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Systematic Review/Meta-Analysis

Your Heart Can't See What Sneakers You Are Wearing: Exercise Training Load in Endurance Athletes Is Inadequately Quantified in Sports Cardiology

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ABSTRACT

Background: Training load may be an important factor underlying the (patho-)physiologic cardiovascular adaptations from endurance exercise. Yet, quantifying training load remains challenging due to the complexity of its components (Frequency, Intensity, Time, and Type [FITT]). In this systematic review we evaluate how training load has been quantified in sports cardiology studies and provide recommendations for how this can be improved.

Methods: A comprehensive search was conducted across PubMed and EMBASE up to October 2024. Studies involving "sports cardiology," "training load," and "endurance sport" were included. Data extraction included study characteristics, training load assessment methods, cardiovascular outcomes, and athlete profiles.

Results: A total of 62 studies with 1,060,700 participants were included in our review. The majority of studies (59.7%) focused on exercise-induced cardiac remodelling, with other topics being cardiac arrhythmias (12.9%), cardiac autonomic adaptation (3.2%), exercise dose-response (6.5%), and coronary heart disease (17.7%). Training load was primarily quantified by questionnaires (58.1%), whereas heart rate monitoring, a more objective measure, was used in only

RÉSUMÉ

Contexte : La charge d'entraînement peut être un facteur important sous-jacent aux adaptations cardiovasculaires (patho-)physiologiques de l'exercice d'endurance. Pourtant, la quantification de la charge d'entraînement demeure complexe en raison de la complexité de ses multiples composantes (Fréquence, Intensité, Temps et Type [FITT]). Dans cette revue systématique, nous évaluons la manière dont la charge d'entraînement a été quantifiée dans les études de cardiologie sportive et proposons des recommandations sur la manière d'améliorer cette quantification.

Méthodes : Une recherche exhaustive a été effectuée dans PubMed et EMBASE jusqu'en octobre 2024. Les études portant sur la cardiologie sportive, la charge d'entraînement et les sports d'endurance ont été incluses. L'extraction des données a porté sur les caractéristiques des études, les méthodes d'évaluation de la charge d'entraînement, les conséquences cardiovasculaires et les profils des athlètes.

Résultats : Au total, 62 études avec 1 060 700 participants ont été incluses dans notre analyse. La majorité des études (59,7 %) portait sur le remodelage cardiaque induit par l'exercice, les autres sujets étant les arythmies cardiaques (12,9 %), l'adaptation cardiaque

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Regular endurance exercise is a potent stimulus for structural, electrical, and functional cardiovascular adaptations. These physiologic adaptations—broadly termed exercise-induced cardiac remodelling (EICR)—are necessary to allow the cardiovascular system to meet the substantial hemodynamic and metabolic demands of endurance exercise and competition.[1,2]

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1.6% of the studies. All studies reported exercise type, but only 19.4% measured all FITT components.

Conclusions: There is a lack of uniformity in the assessment of key FITT variables to quantify training load within the field of sports cardiology, with many studies relying on subjective or incomplete methods. As cardiology moves into the precision medicine era, researchers and clinicians should seek to obtain objective training load information from their athletes according to the FITT framework, and data from use of objective wearable devices represent the optimal way to do this.

autonome (3,2 %), la dose-réponse à l'exercice (6,5 %) et les maladies coronariennes (17,7 %). La charge d'entraînement a été principalement quantifiée par des questionnaires (58,1 %), alors que la surveillance de la fréquence cardiaque, une mesure plus objective, n'a été utilisée que dans 1,6 % des études. Toutes les études ont rapporté le type d'exercice, mais seulement 19,4 % ont mesuré toutes les composantes FITT.

Conclusions : L'évaluation des principales variables FITT pour quantifier la charge d'entraînement dans le domaine de la cardiologie sportive manque d'uniformité, de nombreuses études s'appuyant sur des méthodes subjectives ou incomplètes. Alors que la cardiologie entre dans l'ère de la médecine de précision, les chercheurs et les cliniciens devraient chercher à obtenir des informations objectives sur la charge d'entraînement de leurs athlètes conformément au cadre FITT, et les données issues de l'utilisation de dispositifs portables objectifs représentent le meilleur moyen d'y parvenir.

However, endurance exercise has also been associated with potential pathophysiologic effects. These include acute elevations in biomarkers of cardiac injury and short-term decreases in cardiac function indicative of "cardiac fatigue,"[3] as well as chronic maladaptations, including coronary artery calcification (CAC), myocardial fibrosis, atrial fibrillation, and select cardiomyopathies (eg, arrhythmogenic right ventricular cardiomyopathy).[1,2]

Interestingly, emerging evidence suggests both the physiologic (EICR) and pathophysiologic effects of endurance exercise are associated with either total or components of the acute or chronic exercise dose (ie, training load). As such, sports cardiology studies that quantified training load have shown that endurance athletes performing and/or accumulating the highest volumes of exercise tend to have the most profound EICR, but also present with greater cardiac perturbation (eg, biomarker release[4] and/or cardiac fatigue[3]) and higher rates of CAC,[5] myocardial fibrosis,[3,6] and arrhythmias.[7,8] As an example, Aengevaeren et al. showed that masters' athletes engaging in higher total lifelong volumes of exercise, particularly those reporting the highest volume of very vigorous exercise over the lifespan, tended to have the highest prevalence and progression of CAC.[9] Therefore, in the current era of precision medicine, it is desirable to better understand what level of exercise load is likely safe and appropriate for an individual athlete, given their background and risk of pathology.[1,10] This relation is also critical to understand when the sports cardiologist needs to differentiate features suggestive of pathophysiology from presumed beneficial responses to the athlete's regular training load.[1,2,10] However, addressing these important challenges first requires an understanding of how to objectively quantify training load in a standardized manner in the sports cardiology research setting.

The impact of endurance exercise can be determined with a high level of precision through advances in diagnostic and physiologic assessments (eg, imaging techniques, biomarker assays).[1] However, quantifying training load has proven much more challenging. Training load is a complex phenomenon, encompassing multiple variables, including the Frequency, Intensity, Time, and Type of exercise (termed FITT variables[11]). These combined factors represent the load of a training session or block, but also can be used to estimate the athlete's cumulative training load over a period of years.[2] From a physiologic perspective, training load integrates the external demands of exercise (eg, time, distance, speed, incline, and power output) and the athlete's internal physiologic responses to those demands (eg, heart rate, pulmonary ventilation, whole body oxygen uptake, increase in blood lactate concentration, mental effort).[12] While providing fundamental insights into the effects of endurance exercise on the cardiovascular system, many of the seminal sports cardiology studies have relied mostly on questionnaires or interviews to characterize the different components or correlates of training load (such as sporting discipline, level of competition, or years of training).[3,13,14] However, as the sports cardiology field evolves, addressing critical questions, such as unraveling the genetic contributions or interactions underlying cardiovascular maladaptations in the endurance athlete, requires quantifying exercise dose on a more granular level.[1,15] This can be facilitated by recent advances in—and uptake of—wearable technology (heart rate monitoring, Global Positioning System [GPS] devices, power meters) and online training platforms that can collect and calculate training load and its components.[16-20]

With this background, we performed this scoping review with the aim of providing a systematic overview of how training load has been quantified in studies looking at the impact of endurance exercise on cardiovascular outcomes in endurance athletes. In doing so, we provide recommendations for the improvement of training load quantification as sports cardiology moves into the precision medicine era.

Materials and Methods

Search strategy

This systematic review was conducted in accordance with the guidelines provided by the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA).[21] A comprehensive search was performed across 2 electronic databases: PubMed and EMBASE (Excerpta Medica Database). The search spanned from the inception of each database up to and including October 2024. The search strategy followed

Population, Intervention, Comparison, Outcomes, and Study (PICOS) guidelines to ensure that a broad and inclusive search was conducted. The search strategy was constructed around 3 key concepts: "sports cardiology," "training load," and "endurance sport."

The initial search was conducted in PubMed using Medical Subject Headings (MeSH) terms relevant to each concept. For "endurance sport," the selected MeSH terms included "endurance training," "bicycling," "running," "marathon running," "swimming," and "athletes." For "training load," all studies indexed under appropriate MeSH tems related to this concept were included. The concept of "heart" was approached using MeSH terms selected based on expert consultation from a panel of sports cardiology specialists. All concepts were further supplemented by title/abstract terms corresponding to the MeSH terms. The search terms for each concept were combined using the Boolean operator "OR," whereas the 3 concepts were interconnected using the operator "AND."

The PubMed search strategy was subsequently translated into the EMBASE search using equivalent Emtree terms. Both MeSH and Emtree terms were complemented by free-text terms to ensure comprehensive retrieval of relevant articles across both databases (Supplemental Appendix S1). Duplicate records were removed using Endnote (Clarivate Analytics, Philadelphia, PA). The de-duplicated results were then imported into Rayyan.ai for screening by 2 independent reviewers (C.D. and R.M.) based on title and abstract content. Figure 1 details the PRISMA flowchart.

Study selection

Inclusion criteria were limited to articles published in English. Studies were screened based on the requirement that the 3 key concepts were present in either the title or the abstract. Detailed inclusion and exclusion criteria are outlined in Table 1. After the initial screening, 68 studies were identified as eligible for full-text review. These studies were independently assessed by the 2 reviewers (C.D. and R.M.). Any uncertainties were resolved by deliberating between the reviewers. Ultimately, 62 studies were included in the final review, whereas 9 were excluded for the following reasons: 6 studies were interventional, 3 studies lacked access to full text, and 1 study included a population of divers (Fig. 1).

Data extraction

The following data were extracted from each included study: author, year of publication, sample size, age, training load assessment method, training load variables, athlete level, cardiac outcomes, study design, and follow-up duration.

Data charting process

Data extracted from the 62 included studies were synthesized based on expert consensus and categorized as follows:

- Age: Mean age of participants was calculated using a weighted mean for each subgroup.
- Training load assessment: Methods of assessing training load were categorized into 6 groups: questionnaire, heart rate measurement, interview, race records, training diaries, and unknown.
- Training load variables: Training load was classified according to the FITT principle (frequency, intensity, time, and type of sport).
- Athlete performance level: The “caliber of athlete” variable was used to classify the status or performance level of athletes.
- Cardiac outcomes: Cardiac outcomes were categorized as follows:
  1. Exercise dose-response relationship and cardiovascular (CV) outcomes, when the dose-response relationship between exercise and CV outcomes (CV mortality, CV risk factors) was analyzed.
  2. Cardiac autonomic adaptation, if heart rate variability was studied.
  3. Cardiac arrhythmias, if the development of arrhythmias associated with endurance sport was assessed.
  4. EICR, when structural, functional, or electrophysiologic changes in the heart were investigated.
  5. Coronary heart disease, if the study focused on coronary artery modifications or ischemic events.

The study design and duration of follow-up were also documented for each study.

Statistics

All data were extracted, and basic frequencies and percentages were calculated using GraphPad Prism version 10.2.3 (GraphPad Software, La Jolla, CA). The PRISMA guidelines were followed for reporting items in this review (see PRISMA checklist in Supplemental Appendix S2).

Results

Details of included studies

Sixty-two studies were included (Supplemental Table S1). These studies had a total of 1,060,700 participants (41.8 ± 16 years of age). Of the 62 studies, 37 (59.7%) investigated EICR, and 8 (12.9%) focused on cardiac arrhythmias in sports, 2 (3.2%) on cardiac autonomic adaptation, 4 (6.5%) on the exercise dose-response and cardiovascular outcomes, and 11 (17.7%) on coronary heart disease.

Methods used to quantify training load

To quantify training load, 36 (58%) studies used questionnaires, 5 (8%) conducted athlete interviews, 5 (8%) used race records, 3 (5%) extracted data from training diaries, and 1 (2%) used measurements obtained from heart rate monitors. Notably 12 studies (19%) did not provide details on a quantification method used to derive training load (Fig. 2A).

Reporting and quantification of FITT variables

All 62 studies (100%; Supplemental Table S1) reported the type of exercise performed by athletes, 27 (43.5%) reported a measure of exercise frequency, 53 (85.5%) reported the duration (ie, time) of exercise, and 21 (33.9%) reported some measure of exercise intensity (Fig. 2B; Supplemental Table S1).

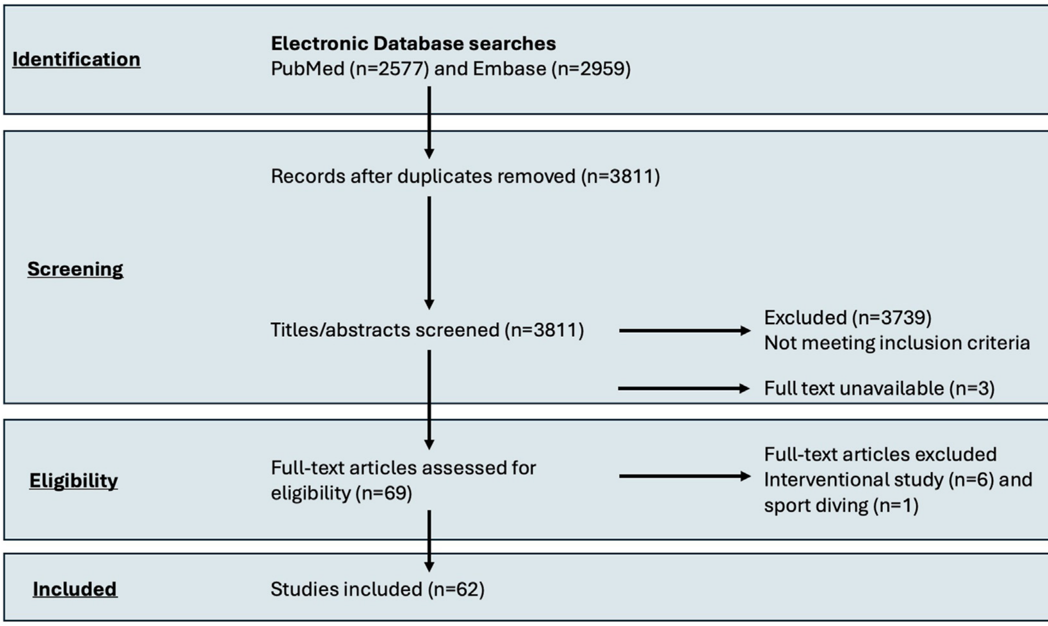

Figure 1. Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) systematic review and meta-analysis flowchart.

Only 12 studies (19.4%; Supplemental Table S1) reported on all FITT principles (frequency, intensity, time, and type of exercise) concurrently (Fig. 2C; Supplemental Table S1). Time and type of exercise was the most commonly reported combination, found in 27 studies (43.5%). A combination of frequency, time, and type was reported in 8 studies (12.9%), most often to quantify training load as metabolic equivalent hours per week (MET-h/wk). A combination of frequency, intensity, and type was reported in 1 study (1.6%). Intensity and type were reported together in 2 studies (3.2%), and 6 studies (9.7%) included intensity, time, and type. In addition, 6 studies (9.7%) reported both frequency and type. Only 1 study used an objective measure of training intensity (heart rate monitors), with the remainder using questionnaires or race duration to derive a measure of exercise intensity.

Discussion

To our knowledge, this is the first systematic review to critically and systematically evaluate the methodology used for quantification of exercise load in endurance athletes in the context of sports cardiology research. We highlight that details of training load were not provided in approximately 19% of studies included in this review. Furthermore, in the majority of the other studies, training load was quantified by questionnaire and/or athlete interviews, which have limitations in precision and accuracy for training load quantification. Moreover, we have illustrated the high degree of variability in the variables assessed and methodologies used, and, importantly, observed that a minority of studies to date have adequately captured all variables necessary to quantify training load according to the standards of the FITT model. The most frequently reported variable was training type. However, the heart does not see what shoes you are wearing, but instead responds physiologically (and in some cases pathologically) to the hemodynamic demands of exercise, so greater attention is required to quantifying other components of training load alongside exercise type.

Quantification of training load in sports cardiology

Findings from this review highlight that exercise dose has not been routinely quantified with sufficient rigor to determine the true dose-response impact of exercise training load on cardiovascular structure, function, and pathology. Indeed, we found that approximately 1 in 5 of the included studies did not quantify training load at all, and only some quantified all the necessary components to derive a true training load. Notably, when total training load was quantified, additional and important insights were provided into the link between endurance exercise and cardiovascular adaptations. For example, it has been proposed that selected adverse outcomes in some endurance athletes (such as CAC,[13] myocardial fibrosis,[3,6] and a predisposition toward atrial and select ventricular arrhythmias[7,8]) may reflect cumulative microtrauma from repeated bouts of an excessive exercise stimulus and/or insufficient recovery over an endurance athlete's lifespan.[22] Indeed, studies included in this review that quantified lifetime exercise dose (as lifetime MET-h/wk) in masters' athletes, have shown that those with greater lifetime exercise doses, and particularly higher doses of exercise at very vigorous intensities, have increased prevalence and progression of CAC than those performing lower doses or achieving their exercise dose at lower intensities of exercise.[23]

Domenech-Ximenos et al. found no differences in weekly training load (measured as MET-h/wk) in endurance athletes with vs without markers of magnetic resonance—derived myocardial fibrosis.[24] In contrast, Tahir et al. reported that accumulated training load in triathletes (defined by distances accumulated in competition) was strongly predictive of myocardial fibrosis,[6] suggesting that accumulated training volume, rather than recent training volume, may be an

Table 1. Inclusion and exclusion criteria

Component	Inclusion criteria	Exclusion criteria
Data source	Peer-reviewed scientific journals	Abstracts, poster presentations, full-text unavailable
Population	Healthy humans, no age restriction	Animals and patient groups
Study design	Observational cohort studies: cross-sectional, longitudinal, and case-control	Reviews, case series, case reports, supervised exercise training intervention studies, and randomized controlled trials
Language	English	Non-English language
Sport	Endurance sports: cycling, running, bi- and triathlon, cross-country skiing, swimming, and rowing	Team sport, strength training, and other

important determinant of myocardial fibrosis. However, cumulative competition distance only represents a proportion of the FITT variables and only a small proportion of the athlete's training load. These initial findings, combined with the limited reporting or assessment of the endurance athlete's training load in sports cardiology to date, highlights an opportunity for sports cardiology research to better understand the contribution of exercise exposure to cardiovascular adaptations previously reported in endurance athletes. Indeed, there is still much to learn about the dose-response nature of training load on the endurance athlete's cardiovascular system, as well as how training load interacts with other factors, such as underlying genetic abnormalities, sex, and ethnicity.[1,15]

Quantification of individual FITT components

Exercise type was the most frequently reported component of training load. However, although training type can help to determine where the athlete's hemodynamic stimulus falls on the static-dynamic spectrum, without information on exercise frequency, duration, and intensity it provides little insight into the actual magnitude of hemodynamic stress. Indeed, the ability to accurately quantify exercise intensity and duration (ie, time) is a key component for contemporary questions in sports cardiology, where higher intensities and/or longer durations of exercise have both been implicated in important issues such as increased postexercise cardiac troponin release; exercise-induced cardiac fatigue[4]; and the higher prevalence of myocardial fibrosis, coronary artery calcification, and atrial arrhythmias.

Of all the FITT variables that contribute to training load, exercise intensity is the most complex, as it can be expressed in and determined by internal (eg, heart rate, blood lactate, oxygen consumption) and/or external (eg, speed, power) factors, as well as in absolute terms (eg, absolute METs or VO_2) or terms relative to an athlete's own capacity (eg, percentage of maximum or threshold values).[12] However, exercise intensity was quantified in only 33.9% of studies and, in most cases, this was quantified from a standardized questionnaire to derive a composite of exercise intensity with duration ± frequency into MET-h or MET-h/wk. At a population level, metrics such as MET-h/wk provide a relatively quick and simple way

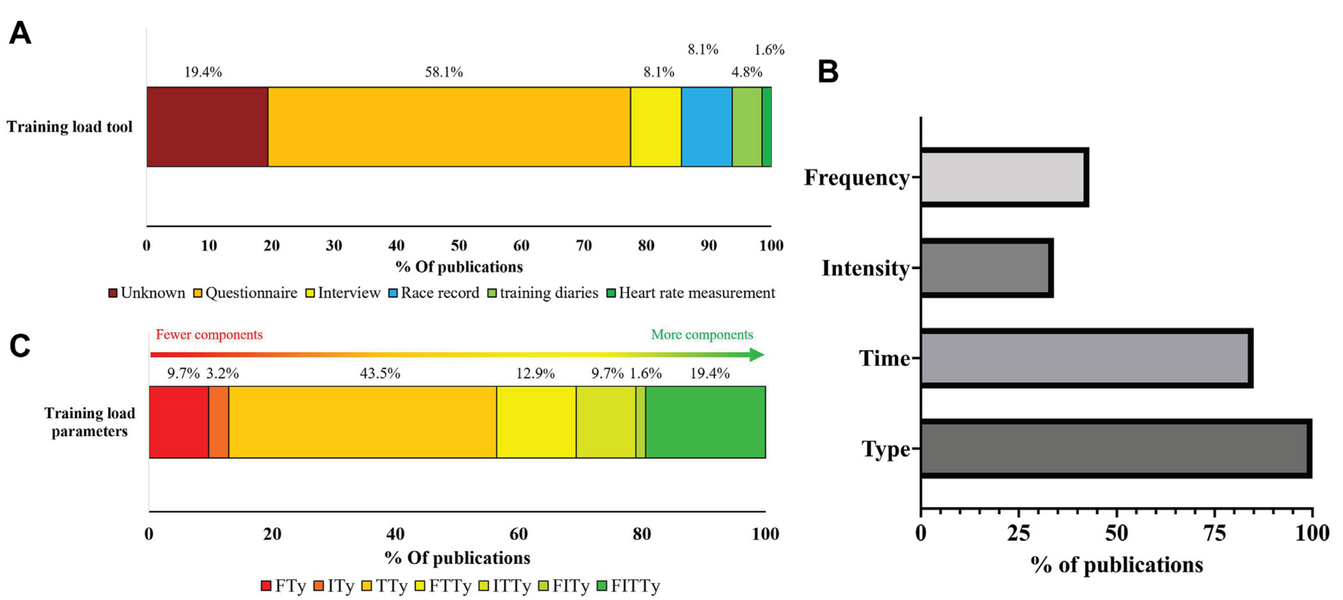

Figure 2. (**A**) FITT measurement tools used to quantify training load. Proportion of tools used to quantify training load in included studies. (**B**) Quantification of individual FITT components in sports cardiology research. Frequency with which each individual FITT component was quantified in the included studies. (**C**) Quantification of combination of FITT components in sports cardiology research. Proportion of studies reporting each training load variable, including Frequency (F), Intensity (I), Time (T), and Type (Ty) of exercise endurance athletes were performing.

to quantify exercise volume (ie, training load), and may be easily implemented to gather historic training load data, including quantification of training loads over the lifespan. However, questionnaire- or interview-derived measures of intensity (or training volume) such as MET-h/wk have several limitations, including inaccuracies due to the increased subjectivity and recall issues from being derived from self-reporting—that is, they often represent the athlete's "best guess."[25-27] Those measures also have a poor ability to discriminate between the training intensities typically performed by athletes, which often exceed the upper limits that can be captured by most questionnaires from which METs are derived.[28,29] For example, the upper MET limit for cycling speed quantified by the Compendium for Physical Activity is 36 kph, which is below what many elite cyclists would perform in numerous training sessions and competition. It is also difficult to quantify exercise load at the individual session level, where it would be cumbersome to remember the time spent at each intensity level, particularly for workouts performed on mixed terrain or with interval-based components.

Other studies used weekly distance, race times, or rankings as a more objective surrogate for duration, intensity, and/or external load. This may represent a more accurate way to quantify the acute absolute external exercise stress to which an athlete is exposed. However, mileage, racing time, or rankings do not provide insight into the internal metabolic or hemodynamic stress placed on the athlete. Furthermore, methods such as race times or placings can only quantify the exercise load at a single snapshot in time and may not be representative of the athlete's cumulative training load over time. Moreover, quantifying external intensity or load (eg, METs, mileage, race times) without any measures of internal load can be particularly problematic in endurance athletes, as the cardiovascular adaptations associated with structured training mean that they can perform the same absolute intensity of exercise at a lower level of physiologic stress.[28] Notably, the only study using an objective tool to quantify internal training load was performed by D'Ascenzi et al., who used heart rate measurements to quantify training load in a longitudinal study assessing EICR in preadolescent competitive male swimmers,[30] but unfortunately the association between EICR and training load was not assessed in their study. Therefore, the lack of objective and precise exercise intensity quantification, particularly with approaches that quantify both internal and external components to exercise intensity, is a critical gap for future research in sports cardiology to move from a "best guess" toward a true representation of endurance exercise dose.

Training load quantification methods in sports cardiology

Our systematic review has also highlighted that the predominant methods used to quantify training load were questionnaires, race records, and athlete interviews. These sources have the advantage of being low cost and easy to use or obtain.[16,17] However, they have substantial limitations when it comes to accurately and reliably quantifying all components of training load at the individual athlete level.[16,17] For example, in a cohort of endurance athletes, we previously compared the agreement between the weekly training load derived from a standardized questionnaire and the training load derived objectively from wearable heart rate monitors.[27] In that study, we reported no significant agreement for weekly training hours, nor frequency, between the 2 measures.[27] Moreover, we found that questionnaires substantially overestimated training volume compared with the measured volume from wearable monitors (12.3 ± 3.8 h/wk vs 7.9 ± 2.4 h/wk).[27] Even exercise frequency—a relatively simple metric to quantify from a questionnaire—was significantly higher when assessed by questionnaire than by heart rate monitor logs (4.8 ± 1.4 vs 4.0 ± 1.0 d/wk).[27] Although questionnaires are likely to provide sufficient a signal-to-noise ratio to differentiate or quantify training load at opposite ends of a spectrum, such as in athletes vs nonathletes (or elite athletes vs amateurs), understanding the dose-response effects from exercise to more complex phenomena within the endurance athlete population will require increased uptake of tools (such as wearable technology) that can quantify training load with the necessary precision to detect the more subtle differences within an athletic population.

Improving endurance training load quantification in sports cardiology

The sports cardiologist or researcher is led to wonder what the optimal approach is to quantify the necessary components of training load in the endurance athlete. However, each quantification method highlighted in this review has unique strengths and limitations (Fig. 3).[12,16,17] Currently, the lack of objective training quantification (and the lack of head-to-head comparisons) means we cannot provide definitive recommendations on the optimal approach to use in different contexts, As such, we can provide recommendations based on the authors' expert opinion. Overall, the major recommendation from this review is that, regardless of the tool used, sports cardiology research needs to more regularly report the quantification of training load. At a minimum, the FITT framework is what we recommend researchers and clinicians should use to ensure that all necessary components for determining the endurance athlete's training load are included.

Quantifying type of exercise. The type of exercise provides important context about the potential hemodynamic stimulus (ie, static vs dynamic load) and metabolic cost of exercise (eg, weight-bearing vs non–weight-bearing exercise), but also provides an important context for what would be an expected training volume for the athlete's sport. Fortunately, exercise type is a relatively simple variable to quantify across measurement tools (ie, questionnaire, interview, wearable technology, or training log).

Quantifying duration and frequency. Measuring the duration and frequency of exercise is a core component of calculating the total number of hours spent performing exercise. If one only requires a general estimation of the athlete's training volume, particularly over a long period of time (such as calculating lifetime training patterns), then questionnaires or athlete interviews may suffice. However, if the aim is to provide more accurate and in-depth interrogation of training frequency and/or duration, particularly patterns over a period of time (such as in the lead-up to symptoms or a certain

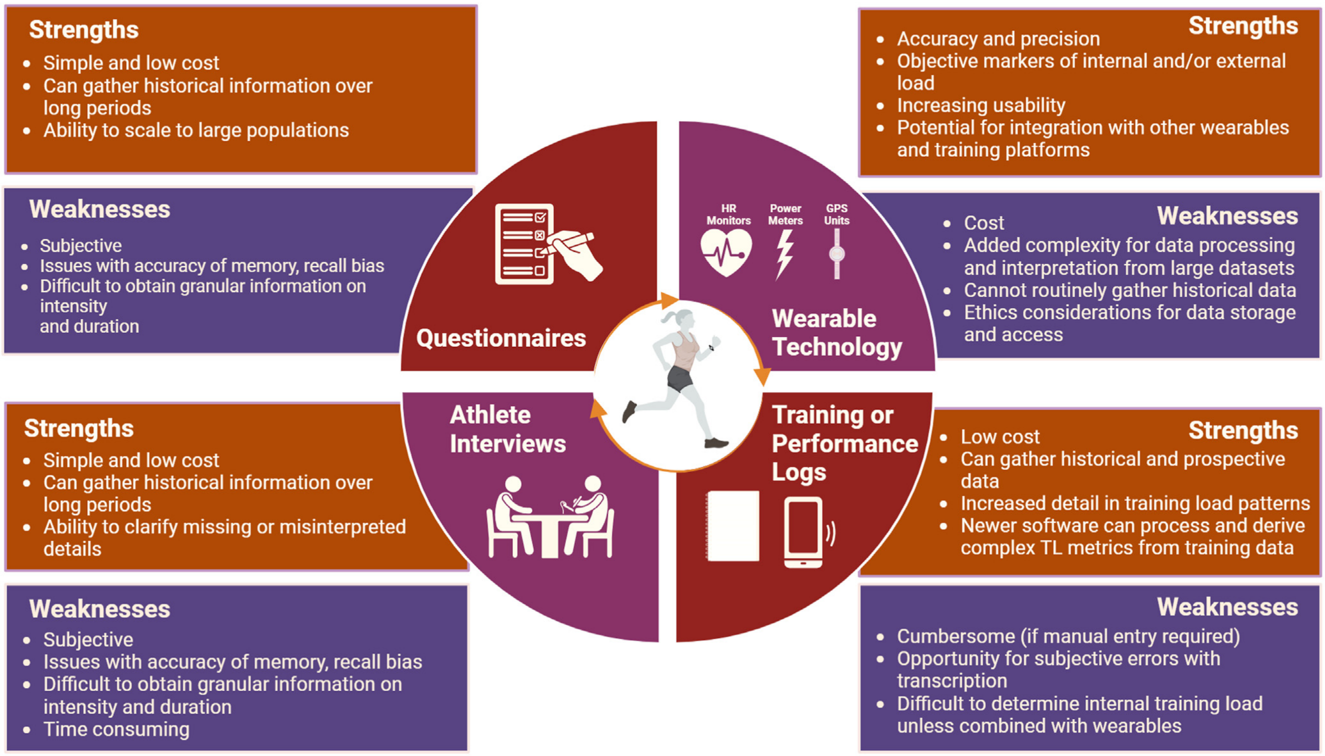

Figure 3. Strengths and weaknesses of training load quantification tools in sports cardiology. Each individual tool has its own unique strengths and weaknesses. An optimal approach for training load quantification in sports cardiology is one that integrates multiple tools together—as denoted by the orange circular arrow at the center of the figure. HR, heart rate; GPS, Global Positioning System. Figure created in BioRender.com.

clinical finding), then objective monitors such as data derived from the athlete's training log and/or wearable device (eg, heart rate monitor, GPS device) would be superior. If the athlete is diligent with recording and uploading their sessions, online training logs can provide the ideal means to objectively quantify duration and frequency of exercise over a specified period. This is advantageous because training duration and frequency in many endurance athletes can vary dramatically from one week to the next, so asking the athlete to remember or report "typical" training durations for a questionnaire or interview (in which a 1-week snapshot is often extrapolated to much longer periods) may dramatically under- or overestimate their annual training volume. A monitoring period of 3-6 months could provide an accurate indication of training load.[27]

Quantifying exercise intensity. As noted earlier, quantifying endurance exercise intensity is complex, there is no unified recommendation on how best to do this, so more in-depth discussion is provided on this topic. If questionnaires or interviews are to be used, then quantifying intensity (and exercise type) using the Compendium of Physical Activities provides a standardized means of classifying the athlete's activity into an absolute intensity of exercise according to its estimated MET requirements. Whenever possible, the questionnaire or interviewer should spend time and attention to ensuring answers are as specific as possible for clarifying the speed and terrain of each type of exercise, as jogging on a flat surface confers a very different external intensity to running at a fast pace on hilly terrain. This approach will be best suited to scenarios requiring a simple and broad overview of the absolute external intensity of exercise performed by the athlete, and may be useful in understanding lifelong engagement with different intensities of exercise that could be cumbersome or difficult to quantify with other approaches (particularly if the athlete has not been training with wearable technology or using training logs for the period of interest). However, questionnaire- or interview-based MET quantification is limited in its ability to capture differences in relative exercise intensity (ie, internal load) between 2 athletes.

Wherever possible, training intensity derived from questionnaire measures should be confirmed—or replaced by more objective wearable methods. Heart rate monitors offer a relatively cheap and simple method to quantify an athlete's internal intensity of exercise by expressing the average intensity or duration of training spent relative to the athlete's threshold or maximal heart rates. As an example, quantifying the accumulated time spent in certain heart rate zones (such as endurance zones vs near maximal zones) allows a more precise understanding of how relative exercise intensity, duration, or their combination are related to phenomena such as cardiac remodelling or arrhythmias, or even more acute changes such as cardiac fatigue or troponin release. Alternative wearables, such as GPS watches or power meters, quantify the athlete's external intensity or load by measuring the speed, terrain, and/or power output throughout the exercise session. They provide a more accurate means of quantifying the absolute energy expenditure of exercise (such as METs or kilocalories).

Moreover, if an athlete's personal best performance is known, wearables can also provide an indication of the internal intensity by relating an athlete's performance in the training session to their known threshold or maximal values. This provides a highly objective measure of weekly, monthly, or yearly training volume (eg, energy expenditure or METs) that could provide insights into how total exercise training load influences longer term adaptations such as changes in cardiac structure or function, coronary artery calcification, or myocardial fibrosis. Ultimately, it is recommended that combining internal (eg, heart rate monitors) with external (eg, GPS devices or power meters) wearables will provide the most wholistic understanding of an athlete's exercise intensity. Gathering historic or lifetime data with wearables may be difficult for older generations of athletes who may have limited exposure or experience with these tools. They may also impose an additional cost on the researcher if a specific monitoring tool is required that the athlete does not possess. However, wearable monitoring is being increasingly adopted among younger to middle-aged athletes (amateur through to elite level) and, as such, access to training load data from wearable technology will continue to improve with each generation of athletes.

- *Quantifying total training load:* The ultimate goal of measuring the FITT components is to come up with a composite measure of training volume or load. It is recommended that data from questionnaires or athlete interviews should multiply session intensity (eg, METs), session frequency, and hours per session to quantify training load as MET-h/wk of training. A similar approach can be taken with data collected from wearable devices. Traditionally, the overwhelming amount of data that could be collected by wearable technology provided substantial challenges for data storage, processing, and interpretation of training load.[16,17] This challenge is being overcome through parallel advances in software for training management and analytics. These platforms (eg, TrainingPeaks, Strava, Golden Cheetah—all available for free, with subscriptions only required for advanced metrics or training prescription)—have replaced the cumbersome handwritten training diaries with a comprehensive data repository that, with relative ease, can derive internal (eg, heart rate training zones, training impulse) and external (eg, intensity factor, training stress score) load over weeks, months, and years. These applications are individualized to the athlete's fitness and allow for comparison across most endurance disciplines (eg, running vs cycling vs swimming). As such, the combination of wearables and training management software represents the ideal scenario for quantifying training load in future sports cardiology studies. This can be done historically by the athlete providing the recorded training load details to the researcher, or prospectively by the athlete recording training sessions over a period of time that can be uploaded to the training management software of the researcher's choosing. However, the biggest considerations for this approach to be successful are the potential ethical and data-sharing implications for collecting and/or using training data obtained via these methods related to data ownership, storage, and security policies (often determined by the companies that own the platforms), and challenges in completely anonymizing training data.[16,17]
- *Additional considerations—athlete caliber:* Although it was not the specific focus of this review, understanding and reporting endurance athlete caliber (ie, amateur, semiprofessional, elite, world class) is also important in the interpretation and assessment of training load and cardiac outcomes in endurance athletes. A cursory review for the reporting of this information in the included studies (see "Athlete performance level" in Supplemental Table S1) suggests that this was also not indicated consistently or in a standardized format in most studies, so additional attention should be given to improving this in future sports cardiology studies. The reader can be directed to an excellent framework provided by McKay et al. on how this can be done consistently, wherein participants are recommended to be differentiated into 6 tiers: sedentary, recreationally active, trained/developmental, highly trained/national level, elite/international level, and world class.[31]

Ultimately, we do not yet know which objective metrics are optimal (or most relevant) for cardiovascular adaptations, so we cannot provide a clear recommendation on the best metric to use. This challenge is not specific to sports cardiology, but it is also acknowledged in the fields of athlete monitoring and coaching more broadly. However, we can make the strong recommendation that sports cardiology research needs to evolve toward measuring rather than estimating training load. Specifically, the researcher or clinician should obtain an objective measure of their athlete's training load according to the FITT framework; when possible, data collection from wearable devices is the most desirable and objective means of this. In doing so, metrics showing the strongest associations with relevant outcomes may reveal themselves.

Limitations

Our review has several limitations worth noting. We chose to focus only on endurance exercise, because the most profound cardiovascular adaptations are associated with endurance exercise. As such, these findings and recommendations should be extrapolated to other sporting disciplines with caution (eg, team sports, skill sports, strength-based sports, or sports with mixed power-endurance requirements, such as kayaking, tennis, or skating).[1,2,10] These disciplines have added complexity when it comes to deriving hemodynamic stress and quantifying training load due to their intermittent and explosive nature, where traditional endurance training metrics, such as heart rate, speed, or power output, may fail to capture the hemodynamic stress induced by the demands of team, skill, and/or strength sports. It is also worth highlighting that there is no unified agreement on the best framework to quantify training load.[16,28] We used the FITT framework because it is simple but clear, and it is used broadly across sports science and exercise physiology[16] and endorsed in recent sports cardiology guidelines.[2,11] However, we acknowledge that other models of training load quantification may provide different or complementary insights. Studies were also limited to those in English, and at least some of the included studies were performed before some of the wearable technology (such as GPS watches or power meters) was accessible or affordable to the populations of interest.

Conclusion

Our review highlights significant limitations in the quantification of endurance training load within the field of sports cardiology. Many studies have relied on subjective or incomplete methods, with a lack of uniformity in the assessment of key FITT variables. As sports cardiology moves into an era of precision medicine, improving training load quantification is crucial for understanding the dose-response relationship between endurance exercise and cardiovascular outcomes. This could be achieved by using the FITT framework in the quantification of training load to ensure all components are measured. Also, integrating historic approaches (questionnaires, athlete interviews) with objective data from wearable technology and advanced training management software provides a more wholistic and objective means to do so.

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Ethics Statement

The research reported has adhered to the relevant ethical guidelines.

Patient Consent

This was a systematic review of previously published, deidentified data, so patient consent was not required for this review.

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Disclosures

None.

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Supplementary Material

To access the supplementary material accompanying this article, visit the online version of the *Canadian Journal of Cardiology* at www.onlinecjc.ca and at https://doi.org/10.1016/j.cjca.2024.12.009.