

LAUREN C. BENSON, PhD¹ • ANU M. RÄISÄNEN, PT, PhD¹ • VALERIYA G. VOLKOVA, BSc¹
KATI PASANEN, PT, PhD^{1,4} • CAROLYN A. EMERY, PT, PhD^{1,3,6}

Workload a-WEAR-ness: Monitoring Workload in Team Sports With Wearable Technology. A Scoping Review

Sport-related injuries are common in youth and adult populations,^{24,35-38,55} leading to financial burden,⁴⁰ decreased physical activity,⁴³ and increased risk of cardiovascular disease, obesity, and osteoarthritis.^{9,50,74} Injuries during sport occur when the stresses and strains applied to body tissue exceed

the maximal strength or failure strain of the tissue. However, noninjurious levels of stress and strain are necessary to elicit positive tissue adaptation.^{33,53}

Balancing the positive and negative effects of training contributes to effective performance and injury prevention.^{4,44,79,84} Yet it is difficult to directly measure the stresses and strains on body tissues in a noninvasive way, particularly outside the laboratory environment. Instead, sport practitioners track and analyze workload, defined as any training-related variable that can be manipulated to elicit a desired response to exercise.⁴⁷

Workload is monitored through measures of external and internal load. External load represents the physical work performed, providing objective information about the quantity and intensity of exercise.^{47,79} The metrics used to quantify external load are specific to the nature of training and include locomotive (eg, distance traveled, number of accelerations) and mechanical (eg, number of jumps, frequency of impacts) metrics, which can be recorded using wearable devices such as inertial measurement units (IMUs)

• **OBJECTIVES:** To (1) identify the wearable devices and associated metrics used to monitor workload and assess injury risk, (2) describe the situations in which workload was monitored using wearable technology (including sports, purpose of the analysis, location and duration of monitoring, and athlete characteristics), and (3) evaluate the quality of evidence that workload monitoring can inform injury prevention.

• **DESIGN:** Scoping review.

• **LITERATURE SEARCH:** We searched the CINAHL, Cochrane Central Register of Controlled Trials, Cochrane Database of Systematic Reviews, Embase, HealthSTAR, MEDLINE, PsycINFO, SPORT-Discus, and Web of Science databases.

• **STUDY SELECTION CRITERIA:** We included all studies that used wearable devices (eg, heart rate monitor, inertial measurement units, global positioning system) to monitor athlete workload in a team sport setting.

• **DATA SYNTHESIS:** We provided visualizations that represented the workload metrics reported, sensors used, sports investigated, athlete characteristics, and the duration of monitoring.

• **RESULTS:** The 407 included studies focused on team ball sports (67% soccer, rugby, or Australian football), male athletes (81% of studies), elite or professional level of competition (74% of studies), and young adults (69% of studies included athletes aged between 20 and 28 years). Thirty-six studies of 7 sports investigated the association between workload measured with wearable devices and injury.

• **CONCLUSION:** Distance-based metrics derived from global positioning system units were common for monitoring workload and are frequently used to assess injury risk. Workload monitoring studies have focused on specific populations (eg, elite male soccer players in Europe and elite male rugby and Australian football players in Oceania). Different injury definitions and reported workload metrics and poor study quality impeded conclusions regarding the relationship between workload and injury. *J Orthop Sports Phys Ther* 2020;50(10):549-563. doi:10.2519/jospt.2020.9753

• **KEY WORDS:** athlete, injury, longitudinal, training load

¹Sport Injury Prevention Research Centre, Faculty of Kinesiology, University of Calgary, Calgary, Canada. ²Tampere Research Center of Sport Medicine, UKK Institute for Health Promotion Research, Tampere, Finland. ³Alberta Children's Hospital Research Institute, University of Calgary, Calgary, Canada. ⁴McCaig Institute for Bone and Joint Health, Cumming School of Medicine, University of Calgary, Calgary, Canada. ⁵Department of Community Health Sciences, Cumming School of Medicine, University of Calgary, Calgary, Canada. ⁶Department of Paediatrics, Cumming School of Medicine, University of Calgary, Calgary, Canada. This review was registered with PROSPERO (CRD42018106853). Dr Benson is funded through a Canadian Institutes of Health Research Postdoctoral Fellowship (MFE-164608). Dr Räisänen is supported through a Canadian Institutes of Health Research Foundation Grant program (principal investigator: Dr Emery) and the Vi Riddell Pediatric Rehabilitation Research Program (Alberta Children's Hospital Foundation). Valeriya G. Volkova is supported through the Natural Sciences and Engineering Research Council of Canada's Collaborative Research and Training Experience Wearable Technology Research and Collaboration training program. Dr Emery is supported by a Canada Research Chair (Tier 1). The Sport Injury Prevention Research Centre is one of the International Olympic Committee Research Centres for the prevention of injury and protection of athlete health. The funding organization had no role in the collection/analysis/interpretation or publication of results. 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 Dr Lauren C. Benson, University of Calgary, Faculty of Kinesiology, 2500 University Drive NW, Calgary, AB T2N 1N4 Canada. E-mail: lauren.benson@ucalgary.ca • Copyright ©2020 *Journal of Orthopaedic & Sports Physical Therapy*

and global positioning systems (GPSs).⁷⁹ Internal load represents the psychophysiological response to external load⁴⁷ and can be reported using subjective measures (eg, session rating of perceived exertion),⁴¹ and portable heart rate monitors have allowed for the recording of objective internal load metrics (eg, heart rate zones and impulse).⁵

Monitoring athlete workload is common among sport practitioners,^{30,57,79,84,86} as technological advances in wearable sensors have made it easier to longitudinally measure a variety of workload metrics.^{30,44,47,84} However, varying definitions of injury, diverse methods, a lack of scientific basis for cutoffs of functional workload ratios, and mathematical shortcomings in calculating workload ratios present challenges to identifying meaningful relationships between workload and injury.^{27,29,32,51,68,69,78,87} Establishing an association between workload and injury requires longitudinal monitoring of large cohorts of athletes,^{14,79} meaning that investigations of this nature are confined to athlete populations with the resources to collect reliable workload and injury data.³⁰

Wearable technology for monitoring workload is novel, and no consensus has been reached regarding the type of sensors used, the number and nature of metrics that are monitored, how they relate to injury, and the specificity of any reported workload-injury relationships to the sport population investigated. Therefore, this scoping review encompassed all studies that used wearable devices for monitoring workload among team sport athletes, with an additional focus on studies that investigated the workload-injury relationship.

We aimed to (1) identify the wearable devices and associated metrics used to monitor workload and the workload metrics used to assess injury risk; (2) describe the situations where workload was monitored using wearable technology, including sports, purpose of the analysis, location and duration of workload monitoring, and athlete characteristics

such as sex, age, and competition level; and (3) evaluate the quality of evidence for workload monitoring to inform injury prevention. Capturing the breadth of this field will benefit researchers and sport practitioners as they develop best practices for workload monitoring and facilitate understanding how workload patterns influence injury.

METHODS

THE SEARCH STRATEGY, ELIGIBILITY criteria, study selection, data extraction, and analysis were specified in a predefined protocol registered with PROSPERO (CRD42018106853).

Eligibility Criteria

Studies that monitored the workload of athletes using wearable devices (eg, heart rate monitor, IMU, GPS, other devices worn by an athlete) in a team sport setting were eligible. Workload monitoring had to occur during normal team practice/training sessions or games/matches. Studies that investigated differences in workload between multiple groups within the team sport athlete population, without intervening in the workload (eg, identifying workload thresholds for injury risk, comparing workload between different levels of competition), were eligible. Peer-reviewed journal articles or conference proceedings published in English since 2000 were included; book chapters, abstracts, and review papers were excluded.

Information Sources and Search Terms

A systematic search for published papers was conducted in MEDLINE (APPENDIX, available at www.jospt.org) and then customized for the CINAHL, Cochrane Central Register of Controlled Trials, Cochrane Database of Systematic Reviews, Embase, HealthSTAR, PsycINFO, SPORTDiscus, and Web of Science databases. All databases were searched for the final time on March 13, 2020. The search strategy identified records that contained at least 1 search term in each of the fol-

lowing 3 themes: wearable technology, workload or injury, and team sports.

Study Selection

The search results from all databases were combined and duplicate studies were removed. All studies were screened for eligibility independently by 2 authors (L.C.B. and A.M.R.) in 2 stages (ie, title, abstract). Discrepancies were resolved by a third author (V.G.V.). The full text was obtained for all studies that passed screening by title and abstract. Three authors (L.C.B., A.M.R., and V.G.V.) each assessed one third of the full-text articles for eligibility, and nominations for exclusion were discussed and agreed on by all 3 authors.

Data Collection

We used an Excel (Microsoft Corporation, Redmond, WA) worksheet to organize the data extracted from each included study: study design; sport; year of publication; workload analyses conducted; country of data collection; sex, age, and number of participants; length of monitoring period; number of sessions recorded; level of competition; wearable sensors used; and workload metrics monitored.

We extracted information about the injury (definition, location), workload metrics, accumulation (acute-chronic workload ratio [ACWR] and/or cumulative), number of metric-accumulation combinations, and results of workload-injury associations from studies that investigated an association between workload and injury.

Three authors (L.C.B., A.M.R., and V.G.V.) each extracted data from one third of the included studies. One author (L.C.B.) combined all data-extraction worksheets, edited for consistency, and consulted the full-text articles to ensure accuracy.

During the data-extraction process, the following assumptions, simplifications, and calculations were made if information was not available in the desired format.

Sport All types of rugby (ie, rugby league, rugby sevens, rugby union) were combined into 1 sport category. Adapted sports (eg, wheelchair basketball, seven-a-side soccer) were considered discrete sport categories.

Workload Analyses Conducted Analyses conducted using workload data were classified as:

- Comparisons of workload across sports, sexes, playing positions, session types (eg, training versus match), participation level (eg, elite versus recreational, levels of disability), workload metrics (eg, wearable-based measures such as heart rate versus participant-reported measures such as rating of perceived exertion), external and internal measures of load within sessions (eg, first half versus second half) and between sessions (eg, pre-season versus competitive season)
- Associations between workload and injury, performance (eg, fitness test, strength), and biomarkers (eg, plasma creatine kinase, blood lactate)
- No analyses (ie, descriptive only)

Country of Data Collection The country of ethics approval was extracted if the country of data collection was not reported. All countries were grouped according to continent.

Sex If the sex of the participants was not reported, we inferred sex from the reported league and level of competition.

Age If age was reported for subsets of the sample (eg, age was reported for position groups), we calculated mean age (ie, for each subset, the mean age was multiplied by the number of participants, then the values for all subsets were summed and divided by the total number of participants).

Workload Monitoring Period The duration of the monitoring period was categorized as (1) 1 session, (2) multiple sessions but not a full season, (3) 1 full season, and (4) multiple seasons. We defined the monitoring period as the length of time participants were in the study (separate from the number of sessions that were recorded during the monitoring period).

Number of Sessions Recorded If only total number of sessions was reported, we calculated the mean number of sessions recorded per participant (ie, total number of sessions divided by number of participants).

Level of Competition We classified the level of competition, based on the terminology used in the study, as (1) international, (2) elite or professional (including academy, elite, first division, high performance, junior, national, and professional), (3) semi-elite (including second division, semi-elite, semi-professional, and sub elite), (4) collegiate and university, and (5) nonelite (including amateur, county, nonelite, nonprofessional, provincial, recreational, schoolboy, state).

Wearable Sensors Used Sensors were only identified if metrics derived from that sensor were reported (eg, for a study that used an IMU containing an accelerometer, gyroscope, and magnetometer but only reported metrics from the accelerometer, we reported on the accelerometer sensor only).

Workload Metrics Monitored Workload metrics were classified according to sensor (eg, heart rate monitor, GPS, accelerometer), units (eg, number, frequency, distance, speed), and condition (eg, sprints, speed zones, direction changes). We did not consider the conditions during which a workload metric was monitored (eg, warm-up, drills, game play, etc) in the team sport setting.

Quality Assessment

We were interested in the quality of evidence informing workload monitoring for injury prevention. We used a custom quality-assessment worksheet adapted from Campos et al¹⁵ and Downs and Black²⁸ to assess the quality of each of the included articles. Our quality assessment addressed reporting, external validity, internal validity (bias and confounding), and statistical power. Each question had 3 possible answers: “yes,” “no,” or “not applicable.”

Three authors (L.C.B., A.M.R., and V.G.V.) pilot tested the quality-assess-

ment worksheet on 6 studies selected at random. The results of these assessments were discussed until a consensus was reached. All studies were independently assessed by 2 authors, and discrepancies were resolved by consensus.

Data Synthesis

The data extracted from each study were recorded in tables, and summaries were presented as visualizations. Specifically, the number of studies with and without injury analyses were displayed according to the sensors used and workload metrics reported. The number of participants monitored with each sensor were summed across each sensor combination, and the mean year of study publication demonstrated trends in how sensor combinations were used for workload monitoring. The included studies were also stratified by the sport investigated, participant sex, and the duration of workload monitoring to illustrate the situations where workload is monitored using wearable technology.

We summarized the overall quality of all included studies, and the subset of studies that investigated an association between workload and injury. We organized the quality-assessment summary according to our 5 quality-assessment topics: reporting, external validity, internal validity (bias and confounding), and statistical power. We considered the overall study quality when generalizing findings regarding the relationship between workload and injury.

RESULTS

Study Selection

THE DATABASE SEARCHES YIELDED 7174 records after duplicates were removed. Following screening, 477 full-text articles were assessed for eligibility, and 407 studies were included (FIGURE 1). The complete results of the data extracted from the 407 studies included in this review, including the study information, workload metrics, and full reference list of the included studies, are

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available online (supplemental material, available at www.jospt.org).

Study Characteristics

The most commonly reported workload metrics were distance in speed zones and total distance measured by a GPS, appearing in 227 (56%) and 220 (54%) studies, respectively, including up to 28 (7%) studies with injury analyses. Distance in speed zones and total distance were also measured using a radio frequency-based tracking system and an accelerometer. The relative total distance and relative distance in speed zones measured by a GPS were the most common metrics expressed as a frequency; 3 studies used relative total distance in injury analyses. The most common accelerometer-based metric was a vector composition of the accelerometer axes, which was used in 125 (31%) studies, 14 with injury analyses and 111 without injury analyses. Heart rate metrics were measured in up to 80 (20%) studies; 2 injury analyses used heart rate metrics. The number or frequency of turns was monitored in 5 (1%) studies using an accelerometer, 7 (2%) studies using a gyroscope, and 2 (0.5%) studies using a magnetometer (FIGURE 2).

The sensor combination that was used to monitor the most participants was a single GPS; the next 3 combinations involved a GPS along with an accelerometer or heart rate monitor, or with both. The sensor combination that had the oldest mean year of publication and most participants was a single heart rate monitor. The newest sensor combinations included components of IMUs (accelerometer, gyroscope, magnetometer) and radio frequency-based tracking systems (FIGURE 3).

The study designs were prospective cohort (89%), retrospective cohort (5%), cross-sectional (4%), or case study/case series (2%). For the first 10 years that were included in this review (2000–2009), there were no more than 2 (0.5%) studies published each year and 8 (2%) studies total. In the subsequent 10 years, the remaining 399 (98%) studies were

published, with 102 (25%) published in the last full year included in this review (2019). Soccer was the most common sport for almost every year in the second decade (FIGURE 4A).

The most common analysis was a comparison of workload across playing position, appearing in 34% of studies, and more than half of those analyses were in soccer or rugby. Associations between workload and injury were studied in 36 (9%) studies, and 81% of those analyses were in soccer, rugby, or Australian football (FIGURE 4B). Over 50% of all studies collected data in Europe, with European soccer data collection representing more than a quarter of all studies. Oceania was the continent with the next largest share of studies, driven by rugby and Australian football studies, representing 9% and 11% of all studies, respectively (FIGURE 4C).

Male participants were included in 81% of studies (FIGURE 5A). Most studies (69%) had a mean participant age between 20 and 28 years (FIGURE 5B). Thirty-one percent of all studies included male soccer participants, 18% included male rugby participants, and 10% included male Australian football participants; the proportions of studies that included female participants in those sports were 4%, 2%, and 0.5%, respectively (FIGURE 5C). The number of athletes monitored was fewer than 25 participants in 235 (58%) studies, and all but 1 study with female participants had a sample size less than 50. There were 17 (4%) studies with more than 100 participants, with the largest study involving more than 525 participants (FIGURE 5D).

Fewer than 25 sessions per participant were recorded in 209 (51%) studies, and 16 of those studies recorded just 1 session per participant. One study recorded over

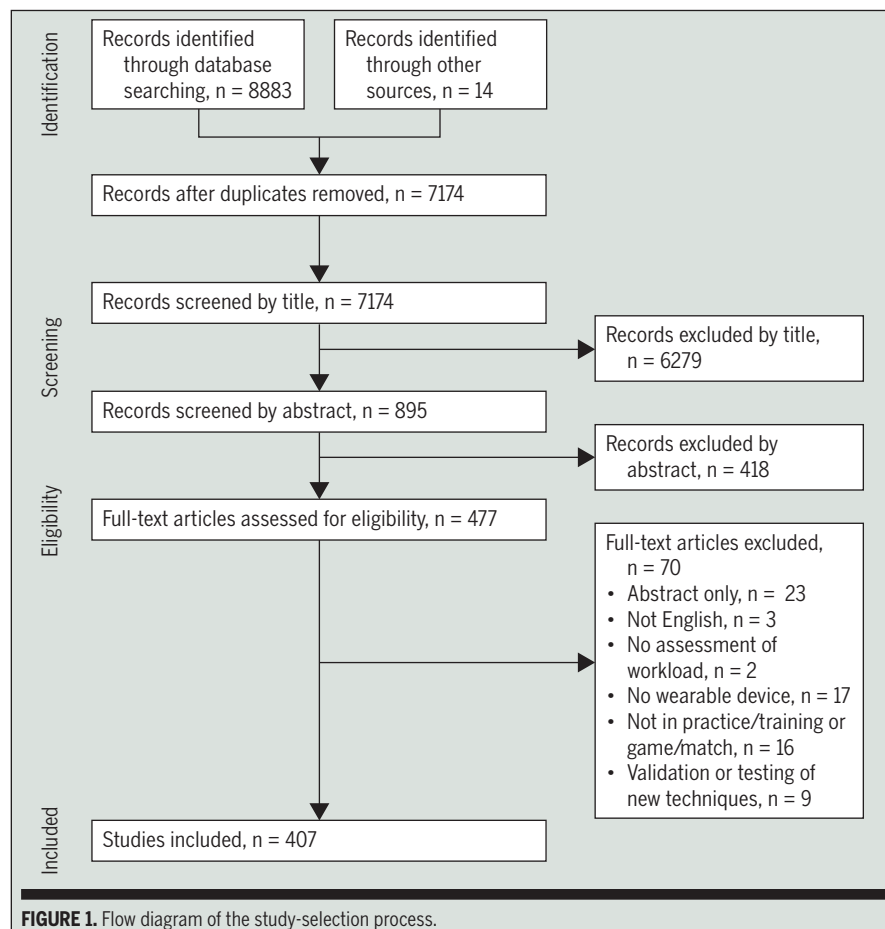


FIGURE 1. Flow diagram of the study-selection process.

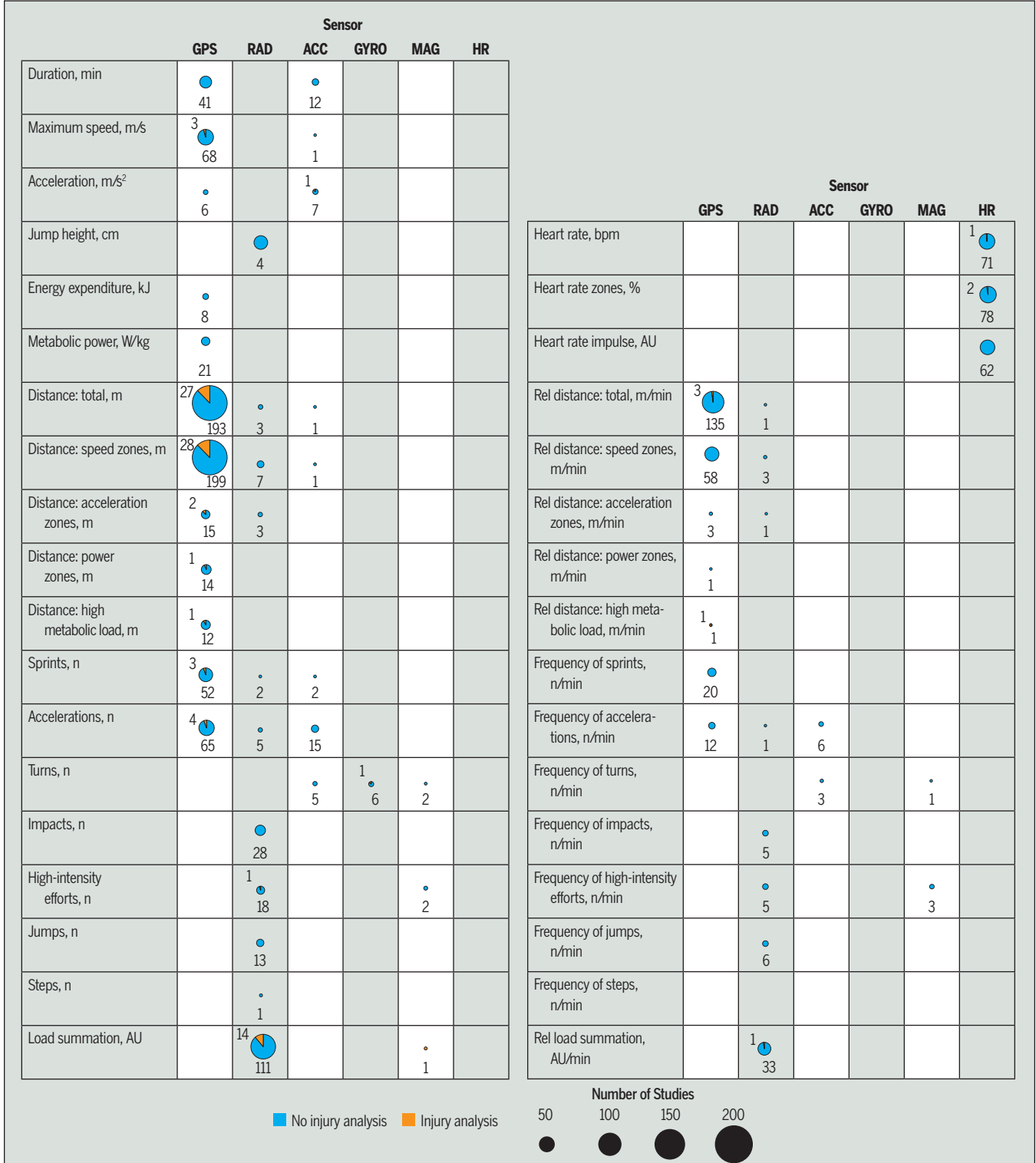


FIGURE 2. The workload metrics monitored are organized according to the sensor used to measure them. The pie charts represent the number of studies that reported each metric, with the number of studies that used the metrics as part of an injury analysis indicated separately. Abbreviations: ACC, accelerometer; AU, arbitrary unit; GPS, global positioning system; GYRO, gyroscope; HR, heart rate monitor; MAG, magnetometer; RAD, radio frequency–based tracking system; Rel, relative. An interactive version of this figure is available at: <https://public.tableau.com/profile/lauren.benson#/vizhome/WorkloadWearableSystematicReview-InteractiveFigures/Figure2MetricsRecorded>

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450 sessions per participant during 1 full season (FIGURE 6A). Seventy-four percent of all studies included elite or professional athletes, with fewer than 5% of those studies monitoring participants for only 1 session (FIGURE 6B). The most common wearable sensors were a GPS, accelerometer, and heart rate monitor (FIGURE 6C).

Summary of Injury Studies

Forty-one studies (10%) reported injuries to athletes during the monitoring period; female athletes were included in 2 studies.^{54,85} In 5 studies, the aim was something other than examining the workload-injury relationship.^{1,13,25,76,85} The 36 remaining studies were primarily focused on Australian football, soccer, and rugby, and included various injury definitions and locations and workload analyses (supplemental material, available at www.jospt.org).

A high ACWR for total distance was associated with a greater risk of injury in Australian football,^{39,64,65} soccer,³ and rugby.^{26,45,46} A high ACWR or exponentially weighted moving average (EWMA) for a variety of high-speed distance measures was also associated with injury.^{10,16,19,22,26,31,39,49,63-65,70,77} One study reported that a low ACWR for high-speed distance in rugby was associated with injury,²² and another study showed a protective effect in soccer when the ACWR for high-speed distance was moderate.⁵⁸

In field hockey⁵⁴ and rugby,⁴² greater distance at low speed or intensity was protective against injuries. Both high^{21,39,42,46,49,59} and low^{10,21,22,59,83} cumulative or chronic total distance and high-speed distance loads were associated with greater injury risk. During the preseason, high and low cumulative total distance was associated with injury in rugby,^{19,20} while greater participation in the preseason was associated with decreased injury risk in rugby.⁹⁰

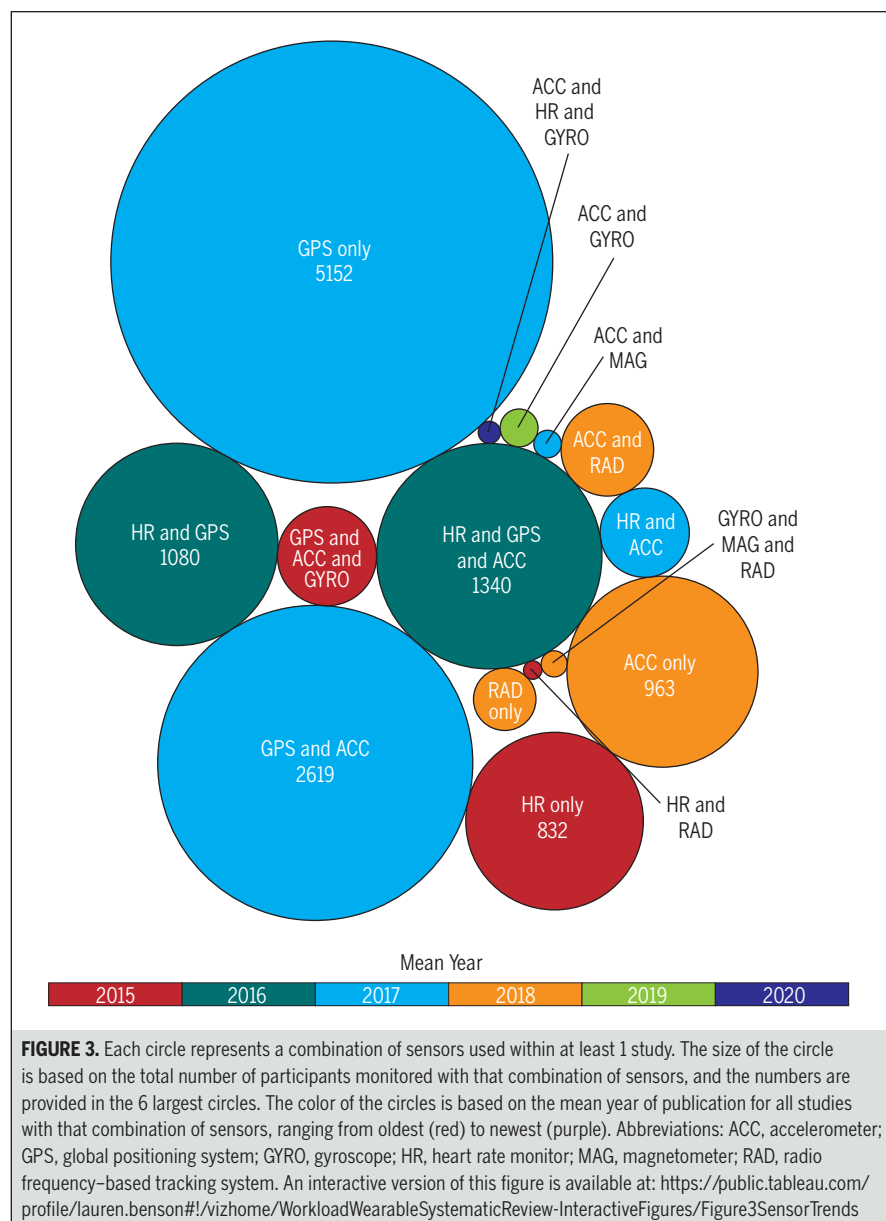
Workload metrics based on accelerations, low⁸⁰ and high^{10,34,39,56,60,80} ACWR or EWMA, low¹⁰ and high^{11,19,39,49} cumulative load, and decreased load vari-

ability⁸⁸ were all associated with greater injury risk.

Quality Assessment

The full results of the quality assessment for each study included in this review (supplemental material, available at www.jospt.org) are available online. No study scored yes on all of the quality assessment items. Between 381 and 407 (94%-100%) studies (30-36 [83%-100%] injury studies) had adequate reporting of the objective, main outcomes,

inclusion/exclusion criteria, summary of main findings, and estimates of variability. Two hundred eight (51%) studies (27 [75%] injury studies) did not clearly describe participant characteristics, with sex and/or age among the most common missing characteristics. One hundred twenty-eight (38%) studies (10 [33%] injury studies) that conducted tests with probability values did not report the actual *P* values. All but 1 study had adequate external validity. Measurement bias was accounted for by reporting of unplanned



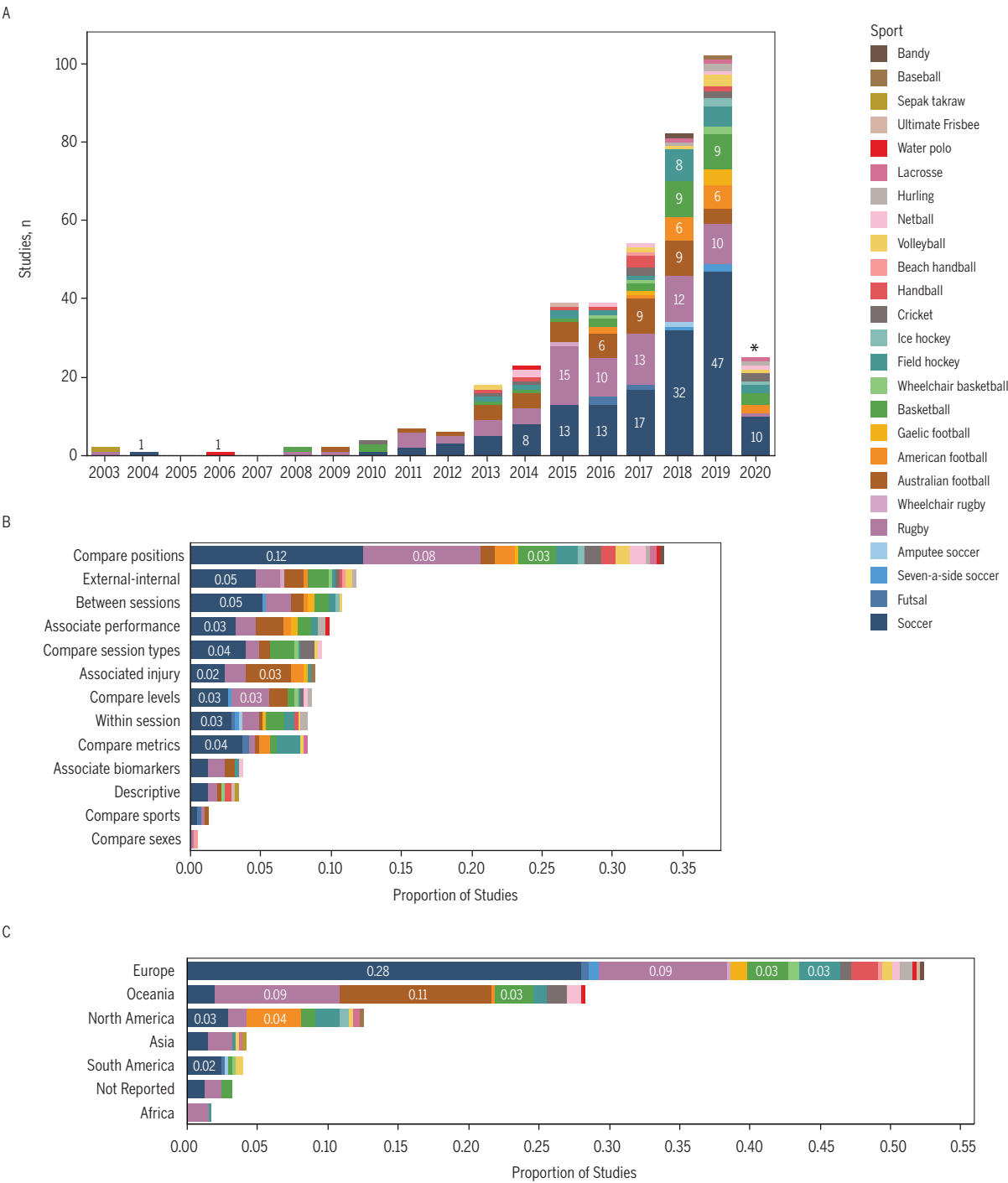


FIGURE 4. General study information is indicated by sport, with similar sports grouped together and displaying different shades of the same color (eg, soccer, futsal, and amputee soccer are all different shades of blue). Sport groups are sorted according to frequency among the studies included in this review. (A) A histogram of the number of studies published in each year, (B) the percentage of studies that performed each of the 13 specified categories of workload analysis, and (C) the percentage of studies with data collection on each continent. For the percentage analyses (panels B and C), percentages were calculated based on the total number of studies included in the review (407), so the sum of the percentages is greater than 100% to account for studies that fit multiple categories (eg, multiple workload analyses, multiple continents for data collection). *Through March 13, 2020. An interactive version of this figure is available at: <https://public.tableau.com/profile/lauren.benson#!/vizhome/WorkloadWearableSystematicReview-InteractiveFigures/Figure4GeneralStudyInformation>

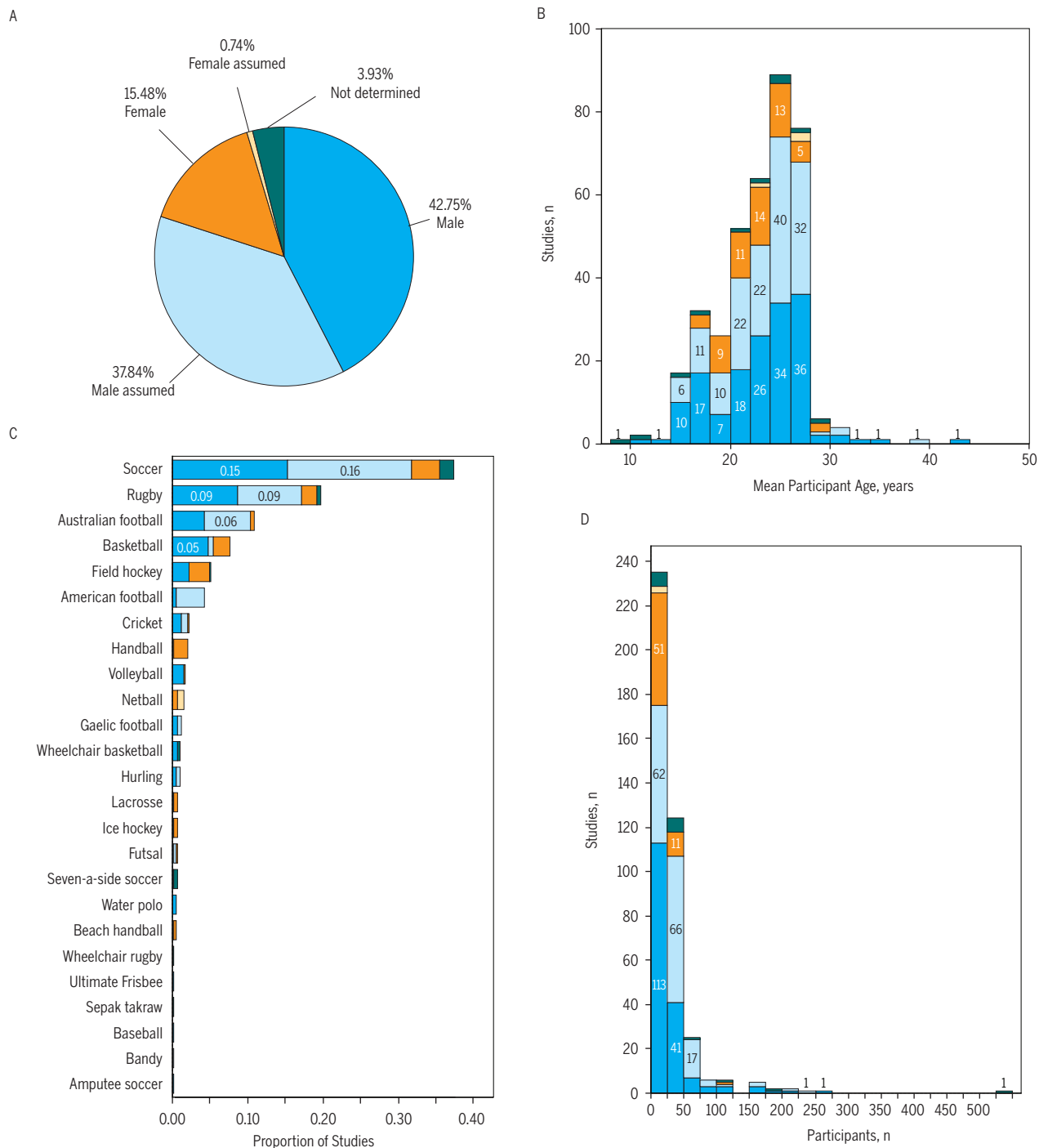


FIGURE 5. Participant information is highlighted by the sex of the participants, with blue corresponding to males, orange corresponding to females, and green indicating that the participant sex could not be determined. Where the sex of the participants had to be assumed (rather than explicitly stated in the text), the color is light blue (male) or light orange (female). (A) A pie chart of the percentage of studies that included participants of each sex. (B) A histogram of the number of studies for mean participant age, binned every 2 years. (C) The percentage of studies for each sport. (D) A histogram of the number of studies for participant sample size, binned every 25 participants. For the percentage analyses (panels A and C), percentages were calculated based on the total number of studies included in the review (407), so the sum of the percentages is greater than 100% to account for studies that fit multiple categories (eg, males and females in the same study, multiple sports). An interactive version of this figure is available at: <https://public.tableau.com/profile/lauren.benson#1/vizhome/WorkloadWearableSystematicReview-InteractiveFigures/Figure5ParticipantInformation>

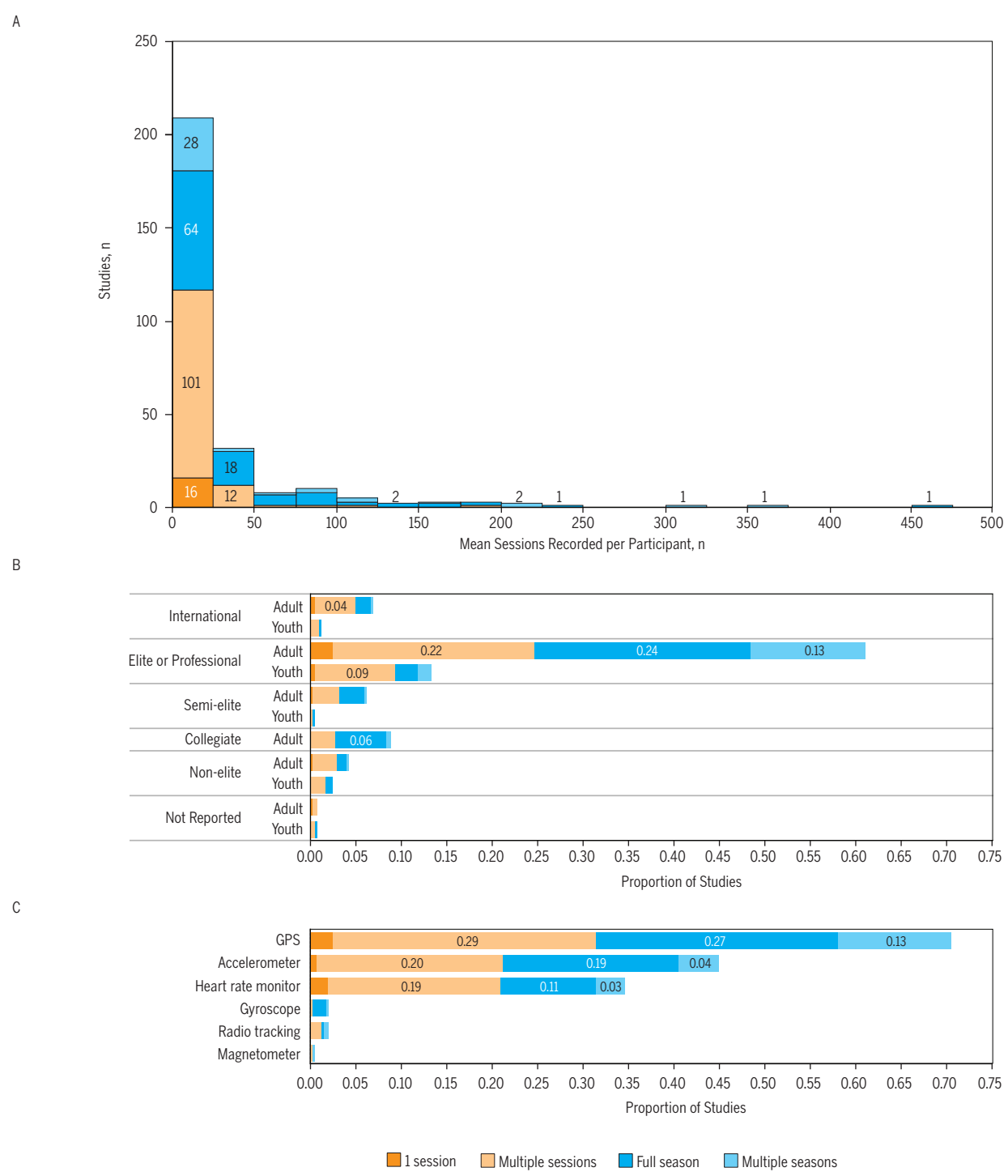


FIGURE 6. Monitoring duration is shown as 1 session, multiple sessions, full season, or multiple seasons. (A) A histogram of the number of studies for mean number of sessions recorded per participant, binned every 25 sessions. (B) The percentage of studies for each competition level, stratified by adult and youth categories. (C) The percentage of studies for each sensor. For the percentage analyses (panels B and C), percentages were calculated based on the total number of studies included in the review (407), so the sum of the percentages is greater than 100% to account for studies that fit multiple categories (eg, multiple competition levels, multiple sensors). Abbreviation: GPS, global positioning system. An interactive version of this figure is available at: <https://public.tableau.com/profile/lauren.benson#!/vizhome/WorkloadWearableSystematicReview-InteractiveFigures/Figure6MonitoringDuration>

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retrospective analysis (407 [100%] studies, 36 [100%] injury studies), use of appropriate statistical tests (390 [96%] studies, 34 [94%] injury studies), and use of valid and reliable main outcome measures (405 [99.5%] studies, 35 [97%] injury studies).

Ninety-six (24%) studies (5 [14%] injury studies) did not appropriately adjust analyses for different lengths of follow-up. When applicable, 49 (24%) studies (10 [36%] injury studies) adjusted for confounding in their analysis.

Thirty-nine (10%) studies (2 [6%] injury studies) described and accounted for characteristics of participants lost to follow-up. Ten (3%) studies (3 [8%] injury studies) provided power descriptions by way of a sample-size justification or a priori effect-size estimates (TABLE).

DISCUSSION

THE RESULTS OF THIS SCOPING REVIEW reflect the very recent growth in the use of wearable technology for

monitoring workload. Over the past 2 decades, there appears to have been a shift from using heart rate monitors in isolation for recording internal load to the use of other sensors that record external load, with or without concurrent use of heart rate monitors. A GPS was the most common sensor for monitoring external training load, and GPS-derived metrics were frequently used in studies that examined the workload-injury relationship. A key limitation of the GPS is that it does not work indoors,^{75,78} so alternative met-

TABLE

SUMMARY OF RESPONSES TO THE QUALITY-ASSESSMENT QUESTIONS FOR ALL STUDIES AND INJURY STUDIES^a

Topic/Question	Yes		No		NA	
	All	Injury	All	Injury	All	Injury
Reporting						
1. Is the hypothesis/aim/objective of the study clearly described?	407 (100.0)	36 (100.0)	0 (0.0)	0 (0.0)	0 (0.0)	0 (0.0)
2. Are the main outcomes to be measured clearly described in the Introduction or Methods section?	405 (99.5)	35 (97.2)	2 (0.5)	1 (2.8)	0 (0.0)	0 (0.0)
3. Are the characteristics of the participants included in the study clearly described? Must specify sex, age, height, and weight	199 (48.9)	9 (25.0)	208 (51.1)	27 (75.0)	0 (0.0)	0 (0.0)
4. Are the inclusion/exclusion criteria described and appropriate?	397 (97.5)	36 (100.0)	10 (2.5)	0 (0.0)	0 (0.0)	0 (0.0)
5. Are the main findings of the study clearly described?	406 (99.8)	36 (100.0)	1 (0.2)	0 (0.0)	0 (0.0)	0 (0.0)
6. Does the study provide estimates of the random variability in the data for the main outcomes?	381 (93.6)	30 (83.3)	26 (6.4)	6 (16.7)	0 (0.0)	0 (0.0)
7. Have actual probability values been reported for the main outcomes?	205 (50.4)	20 (55.6)	128 (31.4)	10 (27.8)	74 (18.2)	6 (16.7)
External validity						
8. Were the setting and conditions of the experiment typical for the population represented by the participants?	406 (99.8)	36 (100.0)	1 (0.2)	0 (0.0)	0 (0.0)	0 (0.0)
Internal validity: bias						
9. If any of the results of the study were based on data dredging, was this made clear?	407 (100.0)	36 (100.0)	0 (0.0)	0 (0.0)	0 (0.0)	0 (0.0)
10. Do the analyses adjust for different lengths of follow-up (eg, time of monitoring)?	309 (75.9)	31 (86.1)	96 (23.6)	5 (13.9)	2 (0.5)	0 (0.0)
11. Were the statistical tests used to assess the main outcomes appropriate?	390 (95.8)	34 (94.4)	12 (2.9)	2 (5.6)	5 (1.2)	0 (0.0)
12. Were the main outcome measures used accurate (valid and reliable)?	405 (99.5)	35 (97.2)	2 (0.5)	1 (2.8)	0 (0.0)	0 (0.0)
Internal validity: confounding						
13. Are the distributions of confounders in each group of participants clearly described and taken into account during the analysis?	49 (12.0)	10 (27.8)	155 (38.1)	18 (50.0)	203 (49.9)	8 (22.2)
14. Have the characteristics of participants lost to follow-up been described and taken into account during the analysis?	39 (9.6)	2 (5.6)	347 (85.3)	34 (94.4)	21 (5.2)	0 (0.0)
Power						
15. Was a sample-size justification, power description, or variance and effect estimates provided?	10 (2.5)	3 (8.3)	394 (96.8)	33 (91.7)	3 (0.7)	0 (0.0)

Abbreviation: NA, not applicable.

^aValues are n (percent).

rics (eg, those derived from accelerometers) are used to monitor workload.⁷⁵

Recent studies used radio frequency-based tracking systems to record distance traveled in indoor sports (eg, basketball⁷²). This type of system has been validated and may be more accurate than the GPS,⁷¹ in addition to being a more versatile workload monitoring system. Devices that include some or all components of IMUs (accelerometer, gyroscope, and magnetometer) are also common, and these devices have the added benefit of not requiring an external satellite or a radio frequency-based system.

Despite the ability to use wearable technology in real-world sporting environments,^{7,89} accessibility has not been uniformly extended across all team sport populations. The studies included in this review primarily investigated a few sports (eg, soccer, rugby, Australian football) within continents where these sports are popular (eg, Europe, Oceania), calling into question the external validity of these studies, as the level of competition may differ between countries. Workload monitoring was disproportionately skewed toward male participants. Most studies monitored elite or professional athletes and athletes between 20 and 28 years of age. Therefore, results may not be generalizable to younger and older populations that compete at a recreational level.

The common approach in studies that investigated the workload-injury relationship was to associate accumulated workload, often using the ACWR, with reported injuries.^{29,32} In addition to established concerns about using this approach to identify meaningful relationships between workload and injury,^{27,53,68,69,87} there was a lack of consistency in how injuries and workload were reported.

- A range of injury definitions were used, even within the same sport, which impacts generalizability.⁸⁷
- Among studies that investigated similar populations (eg, elite male soccer players), workload variables

(eg, total distance, high-speed distance) were multiplied by various workload accumulation calculations (eg, ACWR, cumulative load); up to 756 combinations were reported in 1 study.¹⁰

- Different cut points for binning the quantity of load for each workload-accumulation combination were reported, despite a lack of evidence for whether or how these values should be discretized.⁸⁷ For example, some studies in soccer have classified the load values into 3 categories, based on population mean and standard deviation³ or tertiles,⁴⁹ while others have used quartiles⁵⁸ or created 5 categories using *z* scores.^{10,11}
- Most studies only reported selected results.
- Reported results often did not overlap across studies, and many studies failed to report confidence intervals, making it difficult to compare across studies (even in the same sport and similar populations).

All studies were observational and represented athlete workload in nonexperimental conditions. Common methods problems were failure to provide sample-size justifications a priori and to state or adjust for principal confounders in groups of participants. In longitudinal monitoring of athletes, it is important to describe how missing data and participants lost to follow-up were handled. This information was overwhelmingly not reported. Thus, while most injury studies reported a relationship between workload and injury, the overall poor quality of these studies, combined with inconsistencies in the direction of the workload-injury relationship, calls into question the ability of wearable technology to inform injury prevention efforts.

Practical Recommendations for Researchers

Due to the heterogeneity of study designs, populations, methods, and analytic approaches, there are very few data to support recommendations for workload

monitoring to improve injury prevention in athletic populations. Consensus statements on injury surveillance and data collection for each sport and participant population should be updated to include recent recommendations for wearable devices, workload metrics, accumulation calculations, and cut points for binning load quantity.^{27,48,68,69,87} These steps should be applied to individual sports where workload is also monitored to improve performance and prevent injuries.^{7,23,52,66,67}

All studies included in this review quantified workload, often by reporting easily interpretable metrics such as the overall or relative distance traveled in specific conditions (eg, speed zones, acceleration zones) or the number of certain events (eg, sprints, accelerations, jumps). Perhaps less interpretable are accelerometer load metrics, calculated as a vector composition of the accelerometer axes and reported in arbitrary units. In addition to being less relatable than metrics like distance traveled, there are different equations and descriptions for the sum of accelerometer axes.¹² Previous research in the field of gait analysis has used other accelerometer-based metrics capable of evaluating patterns, magnitude, and variability of movement.^{8,17,18,62} Additionally, a combination of accelerometers, gyroscopes, and magnetometers can enhance the ability to record movement quality. Wearable technology that detects key movement events can also be used to evaluate how athletes are performing these maneuvers in a training or competition setting, and to track changes in these patterns over time.^{2,6,8,61,73,81,82} Monitoring movement quality and workload quantity may inform intervention strategies to prevent sport-related injuries.

While copious workload data can be recorded with wearable technology, often only highly processed data and selected analyses were reported. Future studies should prioritize reporting all findings to facilitate comparison to other investigations through meta-analyses. Additionally, due to inconsistencies in how workload data are binned and accumulated, pub-

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lishing raw data sets as supplementary files should be standard practice.

In addition to improvements in the methodological rigor of workload research in team sports, better representation from sports other than soccer, rugby, and Australian football and from populations that include youth, older adults, female athletes, and nonelite athletes is needed. It is possible that rules prohibiting the use of wearable technology during matches limit comprehensive monitoring of athlete workload in some populations. Future technological advancements should increase the versatility of wearable sensors for use in all settings and facilitate more comprehensive monitoring of athlete workload. Currently, the proliferation of wearable technology in elite or professional sport suggests that it is largely confined to teams and leagues with the resources to purchase equipment and the means to collect and analyze the data. Reductions in cost and effort to use this technology are needed to improve accessibility.

Limitations

This scoping review is a comprehensive summary of all existing research on the use of wearable technology to monitor workload in team sport athletes and highlights the studies that have investigated the workload-injury relationship. We did not calculate a quality-assessment total score due to uncertainty about the proper weighting of questions. While this limited the ability to summarize the overall methodological quality of the included studies, we provided individual scores. It is possible that during the title and abstract screening, some records were removed that would be eligible for inclusion if the full text had been evaluated. Because we only searched studies published in English, it is possible that we missed some relevant data.

CONCLUSION

DISTANCE-BASED METRICS DERIVED from GPS units were common for monitoring workload and were fre-

quently used to assess injury risk. There was a narrow population focus (eg, elite male soccer players in Europe and elite male rugby and Australian football players in Oceania). The large number of possible workload metric and accumulation combinations limits the ability to assess the effect of workload on injury risk. ●

KEY POINTS

FINDINGS: Wearable technology is emerging for monitoring athlete workload, with a trend toward the use of a combination of sensors. Workload monitoring with wearables is common in elite or professional male teams.

IMPLICATIONS: The proliferation of wearable technology in elite or professional sport suggests that its use is largely confined to teams and leagues with the resources to purchase equipment and the means to collect and analyze the data.

CAUTION: Hundreds of workload metrics are being recorded with wearable technology, and the lack of consistency in the reported metrics means that workload data collected from wearables cannot inform recommendations for injury prevention (eg, workload modification strategies).

STUDY DETAILS

AUTHOR CONTRIBUTIONS: Drs Benson and Räsänen made substantial contributions to the conception and design of the work; the acquisition, analysis, and interpretation of data for the work; and drafting the work and revising it critically for important intellectual content. Valeriya G. Volkova made substantial contributions to the acquisition, analysis, and interpretation of data for the work and to revising it critically for important intellectual content. Drs Pasanen and Emery made substantial contributions to the conception and design of the work and to revising it critically for important intellectual content. All authors gave final approval of the version to be published and agreed to be accountable for all aspects of the work to ensure that questions related to

the accuracy or integrity of any part of the work are appropriately investigated and resolved.

DATA SHARING: All data relevant to the study are included in the article or are available as supplemental files.

PATIENT AND PUBLIC INVOLVEMENT: Patients/athletes/public partners were not involved in this research.

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REFERENCES

- Abbott W, Brownlee TE, Harper LD, Naughton RJ, Richardson A, Clifford T. A season long investigation into the effects of injury, match selection and training load on mental wellbeing in professional under 23 soccer players: a team case study. *Eur J Sport Sci*. 2019;19:1250-1256. <https://doi.org/10.1080/17461391.2019.1600586>
- Ahamed NU, Kobsar D, Benson LC, Clermont CA, Osis ST, Ferber R. Subject-specific and group-based running pattern classification using a single wearable sensor. *J Biomech*. 2019;84:227-233. <https://doi.org/10.1016/j.jbiomech.2019.01.001>
- Bacon CS, Mauer AR. Prediction of overuse injuries in professional U18-U21 footballers using metrics of training distance and intensity. *J Strength Cond Res*. 2017;31:3067-3076. <https://doi.org/10.1519/JSC.00000000000001744>
- Banister EW, Calvert TW, Savage MV, Bach T. A systems model of training for athletic performance. *Aust J Sports Med*. 1975;7:57-61.
- Banister EW, Carter JB, Zarkadas PC. Training theory and taper: validation in triathlon athletes. *Eur J Appl Physiol Occup Physiol*. 1999;79:182-191. <https://doi.org/10.1007/s004210050493>
- Benson LC, Ahmed NU, Kobsar D, Ferber R. New considerations for collecting biomechanical data using wearable sensors: number of level runs to define a stable running pattern with a single IMU. *J Biomech*. 2019;85:187-192. <https://doi.org/10.1016/j.jbiomech.2019.01.004>
- Benson LC, Clermont CA, Bošnjak E, Ferber R. The use of wearable devices for walking and running gait analysis outside of the lab: a systematic review. *Gait Posture*. 2018;63:124-138. <https://doi.org/10.1016/j.gaitpost.2018.04.047>
- Benson LC, Clermont CA, Osis ST, Kobsar D, Ferber R. Classifying running speed conditions using a single wearable sensor: optimal segmentation and feature extraction methods. *J Biomech*. 2018;71:94-99. <https://doi.org/10.1016/j.jbiomech.2018.01.034>
- Blair SN, Kohl HW, 3rd, Barlow CE, Paffenbarger RS, Jr., Gibbons LW, Macera CA. Changes in

- physical fitness and all-cause mortality: a prospective study of healthy and unhealthy men. *JAMA*. 1995;273:1093-1098. <https://doi.org/10.1001/jama.1995.03520380029031>
10. 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>
11. 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>
12. Bredt SGT, Chagas MH, Peixoto GH, Menzel HJ, de Andrade AGP. Understanding player load: meanings and limitations. *J Hum Kinet*. 2020;71:5-9. <https://doi.org/10.2478/hukin-2019-0072>
13. Brown W, Greig M. Tri-axial accelerometry as an injury predictor tool in elite soccer. *Int J Athl Ther Train*. 2017;22:44-48. <https://doi.org/10.1123/ijatt.2017-0004>
14. Buchheit M. Applying the acute:chronic workload ratio in elite football: worth the effort? *Br J Sports Med*. 2017;51:1325-1327. <https://doi.org/10.1136/bjsports-2016-097017>
15. Campos S, Doxey J, Hammond D. Nutrition labels on pre-packaged foods: a systematic review. *Public Health Nutr*. 2011;14:1496-1506. <https://doi.org/10.1017/S1368980010003290>
16. 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>
17. Clermont C, Kobsar D, Benson L, Osis S, Ferber R. The use of wearable technology to monitor subject-specific running gait patterns [abstract]. 11th Annual SPoT INnovation (SPIN) Summit; November 2016; Calgary, Canada.
18. Clermont CA, Barden JM. Accelerometer-based determination of gait variability in older adults with knee osteoarthritis. *Gait Posture*. 2016;50:126-130. <https://doi.org/10.1016/j.gaitpost.2016.08.024>
19. Colby MJ, Dawson B, Heasman J, Rogalski B, Gabbett TJ. Accelerometer and GPS-derived running loads and injury risk in elite Australian footballers. *J Strength Cond Res*. 2014;28:2244-2252. <https://doi.org/10.1519/JSC.0000000000000362>
20. Colby MJ, Dawson B, Heasman J, et al. Preseason workload volume and high-risk periods for noncontact injury across multiple Australian Football League seasons. *J Strength Cond Res*. 2017;31:1821-1829. <https://doi.org/10.1519/JSC.0000000000001669>
21. Colby MJ, Dawson B, Peeling P, et al. Improvement of prediction of noncontact injury in elite Australian footballers with repeated exposure to established high-risk workload scenarios. *Int J Sports Physiol Perform*. 2018;13:1130-1135. <https://doi.org/10.1123/ijsp.2017-0696>
22. Colby MJ, Dawson B, Peeling P, et al. Multivariate modelling of subjective and objective monitoring data improve the detection of non-contact injury risk in elite Australian footballers. *J Sci Med Sport*. 2017;20:1068-1074. <https://doi.org/10.1016/j.jsams.2017.05.010>
23. Collette R, Kellmann M, Ferrauti A, Meyer T, Pfeiffer M. Relation between training load and recovery-stress state in high-performance swimming. *Front Physiol*. 2018;9:845. <https://doi.org/10.3389/fphys.2018.00845>
24. Conn JM, Annett JL, Gilchrist J. Sports and recreation related injury episodes in the US population, 1997-99. *Inj Prev*. 2003;9:117-123. <https://doi.org/10.1136/ip.9.2.117>
25. Coppalle S, Rave G, Ben Abderrahman A, et al. Relationship of pre-season training load with in-season biochemical markers, injuries and performance in professional soccer players. *Front Physiol*. 2019;10:409. <https://doi.org/10.3389/fphys.2019.00409>
26. Cousins BEW, Morris JG, Sunderland C, Bennett AM, Shahtahmassebi G, Cooper SB. Match and training load exposure and time-loss incidence in elite rugby union players. *Front Physiol*. 2019;10:1413. <https://doi.org/10.3389/fphys.2019.01413>
27. Dalen-Lorentsen T, Andersen TE, Bjørneboe J, et al. A cherry tree ripe for picking: the relationship between the acute:chronic workload ratio and health problems [preprint]. *SportRxiv*. 2020. Available at: <https://doi.org/10.31236/bsf.io/nhqbz>
28. Downs SH, Black N. The feasibility of creating a checklist for the assessment of the methodological quality both of randomised and non-randomised studies of health care interventions. *J Epidemiol Community Health*. 1998;52:377-384. <https://doi.org/10.1136/jech.52.6.377>
29. Drew MK, Finch CF. The relationship between training load and injury, illness and soreness: a systematic and literature review. *Sports Med*. 2016;46:861-883. <https://doi.org/10.1007/s40279-015-0459-8>
30. Drust B, Atkinson G, Reilly T. Future perspectives in the evaluation of the physiological demands of soccer. *Sports Med*. 2007;37:783-805. <https://doi.org/10.2165/00007256-200737090-00003>
31. Duhig S, Shield AJ, Opar D, Gabbett TJ, Ferguson C, Williams M. Effect of high-speed running on hamstring strain injury risk. *Br J Sports Med*. 2016;50:1536-1540. <https://doi.org/10.1136/bjsports-2015-095679>
32. 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>
33. 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>
34. 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>
35. Emery CA. Injury prevention and future research. *Med Sport Sci*. 2005;48:179-200. <https://doi.org/10.1159/000084289>
36. Emery CA. Risk factors for injury in child and adolescent sport: a systematic review of the literature. *Clin J Sport Med*. 2003;13:256-268. <https://doi.org/10.1097/00042752-200307000-00011>
37. Emery CA, Meeuwisse WH, McAllister JR. Survey of sport participation and sport injury in Calgary and area high schools. *Clin J Sport Med*. 2006;16:20-26. <https://doi.org/10.1097/01.jsm.0000184638.72075.b7>
38. Emery CA, Tyreman H. Sport participation, sport injury, risk factors and sport safety practices in Calgary and area junior high schools. *Paediatr Child Health*. 2009;14:439-444. <https://doi.org/10.1093/pch/14.7.439>
39. Esmaeili A, Hopkins WG, Stewart AM, Elias GP, Lazarus BH, Aughey RJ. The individual and combined effects of multiple factors on the risk of soft tissue non-contact injuries in elite team sport athletes. *Front Physiol*. 2018;9:1280. <https://doi.org/10.3389/fphys.2018.01280>
40. Finch CF, Kemp JL, Clapperton AJ. The incidence and burden of hospital-treated sports-related injury in people aged 15+ years in Victoria, Australia, 2004-2010: a future epidemic of osteoarthritis? *Osteoarthritis Cartilage*. 2015;23:1138-1143. <https://doi.org/10.1016/j.joca.2015.02.165>
41. Foster C, Florhaug JA, Franklin J, et al. A new approach to monitoring exercise training. *J Strength Cond Res*. 2001;15:109-115.
42. Gabbett TJ, Ullah S. Relationship between running loads and soft-tissue injury in elite team sport athletes. *J Strength Cond Res*. 2012;26:953-960. <https://doi.org/10.1519/JSC.0b013e3182302023>
43. Grimmer KA, Jones D, Williams J. Prevalence of adolescent injury from recreational exercise: an Australian perspective. *J Adolesc Health*. 2000;27:266-272. [https://doi.org/10.1016/s1054-139x\(00\)00120-8](https://doi.org/10.1016/s1054-139x(00)00120-8)
44. Halson SL. Monitoring training load to understand fatigue in athletes. *Sports Med*. 2014;44 suppl 2:S139-S147. <https://doi.org/10.1007/s40279-014-0253-z>
45. 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>
46. 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>

47. 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>
48. International Olympic Committee Injury Illness Epidemiology Consensus Group, Bahr R, Clarsen B, et al. International Olympic Committee consensus statement: methods for recording and reporting of epidemiological data on injury and illness in sports 2020 (including the STROBE Extension for Sports Injury and Illness Surveillance (STROBE-SIIS)). *Orthop J Sports Med.* 2020;8:2325967120902908. <https://doi.org/10.1177/2325967120902908>
49. 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>
50. Jebb SA, Moore MS. Contribution of a sedentary lifestyle and inactivity to the etiology of overweight and obesity: current evidence and research issues. *Med Sci Sports Exerc.* 1999;31:S534-S541. <https://doi.org/10.1097/00005768-199911001-00008>
51. Jones CM, Griffiths PC, Mellalieu SD. Training load and fatigue marker associations with injury and illness: a systematic review of longitudinal studies. *Sports Med.* 2017;47:943-974. <https://doi.org/10.1007/s40279-016-0619-5>
52. 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>
53. 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>
54. Kim T, Cha JH, Park JC. Association between in-game performance parameters recorded via global positioning system and sports injuries to the lower extremities in elite female field hockey players. *Cluster Comput.* 2018;21:1069-1078. <https://doi.org/10.1007/s10586-016-0690-6>
55. King MA, Pickett W, King AJC. Injury in Canadian youth: a secondary analysis of the 1993-94 Health Behaviour in School-Aged Children Survey. *Can J Public Health.* 1998;89:397-401. <https://doi.org/10.1007/BF03404082>
56. Li RT, Salata MJ, Rambhia S, Sheehan J, Voos JE. Does overexertion correlate with increased injury? The relationship between player workload and soft tissue injury in professional American football players using wearable technology. *Sports Health.* 2020;12:66-73. <https://doi.org/10.1177/1941738119868477>
57. Malone JJ, Barrett S, Barnes C, Twist C, Drust B. To infinity and beyond: the use of GPS devices

within the football codes. *Sci Med Football.* 2020;4:82-84. <https://doi.org/10.1080/24733938.2019.1679871>

58. Malone S, Owen A, Mendes B, Hughes B, Collins K, Gabbett TJ. High-speed running and sprinting as an injury risk factor in soccer: can well-developed physical qualities reduce the risk? *J Sci Med Sport.* 2018;21:257-262. <https://doi.org/10.1016/j.jsams.2017.05.016>
59. Malone S, Roe M, Doran DA, Gabbett TJ, Collins K. High chronic training loads and exposure to bouts of maximal velocity running reduce injury risk in elite Gaelic football. *J Sci Med Sport.* 2017;20:250-254. <https://doi.org/10.1016/j.jsams.2016.08.005>
60. Mehta S. Relationship between workload and throwing injury in varsity baseball players. *Phys Ther Sport.* 2019;40:66-70. <https://doi.org/10.1016/j.ptsp.2019.08.001>
61. Moe-Nilssen R. A new method for evaluating motor control in gait under real-life environmental conditions. Part 2: gait analysis. *Clin Biomech (Bristol, Avon).* 1998;13:328-335. [https://doi.org/10.1016/s0268-0033\(98\)00090-4](https://doi.org/10.1016/s0268-0033(98)00090-4)
62. Moe-Nilssen R, Helbostad JL. Estimation of gait cycle characteristics by trunk accelerometry. *J Biomech.* 2004;37:121-126. [https://doi.org/10.1016/s0021-9290\(03\)00233-1](https://doi.org/10.1016/s0021-9290(03)00233-1)
63. Murray NB, Gabbett TJ, Townshend AD. The use of relative speed zones in Australian football: are we really measuring what we think we are? *Int J Sports Physiol Perform.* 2018;13:442-451. <https://doi.org/10.1123/ijspp.2017-0148>
64. 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.* 2017;51:749-754. <https://doi.org/10.1136/bjsports-2016-097152>
65. Murray NB, Gabbett TJ, Townshend AD, Hulin BT, McLellan CP. Individual and combined effects of acute and chronic running loads on injury risk in elite Australian footballers. *Scand J Med Sci Sports.* 2017;27:990-998. <https://doi.org/10.1111/sms.12719>
66. Myers NL, Aguilar KV, Mexicano G, Farnsworth JL, 2nd, Knudson D, Kibler WB. The acute: chronic workload ratio is associated with injury in junior tennis players. *Med Sci Sports Exerc.* 2020;52:1196-1200. <https://doi.org/10.1249/MSS.00000000000002215>
67. Myers NL, Knudson D. Ergonomics and biomechanics: racquet sensors for monitoring volume of training and competition in tennis. In: Pallis JM, McNitt-Gray JL, Hung GK, eds. *Biomechanical Principles and Applications in Sports.* Cham, Switzerland: Springer; 2019:3-16.
68. 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>
69. 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>

70. Owen AL, Forsyth JJ, Wong DP, Dellal A, Connelly SP, Chamari K. Heart rate-based training intensity and its impact on injury incidence among elite-level professional soccer players. *J Strength Cond Res.* 2015;29:1705-1712. <https://doi.org/10.1519/JSC.0000000000000810>
71. Pettersen SA, Johansen HD, Baptista IAM, Halvorsen P, Johansen D. Quantified soccer using positional data: a case study. *Front Physiol.* 2018;9:866. <https://doi.org/10.3389/fphys.2018.00866>
72. Pino-Ortega J, Rojas-Valverde D, Gómez-Carmona CD, et al. Impact of contextual factors on external load during a congested-fixture tournament in elite U'18 basketball players. *Front Psychol.* 2019;10:1100. <https://doi.org/10.3389/fpsyg.2019.01100>
73. Reenalda J, Maartens E, Homan L, Buurke JHJ. Continuous three dimensional analysis of running mechanics during a marathon by means of inertial magnetic measurement units to objectify changes in running mechanics. *J Biomech.* 2016;49:3362-3367. <https://doi.org/10.1016/j.jbiomech.2016.08.032>
74. Richmond SA, Fukuchi RK, Ezzat A, Schneider K, Schneider G, Emery CA. Are joint injury, sport activity, physical activity, obesity, or occupational activities predictors for osteoarthritis? A systematic review. *J Orthop Sports Phys Ther.* 2013;43:515-524. <https://doi.org/10.2519/jospt.2013.4796>
75. Ritchie D, Hopkins WG, Buchheit M, Cordy J, Bartlett JD. Quantification of training and competition load across a season in an elite Australian football club. *Int J Sports Physiol Perform.* 2016;11:474-479. <https://doi.org/10.1123/ijspp.2015-0294>
76. Ritchie D, Hopkins WG, Buchheit M, Cordy J, Bartlett JD. Quantification of training load during return to play after upper- and lower-body injury in Australian Rules football. *Int J Sports Physiol Perform.* 2017;12:634-641. <https://doi.org/10.1123/ijspp.2016-0300>
77. Ruddy JD, Pollard CW, Timmins RG, Williams MD, Shield AJ, Opar DA. Running exposure is associated with the risk of hamstring strain injury in elite Australian footballers. *Br J Sports Med.* 2018;52:919-928. <https://doi.org/10.1136/bjsports-2016-096777>
78. Ryan S, Coutts AJ, Hocking J, Kempton T. Factors affecting match running performance in professional Australian football. *Int J Sports Physiol Perform.* 2017;12:1199-1204. <https://doi.org/10.1123/ijspp.2016-0586>
79. Ryan S, Kempton T, Impellizzeri FM, Coutts AJ. Training monitoring in professional Australian football: theoretical basis and recommendations for coaches and scientists. *Sci Med Football.* 2020;4:52-58. <https://doi.org/10.1080/24733938.2019.1641212>

80. Sampson JA, Murray A, Williams S, Sullivan A, Fullagar HHK. Subjective wellness, acute:chronic workloads, and injury risk in college football. *J Strength Cond Res*. 2019;33:3367-3373. <https://doi.org/10.1519/JSC.0000000000003000>
81. Schütte KH, Aeles J, De Beéck TO, van der Zwaard BC, Venter R, Vanwanseele B. Surface effects on dynamic stability and loading during outdoor running using wireless trunk accelerometry. *Gait Posture*. 2016;48:220-225. <https://doi.org/10.1016/j.gaitpost.2016.05.017>
82. Schütte KH, Seerden S, Venter R, Vanwanseele B. Fatigue-related asymmetry and instability during a 3200-m time-trial performance in healthy runners. *34th International Conference on Biomechanics in Sports*. Ae M, Enomoto Y, Fujii N, Takagi H, eds. Tsukuba, Japan: 2016:933-936.
83. Stares J, Dawson B, Peeling P, et al. Identifying high risk loading conditions for in-season injury in elite Australian football players. *J Sci Med Sport*. 2018;21:46-51. <https://doi.org/10.1016/j.jsams.2017.05.012>

84. Taylor KL, Chapman DW, Cronin JB, Newton MJ, Gill N. Fatigue monitoring in high performance sport: a survey of current trends. *J Aust Strength Cond*. 2012;20:12-23.
85. Toohey LA, Drew MK, Finch CF, Cook JL, Fortington LV. A 2-year prospective study of injury epidemiology in elite Australian rugby sevens: exploration of incidence rates, severity, injury type, and subsequent injury in men and women. *Am J Sports Med*. 2019;47:1302-1311. <https://doi.org/10.1177/0363546518825380>
86. Vanrenterghem J, Nedergaard NJ, Robinson MA, Drust B. Training load monitoring in team sports: a novel framework separating physiological and biomechanical load-adaptation pathways. *Sports Med*. 2017;47:2135-2142. <https://doi.org/10.1007/s40279-017-0714-2>
87. Wang C, Vargas JT, Stokes T, Steele R, Shrier I. Analyzing activity and injury: lessons learned from the acute:chronic workload ratio. *Sports Med*. 2020;50:1243-1254. <https://doi.org/10.1007/s40279-020-01280-1>

88. Wilkerson GB, Gupta A, Allen JR, Keith CM, Colston MA. Utilization of practice session average inertial load to quantify college football injury risk. *J Strength Cond Res*. 2016;30:2369-2374. <https://doi.org/10.1519/JSC.0000000000001370>
89. 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>
90. Windt J, Gabbett TJ, Ferris D, Khan KM. Training load-injury paradox: is greater preseason participation associated with lower in-season injury risk in elite rugby league players? *Br J Sports Med*. 2017;51:645-650. <https://doi.org/10.1136/bjsports-2016-095973>



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[LITERATURE REVIEW]

APPENDIX

SEARCH STRATEGY FOR THE MEDLINE DATABASE

(accelerometry/ OR wearable electronic devices/ OR wearable* OR inertial sensor* OR inertial measurement unit* OR imu OR imus OR gyroscope* OR magnetometer* OR acceleromet* OR gps OR global positioning system OR glonass OR heart rate monitor* OR heartrate monitor*)

AND

(arm injuries/ OR athletic injuries/ OR back injuries/ OR joint dislocations/ OR fractures, bone/ OR fractures, cartilage/ OR hand injuries/ OR hip injuries/ OR leg injuries/ OR microtrauma, physical/ OR neck injuries/ OR rupture/ OR shoulder injuries/ OR soft tissue injuries/ OR spinal cord injuries/ OR "sprains and strains"/ OR tendon injuries/ OR thoracic injuries/ OR injury risk OR risk of injury OR training load OR workload OR work load)

AND

(sports/ OR sports equipment/ OR exp athletes/ OR sport* OR baseball* OR basketball* OR broomball* OR cricket* OR dodgeball* OR floorball* OR football* OR futsal* OR handball* OR hockey* OR lacrosse* OR netball* OR polo OR ringette OR rugby OR soccer OR softball* OR volleyball*)

"/" indicates a Medical Subject Headings term; all other terms were used in a title, abstract, and key word search. "" indicates that the search term can have any ending.*

TIM J. GABBETT, PhD^{1,2}

How Much? How Fast? How Soon? Three Simple Concepts for Progressing Training Loads to Minimize Injury Risk and Enhance Performance

Overload is a key principle of training—load must exceed capacity to improve performance. Small, systematic increases in load that are slightly greater than load capacity will improve tolerance of further load.¹⁶ However, if the applied load greatly exceeds load capacity, then tissue tolerance is exceeded and injury may occur.² This clinical commentary addresses key considerations for rehabilitation practitioners when helping an athlete prepare for the demands of competition.

Clinical Questions: How Much? How Fast? How Soon?

Sports medicine practitioners play a role in maximizing the positive and minimiz-

ing the negative adaptations to training—too much training may result in excessive fatigue; too little training may mean athletes are underprepared for competition. Clearly, a balance exists between providing an adequate training stimulus to elicit performance benefits and minimizing the risk of injury. How can practitioners de-

termine how much training is too much? Following injury, how soon can training loads be progressed? How quickly can athletes return to competition?

The Floor, the Ceiling, and Time

When developing rehabilitation or performance programs, 3 key concepts are critical: the “floor,” the “ceiling,” and time. The floor represents the athlete’s current capacity, whereas the ceiling represents the capacity needed to perform the specific activities of the sport. It is possible to safely progress an athlete from the floor to the ceiling, as long as the athlete is afforded adequate time (**FIGURE** panel A).

The Challenges of Getting the Preseason Right

A challenge in most sporting environments is the time required to progress from the floor to the ceiling. If athletes’ training loads are progressed too rapidly, they will be at increased risk of injury.⁶ This scenario occurs all too frequently. Consider athletes who enter a very short training camp (or preseason period), or who have sustained an injury. If the gap between the current capacity and the required capacity is large, then the only way to progress from the floor to the ceiling is to rapidly increase training load to ensure that the athletes are prepared for the first competition game or return to play. Not-

• **BACKGROUND:** When progressing an athlete from rehabilitation to peak performance, load must exceed load capacity. When gradual, systematic increases in load are applied, load capacity will improve. However, if the applied load greatly exceeds load capacity, then tissue tolerance is exceeded and injury may occur.

• **CLINICAL QUESTION:** It is well established that a balance exists between providing an adequate training stimulus to elicit performance benefits and minimizing the risk of injury. How can practitioners determine how much training is too much? Following injury, how soon can training loads be progressed? How quickly can athletes return to competition?

• **KEY RESULTS:** When developing rehabilitation or performance programs, 3 concepts are critical: the “floor,” the “ceiling,” and time. The floor represents the athlete’s current capacity, whereas the ceiling represents the capacity needed to perform the

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• **CLINICAL APPLICATION:** Rehabilitation practitioners should consider and plan the appropriate amount of time required to progress from the floor (eg, rehabilitation) to the ceiling (eg, return to performance). The resilience and robustness that come from training take time, and different physical capacities will adapt at different rates. Progressive, gradual, and systematic increases in training load allow athletes to safely progress to the ceiling, reducing injury risk, improving availability, and enhancing performance. *J Orthop Sports Phys Ther* 2020;50(10):570-573. Epub 15 Nov 2019. doi:10.2519/jospt.2020.9256

• **KEY WORDS:** injury prevention, load, rehabilitation, strength and conditioning, training, workload

¹Gabbett Performance Solutions, Brisbane, Australia. ²Centre for Health Research, University of Southern Queensland, Ipswich, Australia. No funding or grants from any public, commercial, or not-for-profit organizations were used in the preparation of this manuscript. Professor Gabbett works as a consultant to several high-performance organizations, including sporting teams, industry, military, and higher education institutions. Address correspondence to Professor Tim J. Gabbett, Gabbett Performance Solutions, Brisbane, QLD 4011 Australia. E-mail: tim@gabbettperformance.com.au • Copyright ©2020 *Journal of Orthopaedic & Sports Physical Therapy*

withstanding the fact that athletes with poorer physical capacities^{9,11} and musculoskeletal dysfunction¹⁴ are at increased risk of injury, training in this manner is associated with a high risk of injury⁶ and poor performance¹⁰ (FIGURE panel B). Coaches can take more time to safely progress athletes to higher training loads and prepare them for the ceiling, but coaches do not have infinite time. Equally, if an inadequate training stimulus is applied, then the athlete is at risk of being underprepared, underperforming, and reinjury.

How Does One Help Athletes Safely Progress From the Floor to the Ceiling?

The demands of elite performance are constantly evolving; in general, the complexity and physicality are increasing every year.¹ Reducing the ceiling is not a realistic option to help athletes avoid injury and perform well. One option is to take more time to bridge the gap between the floor and the ceiling, although most coaches will be less than impressed if their best athletes are not fit enough to compete in the first game of the season or spend extended periods of time in rehabilitation

(FIGURE panel C). What if we could buy more time prior to the official start of the preseason? If athletes performed a minimum volume of training prior to returning from an extended break, this would have the effect of artificially increasing the length of the preseason period, minimizing the detraining effect induced by the offseason, thereby ensuring that progression to the ceiling was gradual and systematic (FIGURE panel D).

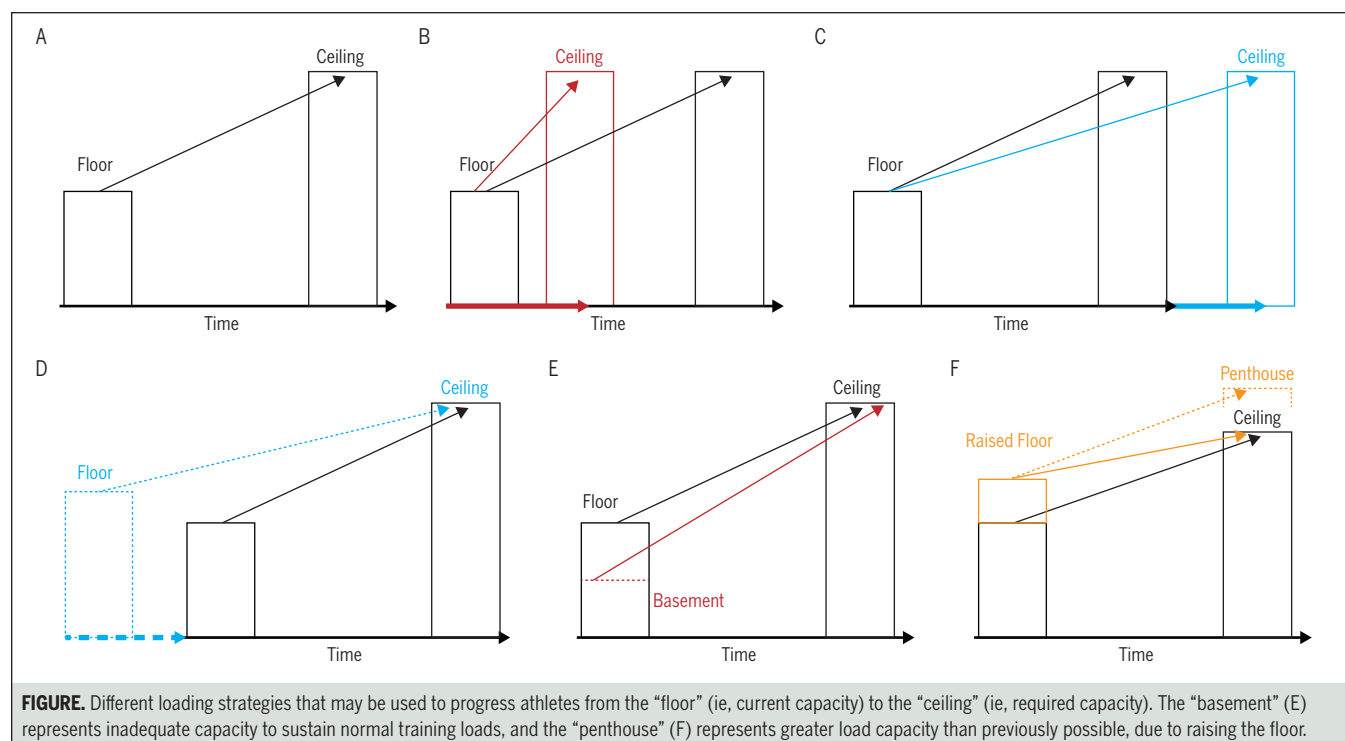
Progressing athletes, of any performance level, from the floor to the ceiling is further complicated when the athlete returns to preseason training in a severely deconditioned state or following offseason surgery. In these examples, the athlete's current capacity is inadequate to sustain normal training loads; rather than having an adequate floor, the athlete's capacity is more like "the basement" (FIGURE panel E). This situation can also occur when athletes are injured; local tissue capacity can immediately decrease, resulting in a reduction in the floor. In this respect, given the same amount of time, progressing the athlete from his or her current capacity to the ceiling would

require rapid changes in training load, in turn increasing injury risk.

Another solution to ensure that athletes are safely progressed from the floor to the ceiling is to raise the floor (FIGURE panel F)—to ensure that when athletes are taking an extended break or enter rehabilitation, they do not allow their physical capacity to fall to the basement. The benefit of raising the floor is that it also provides athletes the opportunity to develop greater load capacity than previously may have been possible (perhaps reaching "the penthouse") (FIGURE panel F). Preparation for sporting activities involves year-round management, monitoring, and manipulation of training load, with an understanding that the ceiling is somewhat of a "moving target"²—different capacities will require development depending on the specific phase of the season and on the factors limiting performance for individual athletes.

What Can Rehabilitation and Performance Staff Do to Help Athletes Achieve Their Performance Goals?

Athletes participate in sport for many reasons, which may differ between elite and



nonelite competitors. Whether competing at an elite or nonelite level, athletes strive for continual improvement and to achieve their personal best performances. To achieve high-level performance, the load capacity of athletes must be adequate to meet the demands required of competition. Athletes cannot perform if their current capacity is well below the capacity required of their sport. Equally, athletes cannot perform if they are injured.

Taking the concepts of the floor, ceiling, and time, there are at least 5 simple ways rehabilitation and performance staff can minimize the risk of injury and give athletes the best chance of achieving their performance goals (TABLE).

Summary: From Risk to Resilience

Training loads can have positive and negative effects. The risk of injury increases with rapid changes in training load. However, not all training load is bad—when prescribed appropriately, it can create resilient and robust athletes, capable of withstanding the high loads of competition and thriving in the most de-

manding passages of play. Systematically increasing training loads, and identifying factors related to load tolerance, not only lowers the risk of injury but also allows athletes to progress to higher training loads typical of those required for elite performance.¹² Importantly, once athletes have reached these high training loads, they are at reduced risk of injury and have greater likelihood of achieving their performance goals—loading allows athletes to withstand further load. ●

KEY POINTS

FINDINGS: This clinical commentary addresses key considerations for rehabilitation practitioners when helping an athlete prepare for the demands of competition. Rehabilitation and reconditioning programs should prepare athletes for the most demanding passages of competition. This will ensure that (1) athletes are able to perform the high-intensity tasks that often determine the outcome of the game, and (2) athletes are at lower injury risk when performing these activities.

IMPLICATIONS: These findings highlight the importance of maintaining an adequate training load (floor) during the offseason and while injured. Preparation for sporting activities involves year-round management, monitoring, and manipulation of training load, with an understanding that the ceiling is somewhat of a “moving target”—different capacities will require development depending on the specific phase of the season and on the factors limiting performance for individual athletes.

CAUTION: Very young and older athletes, and those with a long injury history, poor training history, musculoskeletal deficiencies, and lower strength and aerobic fitness, may have poorer tolerance of rapid increases in training load, while other biomechanical and psychosocial factors can also impact load capacity. Along with gradual loading progressions, a comprehensive assessment of the sport-specific (eg, strength, aerobic fitness) and tissue-specific (eg, musculoskeletal) capacities is required to ensure training loads are progressed on an individual basis.

TABLE

FIVE WAYS TO ENSURE ATHLETES ARE WELL PREPARED FOR THE DEMANDS OF COMPETITION

Description

- 1 Maintain an adequate training load during the offseason³ and while injured. Loading during these periods raises the floor (or, alternatively, ensures athletes avoid the basement) and improves athletes' ability to tolerate load during the preseason and on return to competition
- 2 Identify the ceiling and ensure that training load is proportionate to competition demands.³ Various methodologies (including the use of wearable and video technologies) have been used to assess the sport-specific demands required at the ceiling.^{4,7,8,15} These may include (but are not necessarily limited to) peak running intensities,⁴ longest ball-in-play periods,⁷ and repeated-sprint¹⁵ and repeated-effort activity.⁸ If expensive technology is not available, practitioners are encouraged to access sport-specific literature to inform their training programs. The individual load capacities and the absolute competition demands will differ between elite and nonelite, adult and adolescent, and male and female athletes; training demands should also reflect these differences
- 3 Assess individual differences in training tolerance among athletes. Very young and older athletes¹⁴ and those with a long injury history,⁵ poor training history,¹⁰ musculoskeletal deficiencies,¹² and lower strength¹¹ and aerobic fitness¹³ may have poorer tolerance of rapid increases in training load. Furthermore, other physical (eg, biomechanical, movement patterns) and psychosocial (eg, emotional, lifestyle) factors can impact load capacity.⁵ It might be tempting to rapidly increase training loads in less fit athletes and those with musculoskeletal deficiencies. However, these are the athletes who are least likely to tolerate this type of training progression, and in turn most likely to sustain injury in response to this loading pattern. Along with gradual loading progressions, a comprehensive assessment of the sport-specific (eg, strength, aerobic fitness) and tissue-specific (eg, musculoskeletal) capacities is required to ensure training loads are progressed on an individual basis. It is here that sports medicine professionals (eg, physical therapists and strength-and-conditioning coaches) play a critical role
- 4 Identify and prepare for the most demanding passages of play. Training for the average demands of competition may mean that athletes are underprepared for the “worst-case scenario.”^{8,15} This may trigger at least 2 consequences: (1) athletes are unable to perform the high-intensity tasks that often determine the outcome of the game,¹⁵ and (2) athletes are at greater injury risk when attempting to perform these activities
- 5 Training programs require an understanding of the (1) physical demands of the sport, (2) physical capacities required to perform these activities, and (3) factors that limit performance on an individual basis. Coaches should consider and plan the appropriate amount of time required to progress from the floor to the ceiling. The resilience and robustness that come from training take time, and different physical capacities will adapt at different rates. Progressive, gradual, and systematic increases in training load allow athletes to safely progress to the ceiling, reducing injury risk, improving availability, and enhancing performance

STUDY DETAILS

AUTHOR CONTRIBUTIONS: Professor Gabbett is responsible for all concepts, practical applications, and conclusions presented in this paper.

DATA SHARING: There are no data in this manuscript.

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

REFERENCES

1. Barnes C, Archer DT, Hogg B, Bush M, Bradley PS. The evolution of physical and technical performance parameters in the English Premier League. *Int J Sports Med*. 2014;35:1095-1100. <https://doi.org/10.1055/s-0034-1375695>
2. Cook JL, Docking SI. "Rehabilitation will increase the 'capacity' of your ...insert musculoskeletal tissue here...." Defining 'tissue capacity': a core concept for clinicians. *Br J Sports Med*. 2015;49:1484-1485. <https://doi.org/10.1136/bjsports-2015-094849>
3. Drew MK, Cook J, Finch CF. Sports-related workload and injury risk: simply knowing the risks will not prevent injuries: narrative review. *Br J Sports Med*. 2016;50:1306-1308. <https://doi.org/10.1136/bjsports-2015-095871>
4. Duthie GM, Thornton HR, Delaney JA, Connolly DR, Serpiello FR. Running intensities in elite youth soccer by age and position. *J Strength Cond Res*. 2018;32:2918-2924. <https://doi.org/10.1519/JSC.0000000000002728>

5. Gabbett TJ. Debunking the myths about training load, injury and performance: empirical evidence, hot topics and recommendations for practitioners. *Br J Sports Med*. 2020;54:58-66. <https://doi.org/10.1136/bjsports-2018-099784>
6. 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>
7. Gabbett TJ, Hulin BT. Activity and recovery cycles and skill involvements of successful and unsuccessful elite rugby league teams: a longitudinal analysis of evolutionary changes in National Rugby League match-play. *J Sports Sci*. 2018;36:180-190. <https://doi.org/10.1080/02640414.2017.1288918>
8. Gabbett TJ, Jenkins DG, Abernethy B. Physical demands of professional rugby league training and competition using microtechnology. *J Sci Med Sport*. 2012;15:80-86. <https://doi.org/10.1016/j.jsams.2011.07.004>
9. Gabbett TJ, Nielsen RO, Bertelsen ML, et al. In pursuit of the 'unbreakable' athlete: what is the role of moderating factors and circular causation? *Br J Sports Med*. 2019;53:394-395. <https://doi.org/10.1136/bjsports-2018-099995>
10. Hulin BT, Gabbett TJ, Pickworth NJ, Johnston RD, Jenkins DG. Relationships among player load, high-intensity intermittent running ability, and injury risk in professional rugby league players. *Int J Sports Physiol Perform*. 2020;15:423-429. <https://doi.org/10.1123/ijspp.2019-0139>
11. Malone S, Hughes B, Doran DA, Collins K, Gabbett TJ. Can the workload-injury relationship be moderated by improved strength, speed and repeated-sprint qualities? *J Sci Med Sport*. 2019;22:29-34. <https://doi.org/10.1016/j.jsams.2018.01.010>
12. Malone S, Roe M, Doran DA, Gabbett TJ, Collins K. High chronic training loads and exposure to bouts of maximal velocity running reduce injury risk in elite Gaelic football. *J Sci Med Sport*. 2017;20:250-254. <https://doi.org/10.1016/j.jsams.2016.08.005>
13. Malone S, Roe M, Doran DA, Gabbett TJ, Collins KD. Protection against spikes in workload with aerobic fitness and playing experience: the role of the acute:chronic workload ratio on injury risk in elite Gaelic football. *Int J Sports Physiol Perform*. 2017;12:393-401. <https://doi.org/10.1123/ijspp.2016-0090>
14. Møller M, Nielsen RO, Attermann J, et al. Handball load and shoulder injury rate: a 31-week cohort study of 679 elite youth handball players. *Br J Sports Med*. 2017;51:231-237. <https://doi.org/10.1136/bjsports-2016-096927>
15. Spencer M, Lawrence S, Rechichi C, Bishop D, Dawson B, Goodman C. Time-motion analysis of elite field hockey, with special reference to repeated-sprint activity. *J Sports Sci*. 2004;22:843-850. <https://doi.org/10.1080/02640410410001716715>
16. Verhagen E, Gabbett T. Load, capacity and health: critical pieces of the holistic performance puzzle. *Br J Sports Med*. 2019;53:5-6. <https://doi.org/10.1136/bjsports-2018-099819>



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• **KEY WORDS:** injury prevention, load, rehabilitation, strength and conditioning, training, workload

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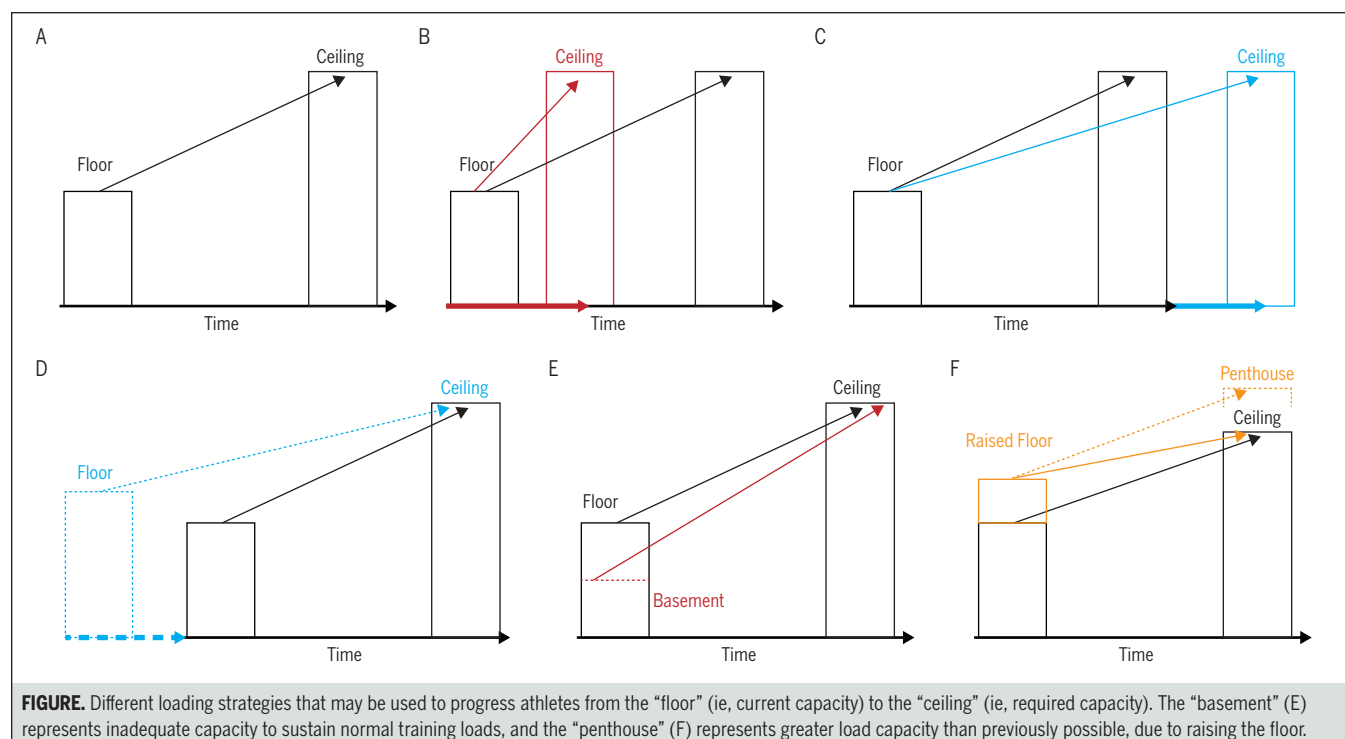
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- 1 Maintain an adequate training load during the offseason³ and while injured. Loading during these periods raises the floor (or, alternatively, ensures athletes avoid the basement) and improves athletes' ability to tolerate load during the preseason and on return to competition
- 2 Identify the ceiling and ensure that training load is proportionate to competition demands.³ Various methodologies (including the use of wearable and video technologies) have been used to assess the sport-specific demands required at the ceiling.^{4,7,8,15} These may include (but are not necessarily limited to) peak running intensities,⁴ longest ball-in-play periods,⁷ and repeated-sprint¹⁵ and repeated-effort activity.⁸ If expensive technology is not available, practitioners are encouraged to access sport-specific literature to inform their training programs. The individual load capacities and the absolute competition demands will differ between elite and nonelite, adult and adolescent, and male and female athletes; training demands should also reflect these differences
- 3 Assess individual differences in training tolerance among athletes. Very young and older athletes¹⁴ and those with a long injury history,⁵ poor training history,¹⁰ musculoskeletal deficiencies,¹² and lower strength¹¹ and aerobic fitness¹³ may have poorer tolerance of rapid increases in training load. Furthermore, other physical (eg, biomechanical, movement patterns) and psychosocial (eg, emotional, lifestyle) factors can impact load capacity.⁵ It might be tempting to rapidly increase training loads in less fit athletes and those with musculoskeletal deficiencies. However, these are the athletes who are least likely to tolerate this type of training progression, and in turn most likely to sustain injury in response to this loading pattern. Along with gradual loading progressions, a comprehensive assessment of the sport-specific (eg, strength, aerobic fitness) and tissue-specific (eg, musculoskeletal) capacities is required to ensure training loads are progressed on an individual basis. It is here that sports medicine professionals (eg, physical therapists and strength-and-conditioning coaches) play a critical role
- 4 Identify and prepare for the most demanding passages of play. Training for the average demands of competition may mean that athletes are underprepared for the “worst-case scenario.”^{8,15} This may trigger at least 2 consequences: (1) athletes are unable to perform the high-intensity tasks that often determine the outcome of the game,¹⁵ and (2) athletes are at greater injury risk when attempting to perform these activities
- 5 Training programs require an understanding of the (1) physical demands of the sport, (2) physical capacities required to perform these activities, and (3) factors that limit performance on an individual basis. Coaches should consider and plan the appropriate amount of time required to progress from the floor to the ceiling. The resilience and robustness that come from training take time, and different physical capacities will adapt at different rates. Progressive, gradual, and systematic increases in training load allow athletes to safely progress to the ceiling, reducing injury risk, improving availability, and enhancing performance

STUDY DETAILS

AUTHOR CONTRIBUTIONS: Professor Gabbett is responsible for all concepts, practical applications, and conclusions presented in this paper.

DATA SHARING: There are no data in this manuscript.

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

REFERENCES

1. Barnes C, Archer DT, Hogg B, Bush M, Bradley PS. The evolution of physical and technical performance parameters in the English Premier League. *Int J Sports Med*. 2014;35:1095-1100. <https://doi.org/10.1055/s-0034-1375695>
2. Cook JL, Docking SI. "Rehabilitation will increase the 'capacity' of your ...insert musculoskeletal tissue here...." Defining 'tissue capacity': a core concept for clinicians. *Br J Sports Med*. 2015;49:1484-1485. <https://doi.org/10.1136/bjsports-2015-094849>
3. Drew MK, Cook J, Finch CF. Sports-related workload and injury risk: simply knowing the risks will not prevent injuries: narrative review. *Br J Sports Med*. 2016;50:1306-1308. <https://doi.org/10.1136/bjsports-2015-095871>
4. Duthie GM, Thornton HR, Delaney JA, Connolly DR, Serpiello FR. Running intensities in elite youth soccer by age and position. *J Strength Cond Res*. 2018;32:2918-2924. <https://doi.org/10.1519/JSC.0000000000002728>

5. Gabbett TJ. Debunking the myths about training load, injury and performance: empirical evidence, hot topics and recommendations for practitioners. *Br J Sports Med*. 2020;54:58-66. <https://doi.org/10.1136/bjsports-2018-099784>
6. 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>
7. Gabbett TJ, Hulin BT. Activity and recovery cycles and skill involvements of successful and unsuccessful elite rugby league teams: a longitudinal analysis of evolutionary changes in National Rugby League match-play. *J Sports Sci*. 2018;36:180-190. <https://doi.org/10.1080/02640414.2017.1288918>
8. Gabbett TJ, Jenkins DG, Abernethy B. Physical demands of professional rugby league training and competition using microtechnology. *J Sci Med Sport*. 2012;15:80-86. <https://doi.org/10.1016/j.jsams.2011.07.004>
9. Gabbett TJ, Nielsen RO, Bertelsen ML, et al. In pursuit of the 'unbreakable' athlete: what is the role of moderating factors and circular causation? *Br J Sports Med*. 2019;53:394-395. <https://doi.org/10.1136/bjsports-2018-099995>
10. Hulin BT, Gabbett TJ, Pickworth NJ, Johnston RD, Jenkins DG. Relationships among player load, high-intensity intermittent running ability, and injury risk in professional rugby league players. *Int J Sports Physiol Perform*. 2020;15:423-429. <https://doi.org/10.1123/ijsp.2019-0139>
11. Malone S, Hughes B, Doran DA, Collins K, Gabbett TJ. Can the workload-injury relationship be moderated by improved strength, speed and repeated-sprint qualities? *J Sci Med Sport*. 2019;22:29-34. <https://doi.org/10.1016/j.jsams.2018.01.010>
12. Malone S, Roe M, Doran DA, Gabbett TJ, Collins K. High chronic training loads and exposure to bouts of maximal velocity running reduce injury risk in elite Gaelic football. *J Sci Med Sport*. 2017;20:250-254. <https://doi.org/10.1016/j.jsams.2016.08.005>
13. Malone S, Roe M, Doran DA, Gabbett TJ, Collins KD. Protection against spikes in workload with aerobic fitness and playing experience: the role of the acute:chronic workload ratio on injury risk in elite Gaelic football. *Int J Sports Physiol Perform*. 2017;12:393-401. <https://doi.org/10.1123/ijsp.2016-0090>
14. Møller M, Nielsen RO, Attermann J, et al. Handball load and shoulder injury rate: a 31-week cohort study of 679 elite youth handball players. *Br J Sports Med*. 2017;51:231-237. <https://doi.org/10.1136/bjsports-2016-096927>
15. Spencer M, Lawrence S, Rechichi C, Bishop D, Dawson B, Goodman C. Time-motion analysis of elite field hockey, with special reference to repeated-sprint activity. *J Sports Sci*. 2004;22:843-850. <https://doi.org/10.1080/02640410410001716715>
16. Verhagen E, Gabbett T. Load, capacity and health: critical pieces of the holistic performance puzzle. *Br J Sports Med*. 2019;53:5-6. <https://doi.org/10.1136/bjsports-2018-099819>



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FRANCO M. IMPELLIZZERI, PhD¹ • PATRICK WARD, PhD¹
AARON J. COUTTS, PhD¹ • LUKE BORNN, PhD² • ALAN MCCALL, PhD^{1,3}

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

The relationship between training (work)load and sports injury is a prominent topic in sports science and medicine research. The hypothesis of a link between training load and sports injury is not new.⁵ Manipulating training load

using new measures of exposure (training load-based metrics), assuming that changing load will cause the injury risk to reduce, has become common and recommended by international sports organizations.⁸

CLINICAL QUESTION

FOR MANY OF US, THE SOLE PURPOSE of reading journal articles is to find information that will help us make



better decisions in the clinic. If one reads something in *JOSPT* or another scientific journal that supports a relationship between training load and injury, should

one accept the findings as true? In this article, we address why it is important for clinicians to critically evaluate the evidence behind conclusions in research (even when these recommendations are endorsed by international organizations), using the training load and injury field as an example.

Most Popular Training Load Metrics

The acute load, chronic load, and their ratio (acute-chronic workload ratio [ACWR]) are measures of exposure embraced by the scientific community and used as prognostic factors for injury risk. These measures of exposure are training load-based metrics that have been developed from a liberal interpretation of Eric Banister's model,⁶ proposed in the 1970s to model training load (impulse) and physical performance. The time frames for acute and chronic workload and for the ACWR were an approximation of the time decays derived from Banister's model.⁶ The decays represented the time needed to dissipate the

• **BACKGROUND:** This article sets the scene for a critique of the research underpinning 2 common clinical assumptions: (1) training workload is a key factor influencing sports injury risk, and (2) training workload can be manipulated to reduce injury risk. In this clinical commentary, we address why it is important for clinicians to critically evaluate the evidence behind research conclusions.

• **CLINICAL QUESTION:** Has research been designed and conducted well enough to help clinicians answer the questions, "What is the relationship between training workload and sports injury risk?" and "Can the metrics based on training workload be used to decrease injury risk?"

• **KEY RESULTS:** In the past decade, many sports injury researchers have developed new measures of exposure, based on internal and external training workload, to study the relationship between training load and injury. Some of these metrics may have been embraced by researchers and clinicians because (1) they are apparently

supported by the scientific literature, (2) they are simple to calculate and use (averages and their ratio), and (3) there is an apparent reasonable rationale/narrative to support using workload metrics. However, intentional or unintentional questionable research practices and overinterpretation of research results undermine the trustworthiness of research in the training load and sports injury field.

• **CLINICAL APPLICATION:** Clinicians should always aim to critically examine the credibility of the evidence behind a research conclusion before implementing research findings in practice. Something that initially looks promising and inviting might not be as revolutionary or useful as one first anticipated. *J Orthop Sports Phys Ther* 2020;50(10):574-576. Epub 1 Aug 2020. doi:10.2519/jospt.2020.9675

• **KEY WORDS:** critical thinking, injury, research quality, training load

¹Human Performance Research Centre, Faculty of Health, University of Technology Sydney, Moore Park, Australia. ²Strategy and Analytics, Sacramento Kings, Sacramento, CA.

³Arsenal Performance and Research Team, Arsenal Football Club, London, United Kingdom. No funding support was 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 • Copyright ©2020 *Journal of Orthopaedic & Sports Physical Therapy*

negative (fatigue) and positive (fitness) effects of training.

In the current-day reinterpretation of Banister's model, acute load represents a surrogate measure of fatigue, and chronic load a surrogate measure of fitness. The 2 components of Banister's equation have been substituted by the ratio of 2 averages (rolling or exponentially weighted moving averages): typically, 1 week for the acute workload and 4 weeks for the chronic workload.⁴ Acute workload, chronic workload, and the ACWR are the metrics one is most likely to see reported in research examining the association between training load and injury.

Training Load Metrics: Make It as Simple as Possible, but Not Simpler

It is not surprising that new measures of exposure have gained popularity among clinicians and researchers. The metrics have been used in most studies and they are simple to calculate, easy to explain to athletes, and based on an apparently plausible rationale (do not train too much, too soon) that fits commonly accepted training principles. However, these metrics are also an excessive simplification of complex injury etiology and of the mechanical load and damage training load generates. One need only take a short wade into the train-

ing load and injury field to find copious and conflicting results regarding the relationship between training load and injury. It is difficult for clinicians to unravel the signal from the noise.¹

Interpreting the Results Correctly and According to the Nature of the Study

Metrics such as ACWR are based on Banister's model of performance, but have been shoehorned into injury research by attributing to them a generic etiological role.² The associations between these measures of exposure and injuries are interpreted as supporting a causal link between load and injury (ie, training load causes injury). Yet, no studies have estimated any causal effects. Erroneous (causal) interpretation is not rare in sport medicine.⁹

Clinicians should always consider whether research results provide evidence of causal effects before deciding to change a prognostic factor (eg, training load) in an attempt to alter the likelihood of an (adverse) event. The interpretation should be coherent with the nature of the study (descriptive, predictive, or causal) and its limitations.

Questionable Research Practices: Key Barriers to Trustworthy Research Results

Questionable research or reporting prac-

tices (QRPs) are problems in research design, analysis, and reporting that impinge on the trustworthiness of the results.³ Some QRPs can have very little effect on research results. Other QRPs can be fatal—obliterating the reader's trust in the results (TABLE).⁷ Hypotheses with unsupported causality, causation that is claimed/assumed without proper designs or without discussing bias, and ignoring nonsignificant results and contradictory evidence are examples of QRPs that blight training load and injury studies.

Research involves specific steps (FIGURE). At each step, there are threats to reproducible science (ie, trustworthy research), such as *P* hacking and hypothesizing after the results are known. It is important to consider how far QRPs might have infiltrated the training load and injury research field and the implications for clinicians aiming to use research in their practice.

SUMMARY

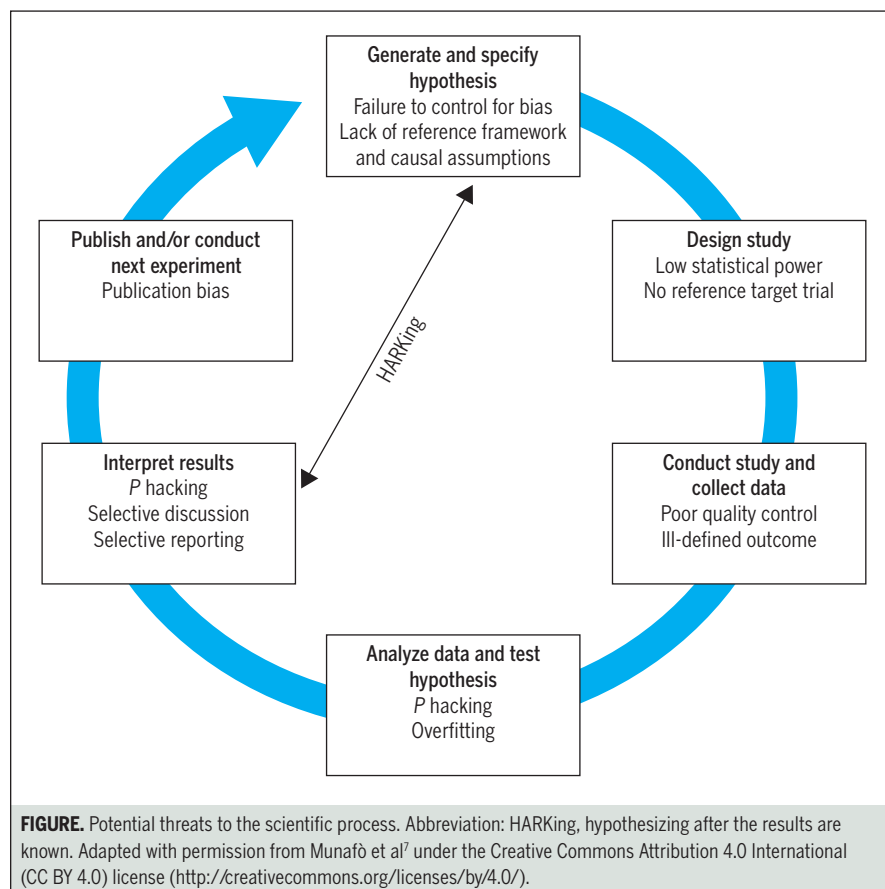
IN THIS ARTICLE, WE OUTLINED WHY IT is important to carefully assess the trustworthiness of research that one intends to use in practice. In part 2, we highlight various issues related to concepts and methods in the training load and injury research field. We focus on

TABLE

LIST OF COMMON QUESTIONABLE RESEARCH PRACTICES^a

- Nonsignificance of results is not addressed
- Causation claimed without appropriate design or analysis
- Hypothesis contains unsupported causality
- Potential causal relationship is not justified
- Causation is claimed without discussing bias
- Inappropriate use of evidence
- Generalization to different population, setting, or location
- Secondary outcomes are overstated
- Clinical relevance of nonsignificant results
- Small effect size is overstated
- Precision of estimate not discussed or considered
- Outcome measure does not reflect objectives
- Supporting literature based on same underlying data
- Abstract does not reflect the main findings
- Title does not reflect the main findings
- Order of discussion differs from aim
- Objectives are phrased differently in discussion
- Generalization is not supported by sample
- Results section contains interpretation
- Conclusion does not reflect outcome measure
- Objectives are not reflected in the discussion
- Conclusions in abstract do not reflect main text
- Limitations are poorly discussed
- Supporting evidence is poorly documented
- Objective is not reflected by the conclusions
- Conclusions do not reflect findings in context
- Impact of limitations on results is not discussed
- Conclusions do not reflect findings
- Contradictory evidence is not mentioned
- Recommendations for practice are lacking or are not supported by findings
- Implications for practice are lacking or are not supported by findings

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decisions researchers can make about hypotheses, study designs, and conducting, analyzing, and reporting research,¹⁰ and how those decisions can impact the trustworthiness of research results.

We aim to raise potential challenges to applying the current research in the training load and injury field, and identify some biases, to improve future research. We hope our commentary encourages clinicians to be careful when applying research in 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. Ardern CL, Dupont G, Impellizzeri FM, et al. Unravelling confusion in sports medicine and sports science practice: a systematic approach

to using the best of research and practice-based evidence to make a quality decision. *Br J Sports Med.* 2019;53:50-56. <https://doi.org/10.1136/bjsports-2016-097239>

2. Gabbett TJ, Hulin BT, Blanch P, Whiteley R. High training workloads alone do not cause sports injuries: how you get there is the real issue. *Br J Sports Med.* 2016;50:444-445. <https://doi.org/10.1136/bjsports-2015-095567>
3. Gerrits RG, Jansen T, Mulyanto J, van den Berg MJ, Klazinga NS, Kringos DS. Occurrence and nature of questionable research practices in the reporting of messages and conclusions in international scientific Health Services Research publications: a structured assessment of publications authored by researchers in the Netherlands. *BMJ Open.* 2019;9:e027903. <https://doi.org/10.1136/bmjopen-2018-027903>
4. 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>
5. Kibler WB, Chandler TJ, Stracener ES. Musculoskeletal adaptations and injuries due to overtraining. *Exerc Sport Sci Rev.* 1992;20:99-126.
6. Morton RH, Fitz-Clarke JR, Banister EW. Modeling human performance in running. *J Appl Physiol* (1985). 1990;69:1171-1177. <https://doi.org/10.1152/jappl.1990.69.3.1171>
7. Munafò M, Nosek B, Bishop D, et al. A manifesto for reproducible science. *Nat Hum Behav.* 2017;1:art 0021. <https://doi.org/10.1038/s41562-016-0021>
8. Soligard T, Swellnus 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>
9. Stovitz SD, Verhagen E, Shrier I. Distinguishing between causal and non-causal associations: implications for sports medicine clinicians. *Br J Sports Med.* 2019;53:398-399. <https://doi.org/10.1136/bjsports-2017-098520>
10. Wicherts JM, Veldkamp CL, Augusteijn HE, Bakker M, van Aert RC, van Assen MA. Degrees of freedom in planning, running, analyzing, and reporting psychological studies: a checklist to avoid p-hacking. *Front Psychol.* 2016;7:1832. <https://doi.org/10.3389/fpsyg.2016.01832>



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FRANCO M. IMPELLIZZERI, PhD¹ • PATRICK WARD, PhD¹
AARON J. COUTTS, PhD¹ • LUKE BORNN, PhD² • 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



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 non-functional 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

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

• **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 RESULTS:** 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

¹Human Performance Research Centre, Faculty of Health, University of Technology Sydney, Moore Park, Australia. ²Strategy and Analytics, Sacramento Kings, Sacramento, CA. ³Arsenal 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 • Copyright ©2020 *Journal of Orthopaedic & Sports Physical Therapy*[®]

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 HARK-

ing 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 al⁶ 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 framework⁶ 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 football⁵⁴ 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.

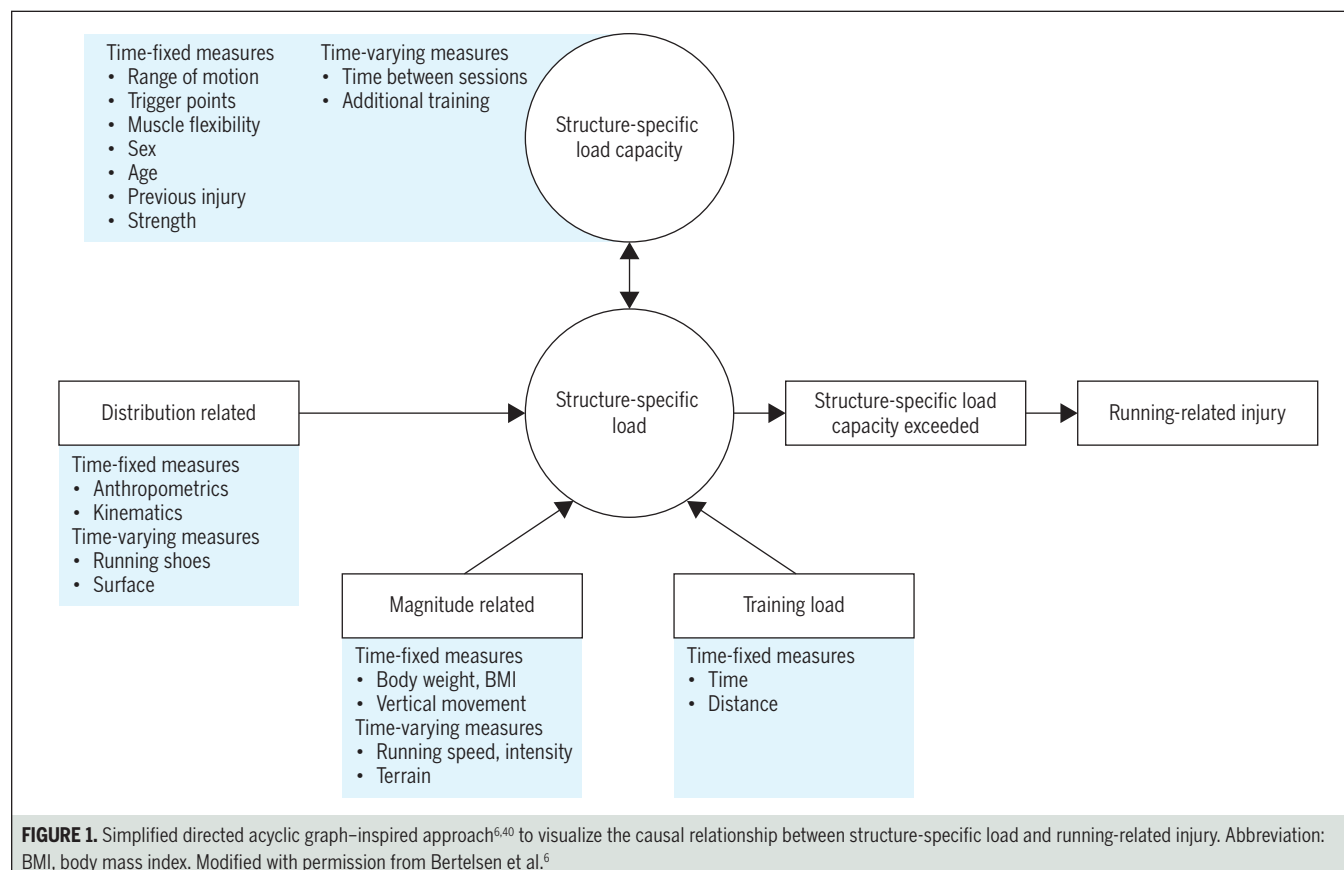
Inconsistency between and within studies in the training load and injury field is often justified by the multifactorial nature of injury etiology. While this is true and models accounting for this complexity have been proposed,^{8,32,33} the multifactorial nature of injury cannot be used as an excuse 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.



[CLINICAL COMMENTARY]

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 measures⁷ 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.

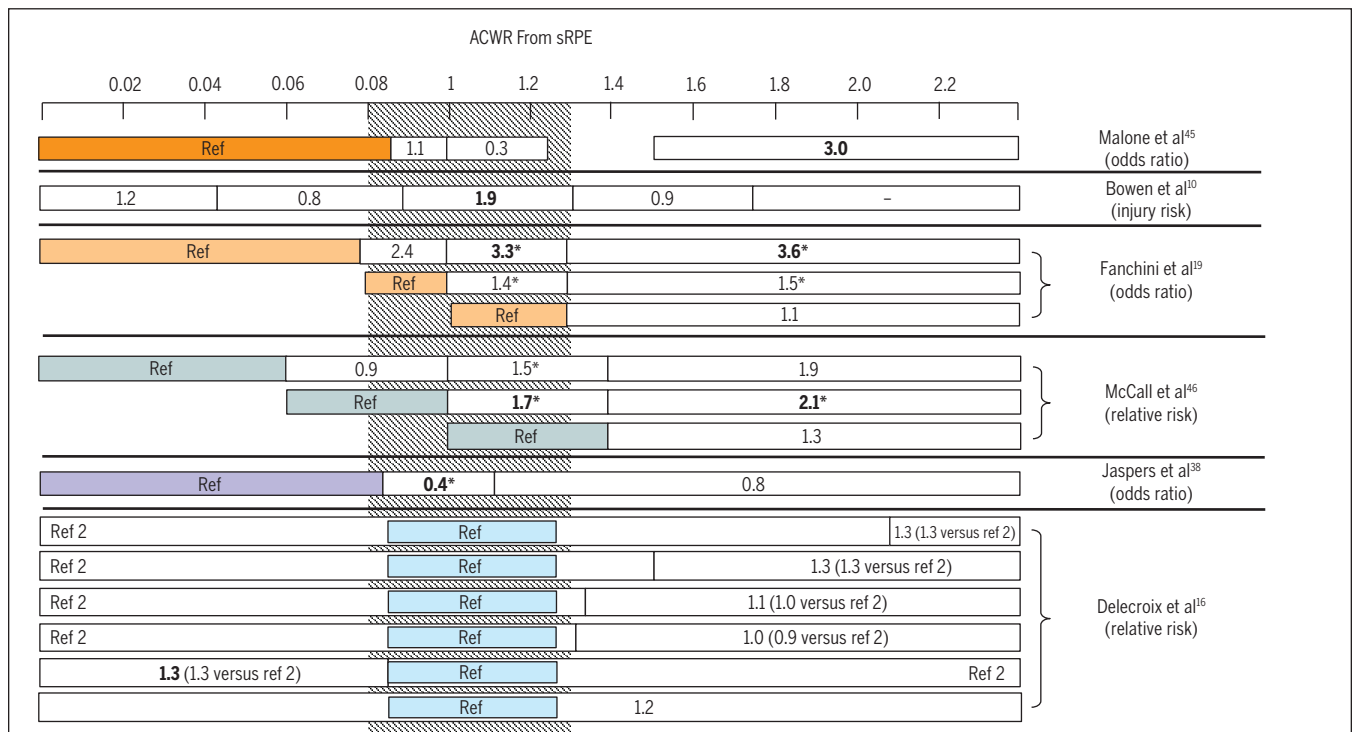


FIGURE 2. Graphical representation of results from studies examining the association between ACWR, calculated using the sRPE, and injuries in soccer. The rectangular boxes represent the ACWR categories used in the studies. When there is no rectangle, that category range was not used or reported in the 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 al¹⁹ and Watson et al⁵⁹ 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-

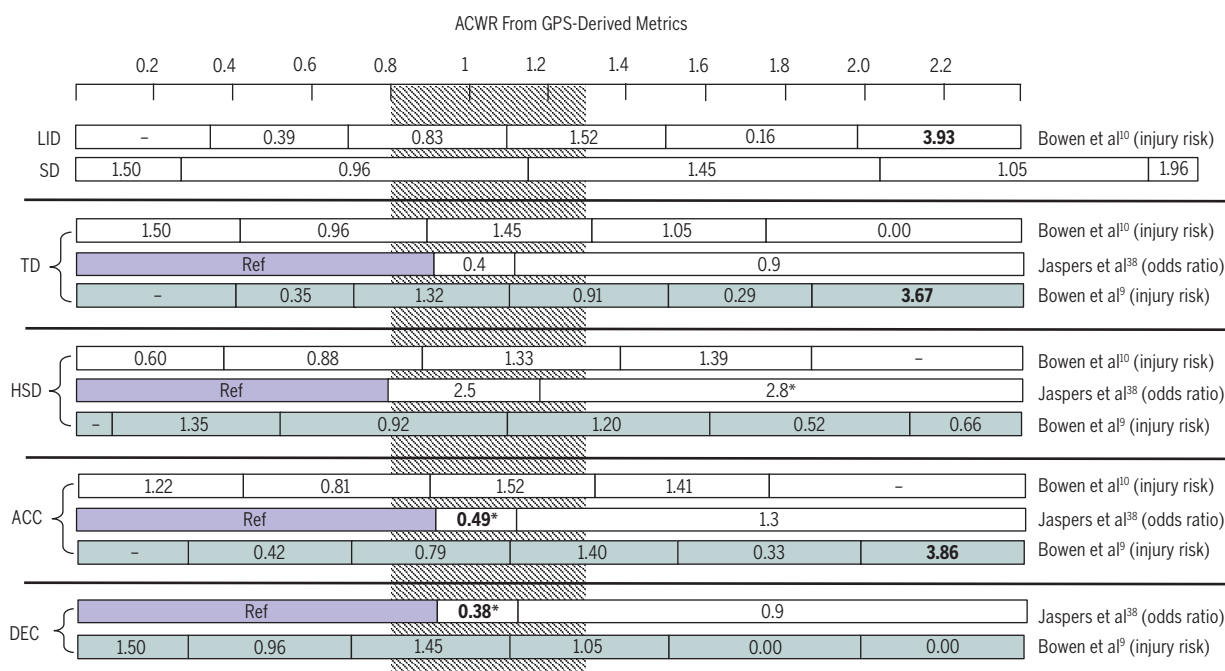


FIGURE 3. Graphical representation of results from studies examining the association between ACWR, calculated using a GPS, and injuries in soccer. The rectangular boxes represent the ACWR categories used in the studies. When there is no rectangle, that category range was not used or reported in the results. 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 al¹⁸ and Watson et al⁵⁹ 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).

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.

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.	

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

- Altman DG, Royston P. The cost of dichotomising continuous variables. *BMJ*. 2006;332:1080. <https://doi.org/10.1136/bmj.332.7549.1080>
- 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>
- 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>
- 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>
- 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>
- 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>
- 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>
- 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>
- 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>
- 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>
- 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>
- 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>
- 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>
- 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.
- 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>
- 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>
- 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>

- 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>
- 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>
- 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>
- 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>
- 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>
- 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>
- 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>
- 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>
- 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>
- 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>
- 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>
- 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>
- 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/ijsp.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/ijsp.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:chronic [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/ijsp.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, Arden 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>



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Focused Issue on Workload and Injury to Share Practical Advice With Clinicians, Athletes, and Coaches

RASMUS ØSTERGAARD NIELSEN, PT, PhD

*Department of Public Health, Aarhus University, Aarhus, Denmark.
Research Unit for General Practice in Aarhus, Aarhus, Denmark.*

CLARE L. ARDERN, PT, PhD

*Editor-in-Chief
Division of Physiotherapy, Karolinska Institute, Stockholm, Sweden.*

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Why Devote a Whole Journal Issue to Workload?

Did you hear about the athlete who got injured while sitting on the couch watching television? Anyone who works with athletes of any age and ability knows the best way for the athlete to avoid injury is to avoid playing sports. Anyone who works with athletes also knows that athletes want to play sports above almost all else. Understanding the relationship between how much sports activity an athlete participates in (ie, workload) and injury will help clinicians, athletes, and coaches know what to do to keep athletes healthy (injury free) and performing their best.

In the October issue of *JOSPT*, we tackle workload and sports injury. Workload (sometimes referred to as training load) is a principal cause of sports injury: injury occurs when the load applied to a body tissue exceeds the tissue's capacity to withstand load.⁷ This is unlikely to occur if the athlete sits on the couch watching television. Clinicians, athletes, and coaches seem to agree: if an athlete does "too much" or trains excessively, that athlete will likely sustain an injury.¹⁰

After 40 Years of Research in the Workload and Injury Field, Is There a Need to Take a Step Back?

For the past 4 decades, sports injury researchers have investigated isolated risk

factors for sports injury, including those related to workload.⁴ Researchers have aimed to use measures of a single factor to predict those athletes who would be more likely to sustain a sports injury.³ Understanding risk factors for injury can help clinicians and coaches identify athletes who might be "at risk." The problem is, this research does not answer the question of what clinicians, athletes, and coaches can do to reduce the risk of injury. Developing effective, targeted interventions to reduce injuries requires research to address the question of why sports injury occurs.^{8,11}

The aim of producing a focused *JOSPT* issue about workload is to share perspectives on key concepts that will help clinicians, athletes, and coaches understand what workload is. This understanding to this question is important to exploring why sports injuries occur and comparing results across studies. In ad-

dition, this issue aims to answer 2 critical questions: How does understanding workload data help clinicians, athletes, and coaches? And who is the end user of the research? Researchers must embrace their audience and assist those working in the field on a daily basis to understand research and data. After all, data are also part of clinical practice.

What Is Workload? How Can We Measure Workload? And Other Clinical Conundrums

The clinician reader of this October issue of the *JOSPT* is in for a treat. Take a deep dive into how researchers measure, monitor, and analyze workload in a scoping review that is a solid platform from which to leap into the rest of the topic.¹² Expand your knowledge of the rapidly developing arena of "wearables."¹ Looking for practical tips on monitoring and progressing training load to avoid injury and improve performance? You will find a bite-sized guide, ready made for clinical practice,² and a helpful guide to measuring and monitoring training stress in runners.⁹

There is a call for researchers to avoid common pitfalls when designing research and analyzing data in the sports injury

field.⁶ You will also find a detailed guide to what to be aware of when reading and implementing training load and injury research findings in the clinic.⁵

Quality Content for You to Apply in the Clinic on Monday

Thank you to the authors for sharing knowledge and contributing to this focused workload issue. We hope *JOSPT* readers find thought-provoking and practical information to help you critically evaluate the content of workload-related articles, and to help the patients and athletes you work with.

Enjoy reading! ●

REFERENCES

1. Benson LC, Räsänen AM, Volkova VG, Pasanen K, Emery CA. Workload a-WEAR-ness: monitoring workload in team sports with wearable technology: a scoping review. *J Orthop Sports Phys Ther.* 2020;50:549-563. <https://doi.org/10.2519/jospt.2020.9753>

2. Gabbett TJ. How much? How fast? How soon? Three simple concepts for progressing training loads to minimize injury risk and enhance performance. *J Orthop Sports Phys Ther.* 2020;50:570-573. <https://doi.org/10.2519/jospt.2020.9256>
3. 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>
4. 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>
5. 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>
6. Impellizzeri FM, Ward P, Coutts AJ, Bornn L, McCall A. Training load and injury part 2: questionable research practices hijack the truth and mislead well-intentioned clinicians. *J Orthop Sports Phys Ther.* 2020;50:577-584. <https://doi.org/10.2519/jospt.2020.9211>
7. 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>
8. Nielsen RO, Simonsen NS, Casals M, Stamatakis E, Mansournia MA. Methods matter and the 'too much, too soon' theory (part 2): what is the goal of your sports injury research? Are you describing, predicting or drawing a causal inference? *Br J Sports Med.* In press. <https://doi.org/10.1136/bjsports-2020-102144>
9. Paquette MR, Napier C, Willy RW, Stellingwerff T. Moving beyond weekly "distance": optimizing quantification of training load in runners. *J Orthop Sports Phys Ther.* 2020;50:564-569. <https://doi.org/10.2519/jospt.2020.9533>
10. Saragiotto BT, Yamato TP, Lopes AD. What do recreational runners think about risk factors for running injuries? A descriptive study of their beliefs and opinions. *J Orthop Sports Phys Ther.* 2014;44:733-738. <https://doi.org/10.2519/jospt.2014.5710>
11. Schooling CM, Jones HE. Clarifying questions about "risk factors": predictors versus explanation. *Emerg Themes Epidemiol.* 2018;15:10. <https://doi.org/10.1186/s12982-018-0080-z>
12. Udy CL, Impellizzeri FM, Lind M, Nielsen RO. How has workload been defined and how many workload-related exposures to injury are included in published sports injury articles? A scoping review. *J Orthop Sports Phys Ther.* 2020;50:538-548. <https://doi.org/10.2519/jospt.2020.9766>

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MAX R. PAQUETTE, PhD¹ • CHRISTOPHER NAPIER, PT, PhD^{2,3}
RICHARD W. WILLY, PT, PhD⁴ • TRENT STELLINGWERFF, PhD⁵

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*



“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

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

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

• **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

¹College of Health Sciences, University of Memphis, Memphis, TN. ²Menrva Research Group, Schools of Mechatronic Systems Engineering and Engineering Science, Simon Fraser University, Surrey, Canada. ³Department of Physical Therapy, University of British Columbia, Vancouver, Canada. ⁴School of Physical Therapy and Rehabilitation Science, University of Montana, Missoula, MT. ⁵Canadian Sport Institute Pacific, Victoria, Canada. 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 Dr Max R. Paquette, College of Health Sciences, University of Memphis, 171b Elma Roane Fieldhouse, Memphis, TN 38152. E-mail: mrpquette@memphis.edu • Copyright ©2020 *Journal of Orthopaedic & Sports Physical Therapy*®

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

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 impulse¹⁵⁻¹⁷ 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”²⁵ 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}

TABLE 1

DEFINITIONS OF VARIOUS METRICS USED TO QUANTIFY RUNNING TRAINING

Metric	Definition	Example	Unit
Training stress ^{33,39}	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 ^{17,25}	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.

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.

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 ago⁷ 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 sup-

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.

^aMetrics were estimated from published biomechanical data.

^bData from Chan-Roper et al⁹ (ie, approximately 1.7% lower cadence with fatigue).

^cData from Hanley and Bissas²¹ (ie, cadence of athletes during the 10000-m World Championship race).

^dData from Arampatzis et al¹ (ie, estimated peak vGRF at different running speeds).

^eData 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.

planting 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 colleagues²⁸ 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 research¹⁴ 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 train-

ing 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 metrics¹² 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

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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](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/g83yu>
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>



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FIGURE 1. Bilateral anteroposterior radiographs of the knees demonstrating osteoblastic, sclerotic, and lytic changes with expansion of the left femur. A lamellated periosteal reaction involving the diaphysis is also apparent. Further, disorganization of the marrow matrix can be appreciated. Physeal growth plates were consistent with skeletal age.



FIGURE 2. Lateral radiograph of the left femur showing circumferential expansion of the femoral diaphysis due to osteoblastic/sclerotic and lytic changes. A lamellated periosteal reaction can be seen extending approximately 13 to 14 cm proximally from the metaphysis. Physeal growth plates were consistent with skeletal age.

Chronic Nonbacterial Osteomyelitis

JAMES PLUMMER, PT, DPT, OCS, SCS, FAAOMPT, *Table Mountain Physical Therapy, Oroville, CA.*

A 9-YEAR-OLD ACTIVE GIRL PRESENTED to physical therapy via direct access with intermittent severe pain deep in the distal third of her left thigh that had a 2-year history. Twenty months prior, her pediatrician ordered radiographs that were noncontributory. She was diagnosed with “growing pains” and treated with acetaminophen. Her medical history was not significant for other pathology.

Upon presentation, the patient reported an inconsistent frequency of pain in the left knee that was only present at night and would wake her from sleep. Her symptoms were not provoked with activity or participation in sports (soccer and gymnastics). Her symptoms would be present for approximately 3 nights

and then absent for 3 weeks. She reported her primary complaint, though absent on presentation, to be a “sharp” pain that was 8/10 on the verbal numeric pain rating scale at its worst. No other constitutional symptoms were reported.

Upon examination, her gait cycle was normal, leg lengths were equivalent, and range of motion at the knee was full and pain free. Her lower extremity strength was 4+/5, with mild pain elicited during resisted knee extension. On palpation, an osseous nontender enlargement of the femur, 1 cm larger in girth, was found 10 cm proximal to the patella. Due to this abnormality, the patient was referred to her pediatrician for imaging.

Radiographs demonstrated an ex-

pansile bone lesion with a mixed matrix concerning for Ewing’s sarcoma (**FIGURES 1 and 2**). An open surgical biopsy determined the mass to be benign and without markers of infectious agents, consistent with nonbacterial osteomyelitis.^{1,2} Conservative management of naproxen was initiated, with a good prognosis. Following biopsy, the patient was cleared to resume usual activities after 2 weeks of weight bearing as tolerated.

Chronic nonbacterial osteomyelitis is a rare autoimmune disorder that frequently affects long bones. It affects girls, from the ages of 7 to 12 years, more often than boys. *J Orthop Sports Phys Ther* 2020;50(10):585. doi:10.2519/jospt.2020.9221

References

1. Buch K, Thuesen ACB, Brøns C, Schwarz P. Chronic non-bacterial osteomyelitis: a review. *Calcif Tissue Int*. 2019;104:544-553. <https://doi.org/10.1007/s00223-018-0495-0>
2. Taddio A, Ferrara G, Insalaco A, et al. Dealing with Chronic Non-Bacterial Osteomyelitis: a practical approach. *Pediatr Rheumatol Online J*. 2017;15:87. <https://doi.org/10.1186/s12969-017-0216-7>



FIGURE 2. Lateral “frog-leg” radiograph of the right hip demonstrating a calcification (arrow) in the medial thigh.

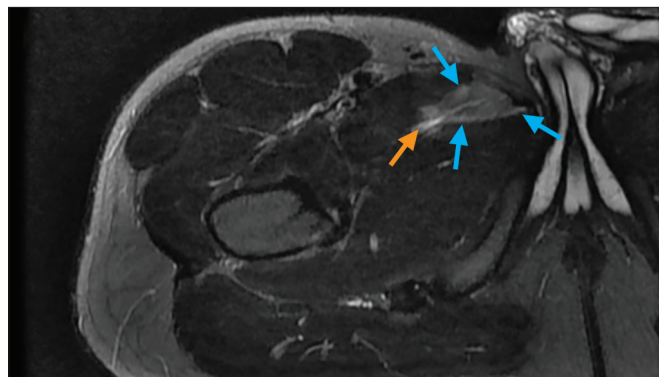


FIGURE 3. Axial, T2-weighted magnetic resonance image of the upper right leg demonstrating an approximately 6 × 2 × 2-cm adductor longus zone of muscle injury (orange arrow), including a roughly 1 × 2-cm zone of intramuscular hematoma (blue arrows).

Myositis Ossificans of the Adductor Longus in a Soccer Player

MICHAEL ZARRO, PT, DPT, SCS, CSCS, *Department of Physical Therapy and Rehabilitation Science, University of Maryland School of Medicine, Baltimore, MD.*

KATHLEEN TAMBERRINO, MS, ATC, *Loyola University Maryland, Baltimore, MD.*

E. MCKENZIE BANE, PT, DPT, ATC, SCS, CSCS, *MedStar Health, National Rehabilitation Network, Columbia, MD.*

A 20-YEAR-OLD MALE COLLEGIATE soccer goalkeeper presented to an athletic trainer during the season complaining of right (dominant kicking leg) groin pain.¹ Symptoms began insidiously 2 weeks prior, as lateral motion and kicking became painful. The athletic trainer identified a mass and hematoma (FIGURE 1, available at www.jospt.org) and suspected myositis ossificans. The patient was referred to the team physician, who ordered radiographs (FIGURE 2) and magnetic resonance imaging (FIGURE 3; FIGURE 4, available at www.jospt.org) to confirm the diagnosis and rule out injuries to the core muscle group, pelvis, and hip. Imaging demonstrated an adductor longus muscle strain with myositis ossificans.² He was prescribed diclofenac, referred to physical

therapy, and allowed to continue competition as tolerated, based on symptoms.

Physical therapy examination revealed limitations in right hip internal rotation, 1- and 2-joint hip flexor and adductor longus extensibility, and lumbar segmental mobility. The adductor squeeze test³ measured 103 mmHg and his scores on the Copenhagen Hip and Groin Outcome Score (HAGOS) physical function in sports and recreation and quality of life subscales were 43.75 and 45 out of 100, respectively (higher scores representing no hip or groin problems).³ No other impairments were noted.

Rehabilitation included progressive adductor loading, lumbopelvic control exercises, hip joint and lumbar spine mobilizations, and adductor longus soft

tissue mobilization. In 9 sessions over 6 weeks, pain-free squeeze improved to 177 mmHg. His HAGOS scores improved to 84.4 and 65.0 on the physical function in sports and recreation and quality of life subscales, respectively. He was able to change directions and kick without symptoms. Initial impairments resolved; however, the mass remained palpable, and radiographs taken 2 weeks after the season (8 weeks after the onset of symptoms) demonstrated no change.

Impairment-based rehabilitation enabled continued sports competition without time loss, despite concerning initial presentation and the presence of myositis ossificans. ● *J Orthop Sports Phys Ther* 2020;50(10):586. doi:10.2519/jospt.2020.9573

References

1. Kerbel YE, Smith CM, Prodomo JP, Nzeogu MI, Mulcahey MK. Epidemiology of hip and groin injuries in collegiate athletes in the United States. *Orthop J Sports Med*. 2018;6:2325967118771676. <https://doi.org/10.1177/2325967118771676>
2. Serner A, Weir A, Tol JL, et al. Characteristics of acute groin injuries in the adductor muscles: a detailed MRI study in athletes. *Scand J Med Sci Sports*. 2018;28:667-676. <https://doi.org/10.1111/sms.12936>
3. Thorborg K, Branci S, Nielsen MP, Langelund MT, Hölmich P. Copenhagen five-second squeeze: a valid indicator of sports-related hip and groin function. *Br J Sports Med*. 2017;51:594-599. <https://doi.org/10.1136/bjsports-2016-096675>