the external load to the lower limbs per kilometer from distance and pace alone.[22] Accordingly, more and more coaches purposely program training volume in minutes (duration) rather than distance, and use internal load metrics (eg, sRPE) to better quantify training stress.[37]

TABLE 1 DEFINITIONS OF VARIOUS METRICS USED TO QUANTIFY RUNNING TRAINING

Metric	Definition	Example	Unit
Training stress[3,9,20]	General term to describe physiological stress resulting directly from training sessions	External load, physiological internal load, tissue internal load, and workloads	See below
Daily stress	General term to describe physiological/psychological stress resulting from nontraining factors	Work, family/relationships, sleep, and financial stress	Visual analog scales and questionnaires
External load[25]	Global term used to define the mechanical physical stresses applied to an athlete	• Duration • Distance • Pace • Ground reaction forces • Contact time • Peak tibial or sacral acceleration • Number of steps • Other biomechanical variables	• Minutes • Miles or kilometers • Minutes per mile or per kilometer • Newtons per body weight • Seconds • Units of gravity • Steps • Varies
Physiological internal load[17,18,25]	Global term used to define the physiological and psychological stresses in response to external loads and daily stress	• Perceived exertion (sRPE) • Heart rate • Heart rate variability • Blood lactate • Other physiological variables	• Scales: 6-20 or 0-10 • Beats per minute • Variability in interbeat time interval • Millimole • Varies
Tissue internal load	Global term used to define internal loads placed on musculoskeletal tissue in response to external loads	• Stress • Strain • Force • Stiffness • Young's modulus	• Pascals • Unitless • Newtons • N/deformation (mm)
Training load[18]	Specific term defined as the product of external and physiological internal loads	• Duration × sRPE • Peak tibial acceleration × sRPE • Number of steps × sRPE	Arbitrary units for all

Abbreviation: sRPE, session rating of perceived exertion.

Alternative Approaches to Quantify Training Load in Runners

Over the last few decades, the combination of sRPE and training volume (duration) has provided alternative approaches to quantify training stress in athletes. Training impulse[15-17] and training load,[16] which both incorporate sRPE (typically on a visual analog scale of 0-10) and session duration, are most commonly used to quantify training stress in athletes.[17,25,37] More recently, the term "training load"[5] has been used in coaching and sports science literature to generally describe the combination of various external and internal physiological loads of training sessions.

One of the major limitations of measuring external training load is that it fails to account for how runners feel during a given training session, which is not only influenced by the external load of the training session but also by the runner's state of recovery and daily stress (eg, sleep, illness, relationships, etc).[30,37]

As such, the interpretation of running distance in isolation is an oversimplified quantification of a runner's training stress due to a failure to account for the athlete's psychobiological/physiological responses (ie, internal training loads) that are influenced by daily stress.[23,27,33] Because sRPE correlates with blood lactate concentration,[11] it can be considered an individualized measure of intensity, and is often the most practical and preferred means to quantify internal training load.[37,38] Nevertheless, coupling external (eg, distance, pace, power, cumulative impact) and internal (eg, sRPE, heart rate, blood lactate) metrics to quantify training load (**TABLE 1**) provides an even more complete quantification of training stress.[16,18,23,24,33]

Because it is challenging to prescribe training loads due to session-to-session variability of the internal load response of an athlete, weekly running volume is commonly used to prescribe training, as it is specific and easily understood. Coaches can qualitatively prescribe intended internal load with instructions like "easy" or "hard effort" or "submaximal effort," or even use an accepted rating of perceived exertion descriptor ("somewhat hard"). However, without monitoring the internal loads experienced by a runner, it is difficult to quantify the overall training response. Thus, training loads, including external load and internal physiological load, are valuable to quantify and monitor running training over time to truly understand the overall training stress.

TABLE 2 Hypothetical Scenarios of 10-km Runs With Estimated Loads

	On Soft Trail in Typical Supportive Running Shoes		
Parameter	**10-km Recovery Run (Fresh)**	**10-km Recovery Run (Very Tired)**	**Ten 1-km Track Repeats in Rigid Spikes**
External loads[a]			
Duration (volume), min:s	37:30	43:20	27:30
Pace, min:s/km	3:45	4:20	2:45
Cadence, steps/min	180	177[b]	198[c]
Estimated steps, n	6750	7669	5445
Estimated peak vGRF, BW[d]	3.1	2.9	3.3
Estimated accumulated vGRF, BW	20925	22240	17969
Estimated peak ATF, BW[e]	10.0	9.1	11.5
Estimated accumulated ATF, BW	67500	70970	62618
Internal loads			
RPE (1-10)	2	5	9
Estimated heart rate, % maximum	70	80	95
Estimated blood lactate, mmol/L	2.5	4.5	≥10
Training loads, AU			
Duration × RPE	75	217	248
Accumulated GRF × RPE (/1000)	42	111	162
Accumulated ATF × RPE (/1000)	135	355	564

Abbreviations: ATF, Achilles tendon force; AU, arbitrary unit; BW, body weight; GRF, ground reaction force; RPE, rating of perceived exertion; vGRF, vertical ground reaction force.

[a] *Metrics were estimated from published biomechanical data.*

[b] *Data from Chan-Roper et al[9] (ie, approximately 1.7% lower cadence with fatigue).*

[c] *Data from Hanley and Bissas[21] (ie, cadence of athletes during the 10000-m World Championship race).*

[d] *Data from Arampatzis et al[1] (ie, estimated peak vGRF at different running speeds).*

[e] *Data from Dorn et al.[13] Estimated muscle forces of the gastrocnemius and soleus were summed to estimate the peak ATF. The peak forces for each tested speed were used to construct a regression to estimate the peak ATF at the speeds presented in this table.*

Regardless of the specific variable used by practitioners, comparisons of current training stress (ie, acute stress/fatigue) relative to training stress in previous training cycles (ie, chronic stress or accumulated fitness) are also critical to understanding training adaptation.[2,7] The concept of quantifying current fatigue (acute) compared to accumulated fitness (chronic) was proposed over 40 years ago[7] but has been popularized more recently with the acute-chronic workload ratio (here, "workload" is synonymous with "load"). Despite the current disagreements and concerns regarding its use to predict or avoid athletic injuries,[26] this ratio can be used to quantify current fatigue relative to accumulated fitness or fatigue of any training metric. Regardless of its ability, or inability, to predict injury risks, comparing acute training load relative to chronic training load may help explain the acute physiological effects of current training stress relative to fitness. Thus, monitoring training stress using a ratio of acute stress to fitness may also help improve training outcomes,[16] although it is critical to conduct research to validate this approach to monitoring training response. Future research should examine how different external and internal training load metrics that seek more specificity (eg, surface specific and/or intensity specific) can be used to quantify training stress in distance runners, and how these metrics relate to training adaptation, fatigue, injury risk, and/or performance outcomes.

Emerging Moderating Factors of Running Training Loads

A promising area of emerging research to quantify training loads may be the supplanting of conventional metrics of external and internal training loads[20,31,34] (**TABLE 2**) with biomechanical metrics, which could improve estimates of training stress in runners. These biomechanical metrics could act as moderating factors (effect-measure modifiers) to external and internal loads and influence the strength of their relationship with training load metrics. Compared with team sports and other endurance sports (eg, cycling and swimming), distance running involves variable running surfaces (eg, road versus trail versus track), often over undulating terrain (eg, hills versus flat), with constant changes in footwear or foot-strike pattern depending on workout or competitive needs (eg, spikes during track sessions versus cushioned shoes during trail-based endurance runs). The distribution and magnitudes of muscle, tendon, bone, and articular forces are influenced greatly by these different running conditions. Coupling quantification of these internal forces with the more traditional metrics of internal and external training loads is becoming feasible with recent technological advances.

The emergence of both commercial and research-grade wearable technology (eg, inertial measurement units) presents the opportunity for continuous monitoring (step by step) of biomechanical factors during running. Wearable sensors can quantify various biomechanical data such as tibial shock, foot-strike angle, ground contact time, and leg stiffness, among others,[12,33,41] to enable a more precise quantification of training stress. Incorporating biomechanical data from wearable devices will give greater depth of knowledge about how running mechanics change in different environments, fatigue states, types of footwear, and running surfaces, and over the course of a training program.[33,36]

Substantial research is required to determine best practices and validity for the integration of biomechanical data into running training quantification. First, it is currently unclear which biomechanical variable(s) might be the most useful in the monitoring of runners. For example, incorporating the cumulative peak vertical ground reaction force experienced by runners during training sessions may improve the predictive ability of running injury epidemiological studies that have previously relied almost exclusively on (1) a single baseline biomechanical analysis and (2) running volume during training periods. However, ground reaction force is a global load experienced by the runner and provides little insight into specific anatomical loads (eg, Achilles tendon force). Second, best practices for classifying training loads derived from biomechanical data are unknown. For instance, determining whether analyzing biomechanical data continuously or categorically (eg, high, low, medium resultant tibial shock magnitude bins)[4] enhances predictive abilities of biomechanical data is presently unknown. Last, the appropriate weighting of biomechanical metrics against other training load metrics has not yet been determined. Namely, it is unclear whether a biomechanical metric should be weighted equally with running volume and sRPE (ie, total number of steps times biomechanical metric magnitude times sRPE) when estimating total training stress (hypothetical examples in **TABLE 2**). These 3 unknowns will require substantial research prior to widespread adoption and use of these data by coaches and clinicians.

Running Training Monitoring and Running-Related Injuries

It is important to consider the multitude of factors that might cause a running-related injury. A recently proposed framework for running-related injury etiology highlights the importance of evaluating the difference between (1) the cumulative loads applied to specific anatomical structures during a running session, and (2) the load capacity of specific anatomical structures that can be modified during a running session.[3] Specifically, a running-related injury occurs when the structure-specific cumulative load of a running session exceeds the structure-specific load capacity. Although it has become increasingly feasible to measure cumulative external loads experienced during a running session via wearable technology (see **TABLE 2**), it is challenging to accurately assess structure-specific internal tissue loads and tissue capacity experienced by the musculoskeletal system. Importantly, these frameworks for running-related injury etiology also need to be applied to individual athlete differences in load capacity (eg, bone density, bone strength, and tendon stiffness), which certainly will also influence model predictive outcomes for running-related injury development. Given the complexity of structure-specific load capacity, it is not surprising that running distance alone is an insufficient guide when prescribing training programs to prevent running-related injury.[6,35] The relationship between cumulative load and cumulative tissue (eg, bone) damage is not linear. Thus, cumulative damage measures may be more advantageous than cumulative load when assessing injury risk in runners.[14]

Considering the relationship between applied loads and resultant tissue damage derived from material testing models will better inform algorithms used to determine structure-specific tissue loads and damage from external loads. For example, Kiernan and colleagues[28] used a waist-mounted accelerometer to estimate the peak vertical ground reaction force experienced during running training sessions. Summing the peak vertical ground reaction force per foot strike across a training session and modeling tissue susceptibility to damage from applied loads derived from material testing research[14] produced a metric of cumulative "damage" per training session. Runners who experienced injuries had greater cumulative peak vertical ground reaction force across a competitive season compared with runners who finished the season injury free. Such new methods and findings are intriguing but require verification in larger and different populations of runners before these metrics can be implemented in daily monitoring to help reduce risk of running-related injury.

Furthermore, the use of external load metrics (eg, ground reaction forces) as a surrogate for internal tissue loads (eg, tibial bone forces) may be misguided. The peak vertical ground reaction force is responsible for only 20% to 30% of peak tibial bone force during running, whereas muscle forces are the largest contributor.[29] Nevertheless, these data suggest that coupling biomechanics obtained from wearable devices with estimates of tissue damage may hold promise for identifying runners who are at risk of experiencing a running-related injury, and for enhanced characterization of peripheral (eg, muscle, tendon, and bone) training stress. In time, wearable devices may provide tissue-level estimates of training loads, provided that the ability of wearable devices to estimate running biomechanics improves. Some commercially available wearable devices provide acceptable estimates of temporospatial metrics, tibial shock, and peak vertical ground reaction force during running, but others still lack the acceptable criterion validity that is necessary prior to considering their use in injury prediction models.[32] Thus, researchers and clinicians are currently limited to estimating external training loads applied to the whole runner rather than at the tissue level. Although training load likely contributes to the development of a running-related injury, overuse injuries in runners are multifactorial. It remains to be seen whether the combination of external load (eg, distance, duration, steps, ground reaction forces), physiological internal load (eg, sRPE), and internal tissue load (eg, stress, strain, stiffness), and adaptation to these loads, will improve our ability to accurately predict injury.

Moving Forward

Training loads likely play a major role in causing running-related injury and facilitating optimal training adaptations. However, there is inconclusive evidence regarding the influence of running training loads and training errors on running injury development.[10] The absence of evidence might be because most studies use running distance as the sole measure of training load. We argue that this approach does not adequately quantify the training stress experienced by runners. Refined approaches for better and safer recommendations for progressing running training are needed.

Future prospective research on running-related injury should appropriately quantify and report training loads. This can be as simple as minutes run per session multiplied by sRPE, which does not require sophisticated measuring devices. We believe the future of training monitoring should emphasize biomechanical external load metrics[12] coupled with internal (ie, physiological/psychological) load metrics. Even with the best monitoring approaches, differences in an individual runner's tissue load capacity will always make injury prediction elusive. Though it may be difficult to change the running culture's obsession with weekly distance, more advanced methods for quantifying running training may improve running training monitoring. Once advanced methods are developed, educating clinicians and coaches will be key to ensuring that these tools and approaches are used effectively to improve injury risk reduction and, ultimately, performance. ◉

STUDY DETAILS

AUTHOR CONTRIBUTIONS: All authors contributed to the theoretical concept, writing, editing, table and figure creation, and revision of this manuscript.

DATA SHARING: There are no data in this manuscript.

PATIENT AND PUBLIC INVOLVEMENT: There were no patients involved in the research.

REFERENCES

1. Arampatzis A, Brüggemann GP, Metzler V. The effect of speed on leg stiffness and joint kinetics in human running. *J Biomech*. 1999;32:1349-1353. https://doi.org/10.1016/s0021-9290(99)00133-5
2. Banister EW. Modeling elite athletic performance. In: Green HJ, MacDougall JD, Wenger H, eds. *Physiological Testing of Elite Athletes*. Champaign, IL: Human Kinetics; 1991:403-424.
3. 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
4. Besier T. The importance of measuring lower limb cumulative load in sport: a mechanobiological approach. *IMU Research*. February 26, 2018. Available at: https://imeasureu.com/2018/02/26/measuring-lower-limb-cumulative-load-sport/
5. 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
6. Buist I, Bredeweg SW, van Mechelen W, Lemmink KA, Pepping GJ, Diercks RL. No effect of a graded training program on the number of running-related injuries in novice runners: a randomized controlled trial. *Am J Sports Med*. 2008;36:33-39. https://doi.org/10.1177/0363546507307505
7. Calvert TW, Banister EW, Savage MV, Bach T. A systems model of the effects of training on physical performance. *IEEE Trans Syst Man Cybern*. 1976;SMC-6:94-102. https://doi.org/10.1109/TSMC.1976.5409179
8. Casado A, Hanley B, Santos-Concejero J, Ruiz-Pérez LM. World-class long-distance running performances are best predicted by volume of easy runs and deliberate practice of short-interval and tempo runs. *J Strength Cond Res*. In press. https://doi.org/10.1519/JSC.0000000000003176
9. Chan-Roper M, Hunter I, Myrer JW, Eggett DL, Seeley MK. Kinematic changes during a marathon for fast and slow runners. *J Sports Sci Med*. 2012;11:77-82.
10. Damsted C, Glad S, Nielsen RO, Sørensen H, Malisoux L. Is there evidence for an association between changes in training load and running-related injuries? A systematic review. *Int J Sports Phys Ther*. 2018;13:931-942.
11. Dantas JL, Doria C, Rossi H, et al. Determination of blood lactate training zone boundaries with rating of perceived exertion in runners. *J Strength Cond Res*. 2015;29:315-320. https://doi.org/10.1519/JSC.0000000000000639
12. Davis JJ, 4th, Gruber AH. Quantifying exposure to running for meaningful insights into running-related injuries. *BMJ Open Sport Exerc Med*. 2019;5:e000613. https://doi.org/10.1136/bmjsem-2019-000613
13. Dorn TW, Schache AG, Pandy MG. Muscular strategy shift in human running: dependence of running speed on hip and ankle muscle performance. *J Exp Biol*. 2012;215:1944-1956. https://doi.org/10.1242/jeb.064527
14. Edwards WB. Modeling overuse injuries in sport as a mechanical fatigue phenomenon. *Exerc Sport Sci Rev*. 2018;46:224-231. https://doi.org/10.1249/JES.0000000000000163

15. Foster C. Monitoring training in athletes with reference to overtraining syndrome. *Med Sci Sports Exerc*. 1998;30:1164-1168. https://doi.org/10.1097/00005768-199807000-00023

16. Foster C, Daines E, Hector L, Snyder AC, Welsh R. Athletic performance in relation to training load. *Wis Med J*. 1996;95:370-374.

17. Foster C, Florhaug JA, Franklin J, et al. A new approach to monitoring exercise training. *J Strength Cond Res*. 2001;15:109-115.

18. Foster C, Rodriguez-Marroyo JA, de Koning JJ. Monitoring training loads: the past, the present, and the future. *Int J Sports Physiol Perform*. 2017;12:S22-S28. https://doi.org/10.1123/ijspp.2016-0388

19. Fry RW, Morton AR, Keast D. Overtraining in athletes. An update. *Sports Med*. 1991;12:32-65. https://doi.org/10.2165/00007256-199112010-00004

20. Gabbett TJ. The training–injury prevention paradox: should athletes be training smarter *and* harder? *Br J Sports Med*. 2016;50:273-280. https://doi.org/10.1136/bjsports-2015-095788

21. Hanley B, Bissas A. Biomechanical Report for the IAAF World Championships London 2017 10,000 m Men's. Leeds, UK: Leeds Beckett University; 2018.

22. Hunter JG, Garcia GL, Shim JK, Miller RH. Fast running does not contribute more to cumulative load than slow running. *Med Sci Sports Exerc*. 2019;51:1178-1185. https://doi.org/10.1249/MSS.0000000000001888

23. 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

24. Impellizzeri FM, Rampinini E, Coutts AJ, Sassi A, Marcora SM. Use of RPE-based training load in soccer. *Med Sci Sports Exerc*. 2004;36:1042-1047. https://doi.org/10.1249/01.mss.0000128199.23901.2f

25. Impellizzeri FM, Rampinini E, Marcora SM. Physiological assessment of aerobic training in soccer. *J Sports Sci*. 2005;23:583-592. https://doi.org/10.1080/02640410400021278

26. 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

27. Johnston R, Cahalan R, O'Keeffe M, O'Sullivan K, Comyns T. The associations between training load and baseline characteristics on musculoskeletal injury and pain in endurance sport populations: a systematic review. *J Sci Med Sport*. 2018;21:910-918. https://doi.org/10.1016/j.jsams.2018.03.001

28. Kiernan D, Hawkins DA, Manoukian MAC, et al. Accelerometer-based prediction of running injury in National Collegiate Athletic Association track athletes. *J Biomech*. 2018;73:201-209. https://doi.org/10.1016/j.jbiomech.2018.04.001

29. Matijevich ES, Branscombe LM, Scott LR, Zelik KE. Ground reaction force metrics are not strongly correlated with tibial bone load when running across speeds and slopes: implications for science, sport and wearable tech. *PLoS One*. 2019;14:e0210000. https://doi.org/10.1371/journal.pone.0210000

30. Matos S, Clemente FM, Brandão A, et al. Training load, aerobic capacity and their relationship with wellness status in recreational trail runners. *Front Physiol*. 2019;10:1189. https://doi.org/10.3389/fphys.2019.01189

31. Meeuwisse WH, Tyreman H, Hagel B, Emery C. A dynamic model of etiology in sport injury: the recursive nature of risk and causation. *Clin J Sport Med*. 2007;17:215-219. https://doi.org/10.1097/JSM.0b013e3180592a48

32. Moore IS, Willy RW. Use of wearables: tracking and retraining in endurance runners. *Curr Sports Med Rep*. 2019;18:437-444. https://doi.org/10.1249/JSR.0000000000000667

33. Napier C, Ryan M, Paquette MR, Menon C. Session RPE in combination with training volume provides a better estimation of training responses in runners. *J Athl Train*. In press.

34. Nielsen RO, Bertelsen ML, Møller M, et al. Training load and structure-specific load: applications for sport injury causality and data analyses. *Br J Sports Med*. 2018;52:1016-1017. https://doi.org/10.1136/bjsports-2017-097838

35. Nielsen RO, Cederholm P, Buist I, Sørensen H, Lind M, Rasmussen S. Can GPS be used to detect deleterious progression in training volume among runners? *J Strength Cond Res*. 2013;27:1471-1478. https://doi.org/10.1519/JSC.0b013e3182711e3c

36. Paquette MR, Miller RH. Reconciling new with old injury paradigms and the need to dig deeper – comment on Nigg et al. [letter]. *Curr Issues Sport Sci*. 2018;3:105. https://doi.org/10.15203/CISS_2018.105

37. Saw AE, Main LC, Gastin PB. Monitoring the athlete training response: subjective self-reported measures trump commonly used objective measures: a systematic review. *Br J Sports Med*. 2016;50:281-291. https://doi.org/10.1136/bjsports-2015-094758

38. Scherr J, Wolfarth B, Christle JW, Pressler A, Wagenpfeil S, Halle M. Associations between Borg's rating of perceived exertion and physiological measures of exercise intensity. *Eur J Appl Physiol*. 2013;113:147-155. https://doi.org/10.1007/s00421-012-2421-x

39. Tran J, Rice AJ, Main LC, Gastin PB. Development and implementation of a novel measure for quantifying training loads in rowing: the T2minute method. *J Strength Cond Res*. 2014;28:1172-1180. https://doi.org/10.1519/JSC.0000000000000248

40. Vickers AJ, Vertosick EA. An empirical study of race times in recreational endurance runners. *BMC Sports Sci Med Rehabil*. 2016;8:26. https://doi.org/10.1186/s13102-016-0052-y

41. Willy RW. Innovations and pitfalls in the use of wearable devices in the prevention and rehabilitation of running related injuries. *Phys Ther Sport*. 2018;29:26-33. https://doi.org/10.1016/j.ptsp.2017.10.003