The proportional distribution of training at different intensities during different phases of the season by elite athletes participating in a variety of endurance sports

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For correspondence: billy.sperlich@uni-wuerzburg.com

Billy Sperlich[1], Manuel Matzka[1] and Hans-Christer Holmberg[2,3]

[1]Integrative and Experimental Training Science, Institute of Sport Sciences, University of Würzburg, Germany, [2]Department of Physiology and Pharmacology, Biomedicum C5, Karolinska Institute, Stockholm, Sweden, [3]Department of Health Sciences, Luleå University of Technology, Luleå, Sweden

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Authors B. Sperlich @BillySperlich, M. Matzka @manuelmatzka and H.C. Holmberg @HCHolmberg1 can be reached on Twitter.

ABSTRACT

This review covers the scientific literature concerning the relative amounts of low-, moderate- and high-intensity training, quantified by different methods, performed by elite (Tier 4) and world-class (Tier 5) athletes participating in a variety of endurance sports during different phases of the season. Information was obtained through a non-systematic search of PubMed for relevant retrospective reports on the distribution of training (TID).

The 34 articles retrieved yielded 175 TIDs, of which 120 involved quantifications on the basis of heart rate, time-in-zone or variations of the session goal approach, with demarcation of zones of exercise intensity utilizing physiological parameters. Next most common (n=37) was the use of velocity or power output as extrinsic parameters of quantification, followed by demarcation of zones on the basis of racing pace, i.e., velocity (n=14). Two studies employed ratings of perceived exertion to quantify TID. Of the TIDs identified, 85 (49%) involved single-case reports, of which 57 (67%) concerned cross-country skiing or the biathlon. Eighty-nine were pyramidal and 8 emphasized the threshold. Overall, 65 were polarized, of which 34 (52%) were derived from single-case reports on cross-country skiers or biathletes.

With respect to training by elite and world-class athletes in all endurance disciplines, 91% (n=160) of the TIDs involved >60% low-intensity endurance exercise. Independent of the method of quantification, the relative amount of time spent in the different zones of exercise intensity varied widely between sports and different phases of the season.

Key Words: blood lactate levels; cardiovascular responses; critical power; endurance sports; exercise intensity zones; exercise intensity; external load; low-intensity exercise; heart rate; internal load; metabolic responses; neuromuscular adaptation; physiological adaptation; psychological adaptation; rating of perceived exertion; strength training; training volume; wearables

INTRODUCTION

Development of the physiological, neuromuscular, and psychological attributes necessary to compete in elite endurance sports requires considerable preparation over a period of several years. Among the several approaches employed to achieve optimal adaptation, appropriate levels and distribution of the intensity, volume, and frequency of training sessions is a prerequisite for success [1].

The total annual volume of training by male and female endurance athletes ranges from 450 to >1000 h/year [2-4], with the relative amounts of semi- and non-specific training depending on the type of sport and the nature and schedule of competitions involved. The training characteristics that differ most include the following:

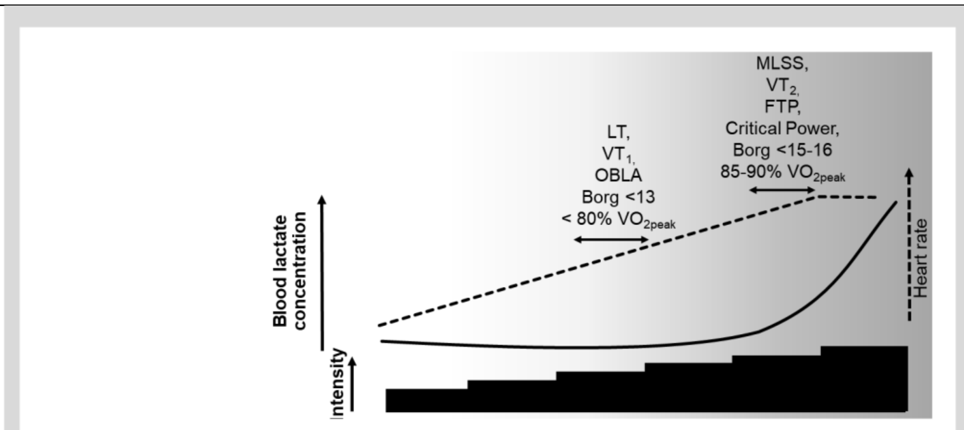
i) the amount of specific, semi-specific (e.g., on a kayak ergometer in the case of kayakers) and non-specific training (e.g., cycling by speed skaters);
ii) the mode of exercise (e.g., swimmers who specialize in the butterfly or breaststroke and cross-country skiers who utilize the different classical and skating techniques);
iii) the major muscle groups (e.g., lower-body, upper-body, or whole-body) focused on;
iv) the type of muscle contraction primarily involved, i.e., concentric, eccentric, and/or isometric;
v) the overall biomechanical load, which can be weight-bearing or not and influence the intensity and duration of training significantly;
vi) the external resistance arising from the terrain (uphill or on different surfaces, such as grass, sand, pavement, etc.), fluid and air dynamics;
vii) the ambient conditions employed, such as hypoxia, hyperoxia, or heat training, which can affect physiological adaptations to exercise;
viii) combining different types of strength, power, and speed training, which can enhance neuromuscular coordination and improve the efficiency of movement; and
ix) the relative amounts of low (with blood lactate levels <2 mmol/L) , moderate- (2-4 mmol/L) and high-intensity exercise (>3-4 mmol/L), which can affect metabolic and cardiovascular responses [5].

To optimize the relative amounts of specific and non-specific training and, thereby, physiological adaptations and performance, coaches and athletes must take all these factors into careful consideration.

In addition, when planning the total volume of training, the intensity must be increased carefully in order to further optimize key physiological, biomechanical, and psychological responses [5-8]. In this context numerous researchers, coaches and sport federations have defined different levels of exercise intensity either on the basis of internal (e.g., heart rate and blood lactate levels) [9-20] or external indicators of load (e.g., power output and race-pace) [20-28].

Internal indicators of load as a basis for defining exercise intensity.

Methodological advancements in testing have enabled identification of several physiological markers of exercise intensity, ranging from predominantly aerobic to anaerobic, including ventilatory parameters [29, 30], levels of blood lactate [31-37], and heart rate [38] (Figure 1). These markers have provided a basis for defining different zones of training intensity, which vary for different sports and modes of exercise. Sometimes, sport federations recommend a certain model, often involving 5 or 7 different zones of exercise intensity, in order to simplify the terminology employed in connection with coaching and assessment. As also illustrated in Figure 1, 3-, 5- and 7-zone models utilize numerous different parameters for categorization [39-41].



Domain	moderate low / heavy medium / severe high
3-zone model	Zone 1 Zone 2 Zone 3
5-zone model	Z1 Z2 Z3 Z4 Z5
7-zone model	Z1 Z2 Z3 Z4 Z5 Z6 Z7
% HR_{max} [%]	50 65-72 72-80 80-85 92-100
Blood lactate [mmol/L]	<1.5 1.5-2.5 2.0-4.0 3.0-6.0 >6.0
% VO_{2max} [%]	55-69 70-79 80-84 85-89 90-100
Perceived exertion [Borg 1-10]	1 2 3 4 5 6 7 8 9 10
Perceived exertion [Borg 6-20]	8 9 10 11 12 13 14 15 16 17 18 19 20

Figure 1. The classification of zones and associated physiological adaptations associated with a model that distinguishes between moderate, heavy, and very heavy exercise intensity [31, 42-47]. LT1 = first lactate threshold, LT2 = second lactate threshold, VT1 = first ventilatory threshold, VT2 = second ventilatory threshold, OBLA = Onset of Blood Lactate Accumulation, VO2peak = peak oxygen consumption, MLSS = maximal lactate steady-state, FTP = functional threshold power, Borg = perceived extent of exertion on the Borg 1-10 and 6-20 scales.

In connection with training for certain sports, such as track cycling where the ambient conditions are more or less constant, a 7-zone model may allow fine-tuning of the exercise intensity. In contrast, conditions (terrain, snow, wind, and technique) during cross-country skiing vary considerably and a more “flexible” 5-zone model may be more appropriate. For simplicity and to facilitate comparisons, a 3-zone model (moderate, heavy, and severe intensity) with demarcations based primarily on physiological parameters (Figure 1) is employed most often in research designed, e.g., to assess the dose-response relationship between intensity and adaptation/outcome. Independent of the model adopted, it is important to be aware that for certain sports, such as the triathlon, the optimal targeted intensity, as well as the relative amounts of non- or semi-specific training, may vary for every individual discipline.

In addition to monitoring physiological parameters, in practice subjective rating of perceived exertion (RPE) is employed as a valid and simple tool for monitoring and prescribing different exercise intensities (Figure 1; [40, 48-50]).

External parameters as a basis for defining exercise intensity.

For practical reasons, particularly during the season of competition and in connection with training sessions designed specifically to improve competitive performance, it is also common to design training on the basis of the racing pace targeted by each individual athlete [9, 21-23, 51]. For instance, in the case of running, the domains of exercise intensity are defined as moderate = <85% of this target pace, heavy = 85-95%, and severe = >95%. In their studies of middle- and long-distance runners, Kenneally and co-workers [21, 22, 51] were the first to implement this approach for quantification of exercise intensity in a research setting.

The reasoning underlying this approach is that both internal (e.g., the central nervous system, biomechanical characteristics, and cardiopulmonary system of the athlete) and external factors (e.g., ambient conditions and the strategy employed during competition) influence performance and, therefore, laboratory measurements of physiological parameters on their own are not accurate indicators of competitive performance [21]. Nonetheless, previous comparisons have revealed good interindividual agreement between assessment of exercise intensity based on racing pace and physiological measures [21-23]. However, this does not necessarily mean that the approach based on racing pace, with its own shortcomings, is valid [23]. For example, as with all external parameters, the actual intensity at any given pace is influenced by ambient conditions such as altitude, wind, and surface conditions, as well as, in the case of aquatic sports performed outdoors (e.g., kayaking, rowing, open-water swimming), stream velocity, waves and the depth and temperature of the water. Moreover, an individual´s racing pace may vary considerably and should consequently be assessed frequently.

Relative amounts of training at different intensities

Both researchers and practitioners divide exercise intensity into different zones in order to quantify and prescribe the relative amounts of training in these zones during a single training session, mesocycle, macrocycle, or entire season. Although several multizone models exist, the three zones i.e., Zone 1 (Z1; low intensity), Z2 (moderate intensity), and Z3 (heavy intensity) is often employed for scientific purpose, with the distribution of exercise between these zones being quantified in terms of the time spent in each.

Many different TIDs may be designed and executed by endurance athletes and their coaches and, indeed, numerous patterns have been investigated [38]. Among high- to elite-level athletes in many endurance sports, the pyramidal and polarized distributions, both of which involve spending 60-90% of training time in Z1, are currently most widely discussed and thoroughly characterized. The pyramidal pattern involves relatively more time or sessions in Z2 than in Z3 (Z1 > Z2 > Z3) than the polarized pattern (Z1 > Z3 > Z2). Among these TIDs studied by researchers, there is considerable variation in the relative amount of time spent in each individual zone and they are not always readily distinguishable. Therefore, to establish clarity, Treff and colleagues [52] have proposed a so-called Polarization-Index calculated as follows:

*Polarization Index (in arbitrary units) = log 10(Z1/Z2 * Z3 * 100)*

where Z represents the amount of time spent in each zone. Only TIDs with values > 2.0 are considered polarized.

Approaches to quantification

In connection with analyzing and prescribing a TID, the method utilized for quantification must be taken into consideration. The methods currently available are essentially based on four different types of data, i.e., i) intrinsic parameters (e.g., heart rate, blood levels of lactate, ventilatory parameters); ii) extrinsic parameters (e.g., velocity, power output); iii) subjective variables (e.g., RPE); and iv) measures based on competitive performance (e.g., % of racing pace) (see Table 1 for a comprehensive summary).

Table 1. Methods for quantifying the TID on the basis of intrinsic and extrinsic variables.

Load	Method of Quantification	Variable	Abbreviation	Unit	References
Intrinsic	Heart rate time-in-zone	Heart rate	HR-TiZ	Time	[10, 11, 24, 53]
	Heart rate session goal	Heart rate	SGSession	Number of sessions	[15, 16, 53, 54]
	Heart rate session goal - total time/session		SGTime	Time	[49]
	Heart rate session goal/time-in-zone	Heart rate	HR-TiZ/SG	Time	[15, 16, 39]
	Session RPE	Subjective	sRPE	Number of sessions	[49]
	RPE time-in-zone	Subjective	RPE-TiZ	Time	[49]
Extrinsic	Velocity time-in-zone	Velocity	V-TiZ	Time	[12, 17, 21, 22, 25, 26]
	Power time-in-zone	Power	PO-TiZ	Time	[20, 24, 55]
	Race pace time-in-zone	Competitive performance	RP-TiZ	Time	[21, 22]

Despite the validity of each individual method, empirical evidence demonstrates unequivocally that the TID obtained is heavily dependent on the method employed, as observed by researchers focusing on a variety of sports, including running [9, 21, 56], cross-country skiing [40], cycling [14, 57-59], swimming [49], rowing [60] and kayaking [23].

Clearly, the suitability of each individual method for specific purposes must be carefully evaluated. For instance, when the primary objective of training is to induce specific physiological adaptations, heart rate or blood levels of lactate may serve as a valid basis for defining zones of exercise intensity, particularly in connection with sessions at lower to moderate intensities (Z1, Z2) [23, 61-65]. On the other hand, when utilizing higher intensity exercise, velocity and/or power may provide a more suitable basis [23, 61, 62], especially in light of the relatively slow kinetic of heart rate during exercise of rapidly varying intensity or the cardiac drift during prolonged exercise [61, 62].

In addition, when attempting to improve racing pace, it would appear desirable to structure and analyze training sessions on the basis of actual race performance. Since optimal race performance depends on utilization of various physiological capabilities, the training needs of different individuals, even those training for the same event, may vary considerably. In addition, intensity based on racing pace must be adjusted frequently, since an individual's level of performance varies continuously. In this context, even though physiologically based measures may not be ideal for improving race-specific performance, they remain valuable for identifying potential areas for individual improvement.

Currently, as reflected in recent publications [66-68], the topic of optimal patterns of TID for endurance athletes is being fervently debated. In 2015, Stöggl and Sperlich [5] wrote a comprehensive review of the literature then available on retrospective analysis of TID in connection with various endurance sports and phases of the season, but without taking the method utilized for quantification into consideration. Since then, numerous analyses, both prospective and retrospective, of relevance to the assessment of TID by athletes participating in diverse sports have appeared [13, 15, 16, 20-22, 24, 27, 28, 55, 58, 69, 70].

In the present overview, we examine the existing literature on retrospective analysis of TID by elite endurance athletes, taking especially into consideration the different methods employed for quantification, sport disciplines, and phases of the season. In addition to summarizing findings to date and thereby identifying typical patterns of TID associated with different sports, we discuss potential future implications for research in this field, as well as for training by elite endurance athletes.

METHOD

The articles discussed here were retrieved through a non-systematic search of PubMed (last search on February 5, 2023) utilizing various combinations of search terms such as "training intensity distribution," "TID," "training intensity," "endurance training," "training characteristics," "endurance," "training," and "athletes." Furthermore, the reference lists of the articles retrieved were scrutinized for additional publications that might be of relevance. The criteria for inclusion were as follows:

Only peer-reviewed research articles in English that described investigations of the TID based on intrinsic (e.g., heart rate), extrinsic (e.g., velocity, power) and/or subjective (e.g., rating of perceived exertion) parameters.

Only studies involving endurance athletes categorized (according to the framework provide by McKay et al. [71]) as elite or competing at the international (Tier 4) and/or World Class (Tier 5) level.

Since the five prospective experimental studies identified [72-76] entailed altering the typical training and daily routine of the athletes involved considerably, these were excluded.

In each article reviewed, we searched for data concerning the TID that were expressed either as percentages or absolute numbers. When the data were presented in figures, we utilized the WebPlotDigitizer program (https://automeris.io/WebPlotDigitizer/) to obtain the actual values by comparing the pixel length of the relevant axis to the distance to the value of interest [77]. The different methods for evaluating TID were categorized as summarized in Table 1.

When a study involved the use of more than one method to quantify the TID, each method was considered separately. If the TIDs for different phases of training were presented separately, the TID for each phase, categorized as the preparatory phase or competition phase, was considered individually. Whenever possible, the preparatory phase was further subdivided into specific sub-phases where the general preparatory phase and the specific preparatory phase where considered individually if possible and the competition phase was further subdivided into the pre-competition and main competition phase if possible (cf. [78] and see Figure 3 for details). Three studies provided data collected in connection with training camps at elevated altitude and these phases were categorized as preparatory [15, 53, 69].

The TID was classified as seasonal if it concerned one entire season (which is typically 45-52 weeks in duration) or multiple seasons (e.g., the 5 most successful seasons). In addition, in the case of sports with more than one season of competition each year, a TID for a full cycle of training, from the preparatory phase to the competition phase (approximately 26 weeks), was also considered seasonal. Moreover, in cases where the subjects were subdivided on the basis of factors such as long-distance versus middle-distance, sex, or responders versus non-responders, each category was considered separately.

In the case of articles which did not present the TID in terms of the three-zone model [40], we attempted to convert the data to this model. For instance, Mujika and colleagues [12] employed a five-zone model, where Z3, Z4, and Z5 all involved intensities above the anaerobic threshold (i.e., blood lactate levels > 4 mmol/L). In this and other such cases, the data from these three zones were combined and considered to represent Z3 of the three-zone model [40].

The TIDs were categorized as follows: (1) “polarized” when Z1 > Z3 > Z2 and the Polarization Index was > 2.0; (2) “pyramidal” when Z1 > Z2 > Z3; (3) “threshold” when Z2 > Z1 > Z3; (4) “Z2+Z3 even” when there was no difference in the amount of time spent in Z2 and Z3; (5) “no Z3” in the case of two-zone models with Z1 > Z2; and (6) “other” for any other pattern.

Results

Study characteristics

Our search of the scientific literature dealing with retrospective quantification of TID yielded 34 articles involving 437 elite athletes (see Figure 2).

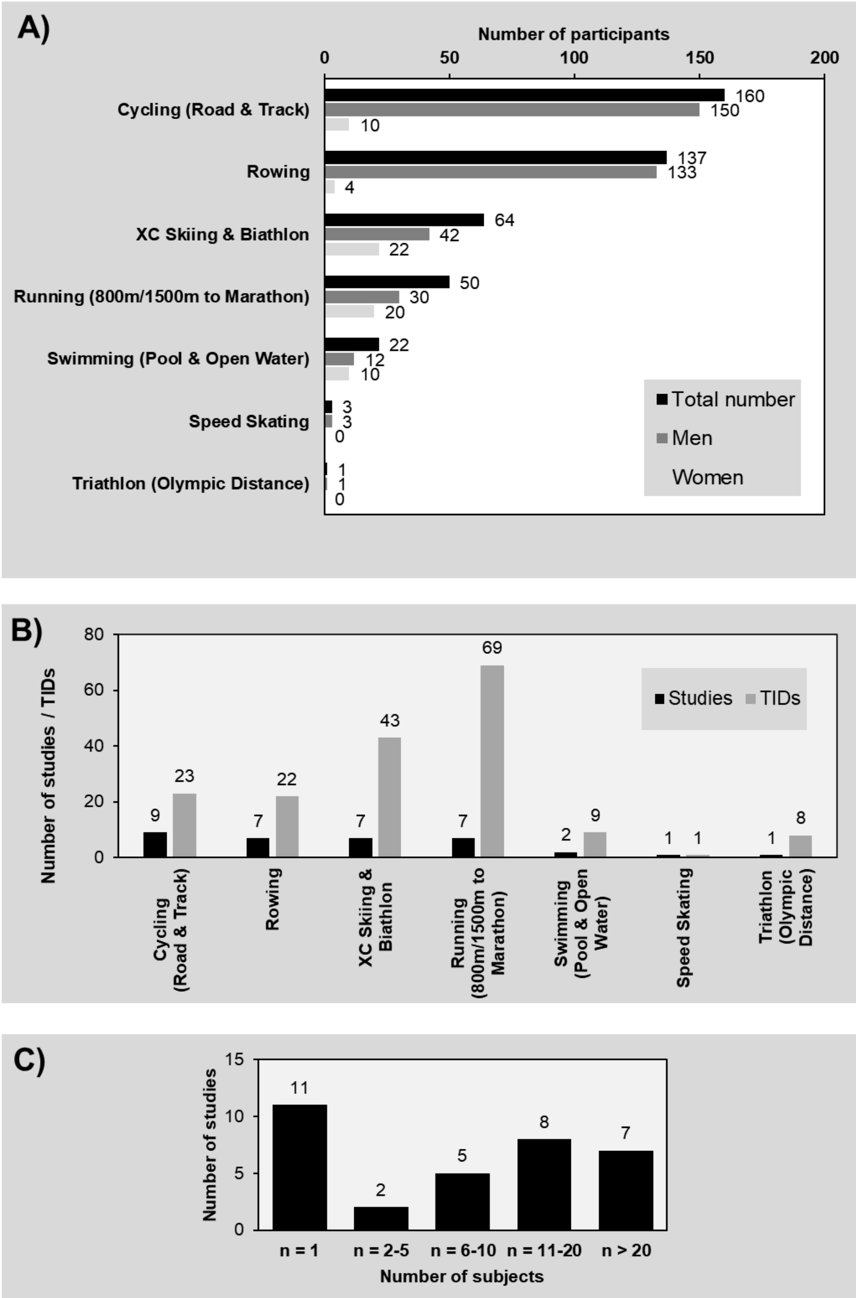


Figure 2. A) The sporting disciplines and numbers of participants involved in the studies retrieved. B) The number of investigations on and TIDs reported for each individual sport. C) The sizes of the study populations involved in the studies retrieved.

Eleven single-case analyses [13, 15, 16, 18, 20, 22, 55, 69, 79-81] reported 85 TIDs (including 57 TIDs from cross-country skiing and biathlon); two studies involving 2-5 athletes reported 7 TIDs [39, 49]; 5 observations involving 6-10 athletes reported 28 TIDs [14, 17, 21, 54, 60]; 8 studies involving 11-20 subjects reported 27 TIDs [12, 19, 25, 26, 57, 59, 82]; and 8 investigations with n>20 reported 28 TIDs [10, 24, 27, 28, 41, 53, 83, 84]. The mean age of all athletes involved was 26±4 years (with 5 articles not providing this information).

In total, the TIDs for 437 athletes (371 men and 66 women) participating in different endurance sports were reported. Altogether, 175 of these TIDs could be categorized as being associated with specific phases of the season, different methods of quantification and/or different sub-groups.

In all but two studies [17, 41], a three-zone TID could be extracted or constructed. Those two provided information that could only be classified as Z1 and Z3.

Figure 3 illustrates the TID values connected with the various sports, methods of quantification and phases of the season.

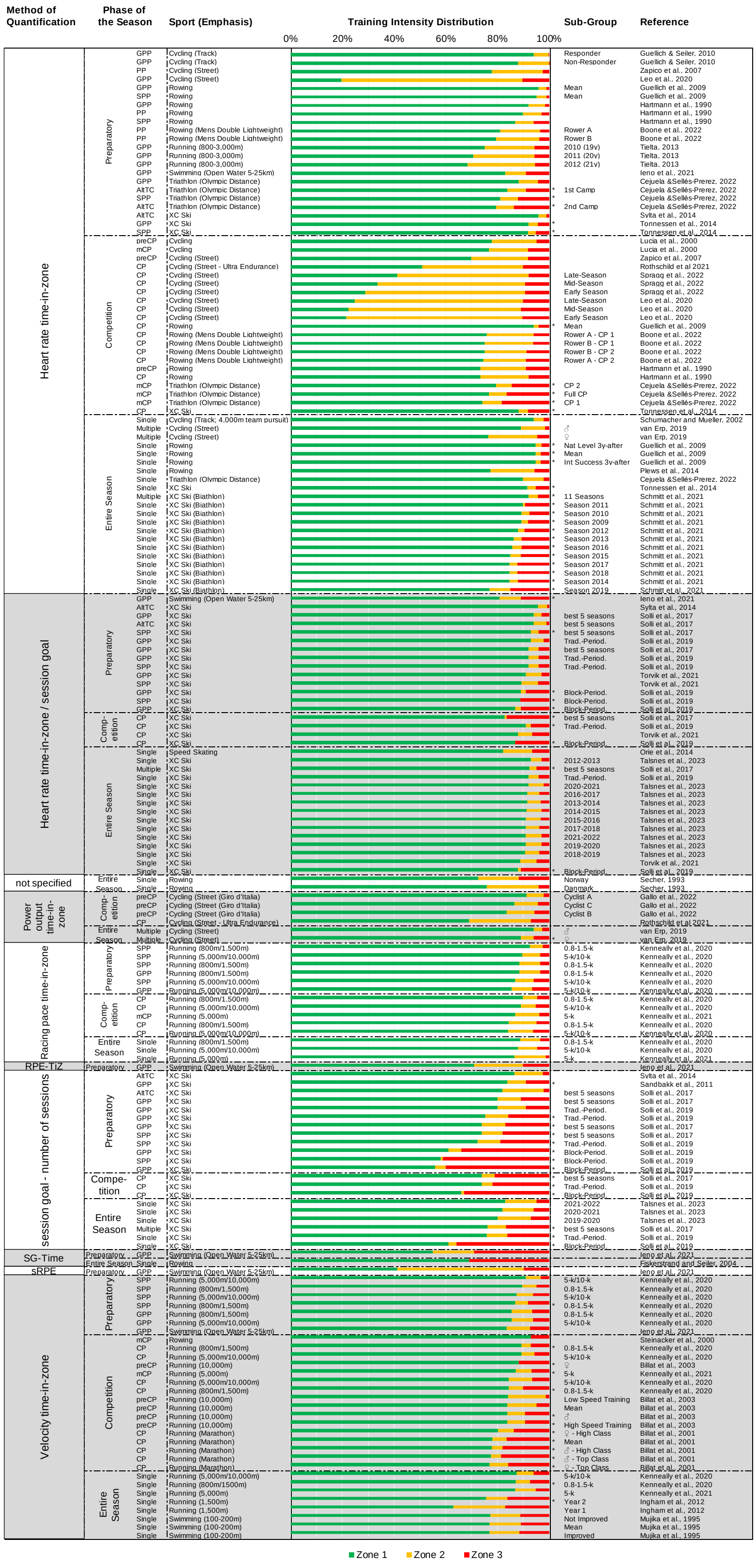
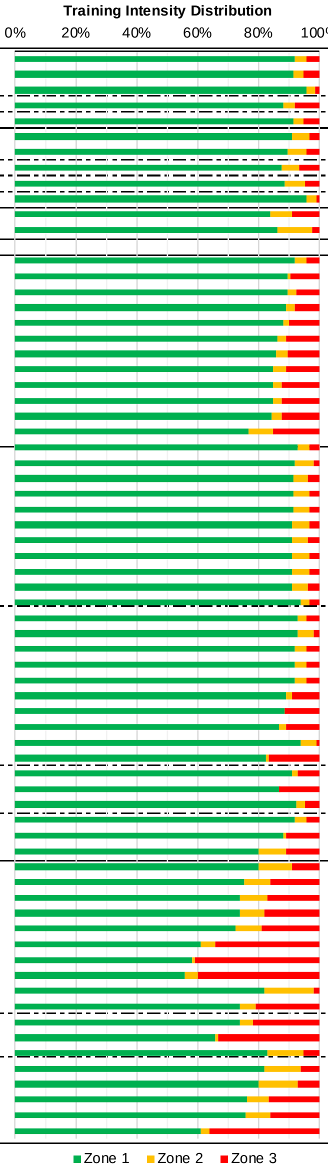


Figure 3a. The distributions of training intensity reported categorized on the basis of (1) method of quantification, (2) phase of the season, (3) sport, and (4) proportion of time spent in Zone 1. SG-Time = Heart rate session goal – Total time/session, sRPE = Session rating of perceived exertion, RPE-TiZ = RPE time-in-zone, CP = Competition phase, GPP = General Preparatory Phase; SPP = Specific preparatory phase, PP = Entire preparatory phase, ♀ = female, ♂ = male, * = polarized training intensity distribution.



Method of Quantification	Phase of the Season		Polarization Index	n	Wks	Sub-Group	Volume	Reference
n > 1								
HR-TiZ	Preparatory	GPP	2.03	11	18		73 hrs/mo	Tonnessen et al., 2014
		SPP	2.17	11	9		69 hrs/mo	Tonnessen et al., 2014
		AltTC	1.56	29	2		38.2 hrs	Sylta et al., 2014
	Competition	CP	2.30	11	13		48 hrs/mo	Tonnessen et al., 2014
	Entire Season	Single	2.17	11	52		724 hrs (94%)	Tonnessen et al., 2014
HR-TiZ/SG	Preparatory	GPP	1.69	12	16		85 hrs/mo	Torvik et al., 2021
		SPP	1.80	12	12		87 hrs/mo	Torvik et al., 2021
	Competition	CP	1.99	12	20		38.2 hrs	Torvik et al., 2021
	Entire Season	Single	1.82	12	30		75 hrs/mo	Torvik et al., 2021
	Preparatory	AltTC	1.33	29	2		795 hrs (92%)	Sylta et al., 2014
SG	Preparatory	GPP	2.03	8	26		404 hrs (91%)	Sandbakk et al., 2011
		AltTC	1.27	29	2		38.2 hrs	Sylta et al., 2014
n = 1								
HR-TiZ	Entire Season	Multiple	2.03	1	52	11 Seasons	585 hrs (92%)	Schmitt et al., 2021
		Single	3.03	1	52	Season 2011	597 hrs (87%)	Schmitt et al., 2021
		Single	2.39	1	52	Season 2010	632 hrs (91%)	Schmitt et al., 2021
		Single	2.45	1	52	Season 2009	632 hrs (90%)	Schmitt et al., 2021
		Single	2.58	1	52	Season 2012	634 hrs (92%)	Schmitt et al., 2021
		Single	2.51	1	52	Season 2013	571 hrs (92%)	Schmitt et al., 2021
		Single	2.40	1	52	Season 2016	627 hrs (92%)	Schmitt et al., 2021
		Single	2.37	1	52	Season 2015	592 hrs (93%)	Schmitt et al., 2021
		Single	2.55	1	52	Season 2017	577 hrs (94%)	Schmitt et al., 2021
		Single	2.55	1	52	Season 2018	548 hrs (94%)	Schmitt et al., 2021
		Single	2.48	1	52	Season 2014	534 hrs (95%)	Schmitt et al., 2021
		Single	2.16	1	52	Season 2019	500 hrs (94%)	Schmitt et al., 2021
HR-TiZ/SG	Entire Season	Single	1.86	1	47	2012-2013	16 hrs/wk	Talsnes et al., 2023
		Single	1.49	1	47	2020-2021	20 hrs/wk	Talsnes et al., 2023
		Single	1.85	1	47	2016-2017	21 hrs/wk	Talsnes et al., 2023
		Single	1.76	1	47	2013-2014	17 hrs/wk	Talsnes et al., 2023
		Single	1.71	1	47	2014-2015	19 hrs/wk	Talsnes et al., 2023
		Single	1.74	1	47	2015-2016	19 hrs/wk	Talsnes et al., 2023
		Single	1.85	1	47	2017-2018	19 hrs/wk	Talsnes et al., 2023
		Single	1.66	1	47	2021-2022	21 hrs/wk	Talsnes et al., 2023
		Single	1.66	1	47	2019-2020	21 hrs/wk	Talsnes et al., 2023
		Single	1.82	1	47	2018-2019	21 hrs/wk	Talsnes et al., 2023
	Preparatory	GPP	1.97	1	13	best 5 seasons	18.3 hrs/wk	Solli et al., 2017
		SPP	2.09	1	9	best 5 seasons	18.5 hrs/wk	Solli et al., 2017
		GPP	1.57	1	13	Trad.-Period.	16.9 hrs/wk	Solli et al., 2019
		GPP	1.96	1	13	best 5 seasons	19.4 hrs/wk	Solli et al., 2017
		GPP	1.96	1	13	Trad.-Period.	19.2 hrs/wk	Solli et al., 2019
		SPP	1.96	1	9	Trad.-Period.	17.2 hrs/wk	Solli et al., 2019
		GPP	2.60	1	13	Block-Period.	17.9 hrs/wk	Solli et al., 2019
		SPP	3.99	1	9	Block-Period.	15.1 hrs/wk	Solli et al., 2019
		GPP	2.68	1	13	Block-Period.	17.6 hrs/wk	Solli et al., 2019
		AltTC	1.27	1	2	best 5 seasons	26.1 hrs/wk	Solli et al., 2017
	Competition	CP	3.21	1	13	best 5 seasons	12.8 hrs/wk	Solli et al., 2017
		CP	2.50	1	13	Trad.-Period.	14.0 hrs/wk	Solli et al., 2019
		CP	4.05	1	13	Block-Period.	9.3 hrs/wk	Solli et al., 2019
	Entire Season	Multiple	2.18	1	52	best 5 seasons	849 hrs (91%)	Solli et al., 2017
		Single	1.96	1	52	Trad.-Period.	836 hrs (89%)	Solli et al., 2019
		Single	2.99	1	52	Block-Period.	746 hrs (94%)	Solli et al., 2019
SG-Session	Preparatory	GPP	1.99	1	13	best 5 seasons	18.5 hrs/wk	Solli et al., 2017
		GPP	1.82	1	13	Trad.-Period.	18.3 hrs/wk	Solli et al., 2019
		GPP	2.13	1	13	Trad.-Period.	19.2 hrs/wk	Solli et al., 2019
		GPP	2.15	1	13	best 5 seasons	19.4 hrs/wk	Solli et al., 2017
		SPP	2.22	1	9	best 5 seasons	16.9 hrs/wk	Solli et al., 2017
		SPP	2.19	1	9	Trad.-Period.	17.2 hrs/wk	Solli et al., 2019
		GPP	2.62	1	13	Block-Period.	17.9 hrs/wk	Solli et al., 2019
		SPP	3.38	1	9	Block-Period.	15.1 hrs/wk	Solli et al., 2019
		GPP	2.75	1	13	Block-Period.	17.6 hrs/wk	Solli et al., 2019
		AltTC	1.01	1	2	best 5 seasons	26.1 hrs/wk	Solli et al., 2017
	Competition	CP	2.49	1	13	best 5 seasons	14.0 hrs/wk	Solli et al., 2017
		CP	2.61	1	13	Trad.-Period.	12.8 hrs/wk	Solli et al., 2019
		CP	3.34	1	13	Block-Period.	9.3 hrs/wk	Solli et al., 2019
	Entire Season	Single	1.54	1	47	2021-2022	21 hrs/wk	Talsnes et al., 2023
		Single	1.61	1	47	2020-2021	20 hrs/wk	Talsnes et al., 2023
		Single	1.63	1	47	2019-2020	21 hrs/wk	Talsnes et al., 2023
		Multiple	2.24	1	52	best 5 seasons	849 hrs (91%)	Solli et al., 2017
		Single	2.18	1	52	Trad.-Period.	836 hrs (89%)	Solli et al., 2019
		Single	2.86	1	52	Block-Period.	746 hrs (94%)	Solli et al., 2019

Figure 3b. Cross-country skiing and biathlon: Characterization of all the distributions of training intensity reported with respect to (1) method of quantification, (2) phase of the season, (3) proportion of time spent in each zone, (4) polarization index, (5) sample size, and (6) the period of observation.

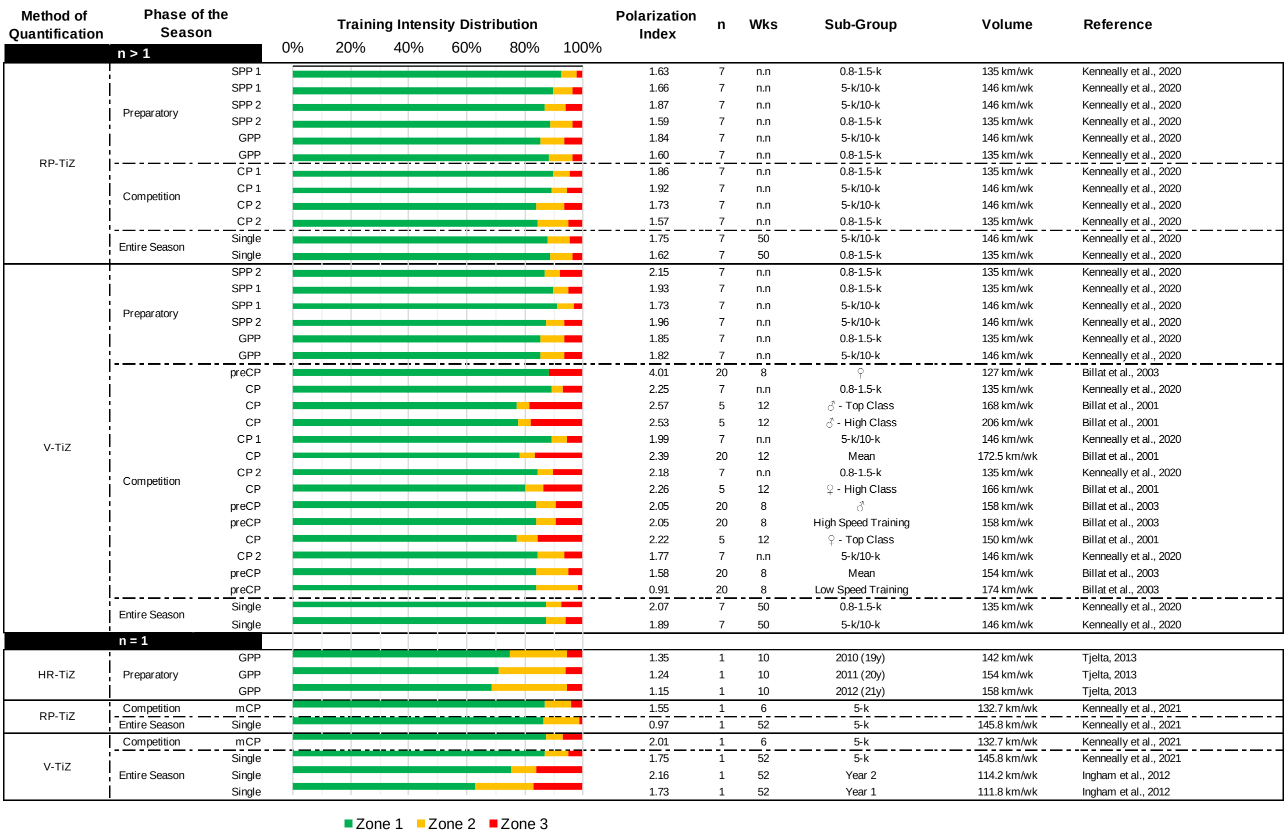


Figure 3c. Running: Characterization of all the distributions of training intensity reported with respect to (1) method of quantification, (2) phase of the season, (3) proportion of time spent in each zone, (4) polarization index, (5) sample size, and (6) the period of observation.

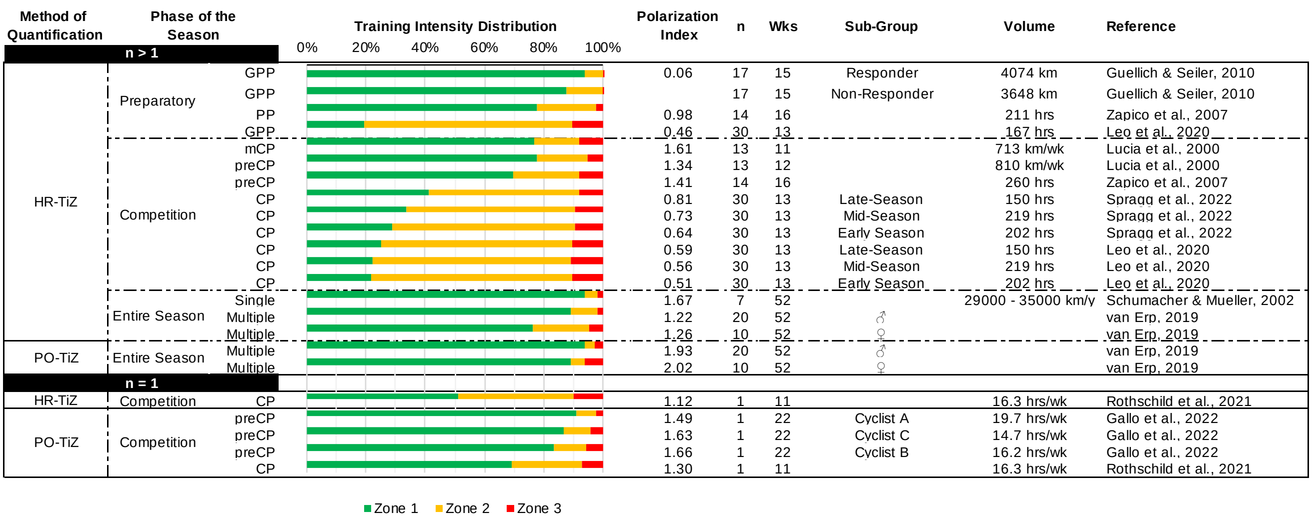


Figure 3d. Cycling: Characterization of all the distributions of training intensity reported with respect to (1) method of quantification, (2) phase of the season, (3) proportion of time spent in each zone, (4) polarization index, (5) sample size, and (6) the period of observation.

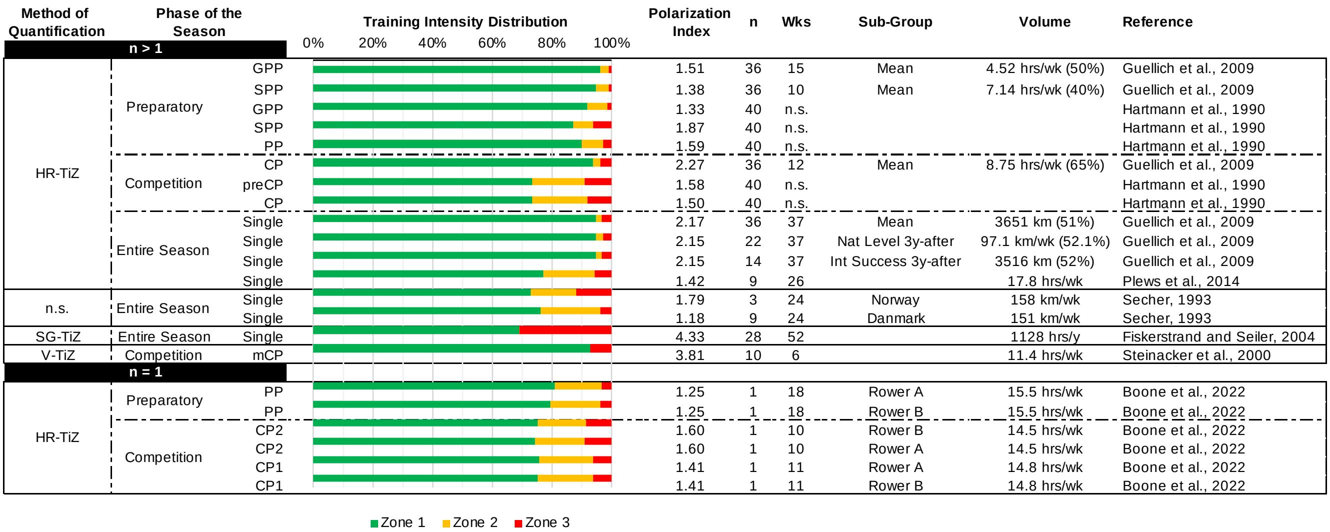


Figure 3e. Rowing: Characterization of all the distributions of training intensity reported with respect to (1) method of quantification, (2) phase of the season, (3) proportion of time spent in each zone, (4) polarization index, (5) sample size, and (6) the period of observation.

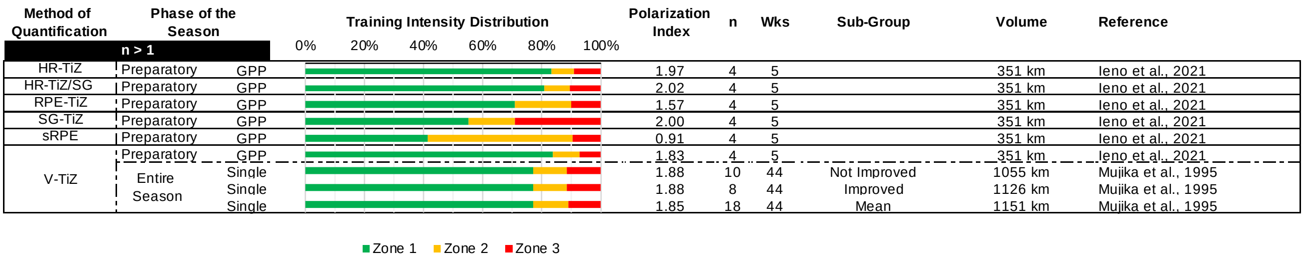


Figure 3f. Swimming: Characterization of all the distributions of training intensity reported with respect to (1) method of quantification, (2) phase of the season, (3) proportion of time spent in each zone, (4) polarization index, (5) sample size, and (6) the period of observation.

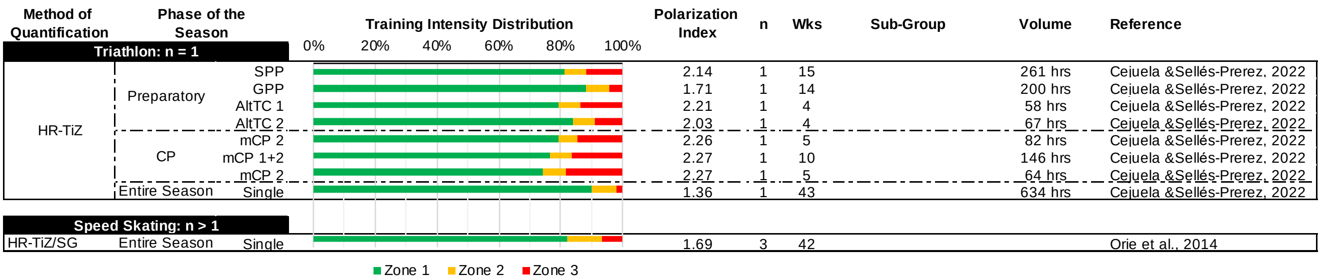


Figure 3g. Triathlon and Speed Skating: Characterization of all the distributions of training intensity reported with respect to (1) method of quantification, (2) phase of the season, (3) proportion of time spent in each zone, (4) polarization index, (5) sample size, and (6) the period of observation.

Sporting disciplines

TID values could be derived for tier 4 or 5 athletes competing in cycling (9 studies; [14, 20, 24, 27, 28, 55, 57, 59, 83]), rowing (7 studies; [10, 17, 41, 60, 79, 82, 84]), running (6 studies; [18, 21, 22, 25, 26, 80]), cross-country skiing (7 studies; [15, 16, 19, 53, 54, 81, 85]), swimming (2 studies; [49, 86]), the triathlon [69], ice speed skating [39], and the biathlon [13]).

The single-case reports concerned running [18, 22, 80], cross-country skiing [15, 16, 81], cycling [20, 55], the triathlon [69], and the biathlon [13]. In addition, in connection with one study in which the TIDs for the two rowers were analyzed individually, these were defined as single-case [79].

Different Phases of the Season

Of the 175 TIDs extracted, 51 involved an entire season and 7 multiple seasons. Fifty-seven were derived from the preparatory phase (4 for the entire preparatory phase, 34 for the general preparatory phase, and 19 for specific preparatory phase) and 53 from the competition phase (35 for this entire phase, 7 for the main phase, and 11 for the pre-competition phase). In addition, 7 TIDs were reported from training camps conducted at elevated altitude during preparatory phase.

Of the 85 single-case TIDs, 25 involved preparatory phases, 20 the competition phase, 36 the entire season and four training camps at elevated altitude.

Methods of Quantification

As documented in Figure 4, the 175 TIDs reported in the 34 studies analyzed here were categorized as employing one of 9 different methods of quantification (Table 1), with one study describing two TIDs [82] lacking this information.

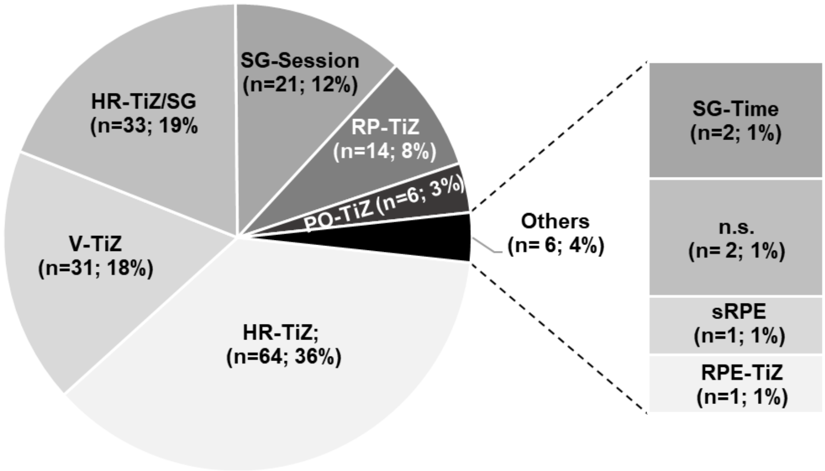


Figure 4. The different methods employed to quantify TID in the studies analyzed here. HR-TiZ = Heart rate time-in-zone, V-TiZ = Velocity time-in-zone, HR-TiZ/SG = Heart rate session goal / time-in-zone, SG-Session = Heart rate session goal – number of sessions, RP-TiZ = Race pace time-in-zone, PO-TiZ = Power time-in-zone, SG-Time = Heart rate session goal – total time/session, n.s. = not specified, sRPE = Session rating of perceived exertion, RPE-TiZ = RPE time-in-zone.

Overall, determination of 120 TIDs involved defining zones of exercise intensity on the basis of heart rate; 37 employed zones of velocity or power output as external parameters; 14 were based on racing pace; and two on subjective rating of perceived exertion.

Determination of 101 TIDs involved defining zones of exercise intensity on the basis of physiological benchmarks, including the actual time-in-zone for each session.

Eight articles included direct comparison of different methods for quantifying TID: two compared V-TiZ and RP-TiZ [21, 22]; two compared HR-TiZ and PO-TiZ [20, 24]; two compared HR-TiZ/SG and SG-Session [15, 16, 81]; one compared HR-TiZ, HR-TiZ/SG and SG-Session [53]; and one compared HR-TiZ, HR-TiZ/SG, sRPE, V-TiZ, SG-Time and RPE-TiZ [27] with one another.

Analysis of the TIDs.

Figure 3 illustrates comprehensively the TIDs associated with different sports, categorized on the basis of the number of athletes involved (group analysis or single-case reports), method of quantification, and phase of the season and also including the Polarization Index, number of subjects, duration of the study, and sub-group analysis. As shown, these TIDs varied considerably – the proportion of time spent in Z1 from 20-96% and in Z2 and Z3 0-70% and 0-41%, respectively. The median amount of time spent in each zone was 85%, 7%, 6% for Z1, Z2, and Z3, respectively.

Overall, 65 (37%) of the 175 TIDs demonstrated a Polarization Index > 2.0, with 42 (65%) being derived from single-case studies, of which 34 (52% of all polarized TIDs) involved cross-country skiing (n=22) and the biathlon (n=12). Eighty-nine (51%) of the 175 TIDs were pyramidal, of which 31 were derived from single-case reports. Table 2a and 2b highlight the percentages of each method of quantification with regards to pyramidal and polarized TIDs, as well as percentages of the total number of TIDs that were polarized or pyramidal with respect to each method of quantification.

Table 2a. Percentages of each method of quantification with respect to pyramidal (n=89) and polarized (n=65) TIDs.

Method of Quantification	Pyramidal	Method of Quantification	Polarized
Heart rate time-in-zone	34%	Heart rate time-in-zone	40%
Heart rate time-in-zone/session-goal	19%	Session goal - number of sessions	22%
Velocity time-in-zone	16%	Velocity time-in-zone	22%
Racing pace time-in-zone	16%	Heart rate time-in-zone/session-goal	15%
Session goal - number of sessions	7%	Power output time-in-zone	2%
Power output time-in-zone	6%	Session goal - total time/session	0%
RPE time-in-zone	1%	Racing pace time-in-zone	0%
Session goal - total time/session	0%	RPE time-in-zone	0%
Session RPE	0%	Session RPE	0%

Table 2b. Percentages of the total number of TIDs (in brackets) that were polarized or pyramidal with respect to each method of quantification

Method of Quantification	Pyramidal	Method of Quantification	Polarized
Racing pace time-in-zone	100% (14)	Session goal - number of sessions	67% (21)
RPE time-in-zone	100% (1)	Velocity time-in-zone	45% (31)
Power output time-in-zone	83% (6)	Heart rate time-in-zone/session-goal	30% (33)
Heart rate time-in-zone/session-goal	52% (33)	Heart rate time-in-zone	41% (64)
Heart rate time-in-zone	47% (64)	Power output time-in-zone	17% (6)
Velocity time-in-zone	45% (31)	Session goal - total time/session	0% (2)
Session goal - number of sessions	29% (21)	Racing pace time-in-zone	0% (14)
Session goal - total time/session	0% (2)	Session RPE	0% (1)
Session RPE	0% (1)	RPE time-in-zone	0% (1)

Independent of the method of quantification and phase of the season, 93% (n=163) of all the TIDs involved >60% of the time spent in Z1, 91% (n = 160) ≥65% of the time spent in this zone, 82% (n=144) ≥75% and 51% (n=89) ≥85%. With respect to Z2, 71% (n=124), 27% (n=48) and 8% (n=14) of all the TIDs involved ≥5%, ≥10% and ≥ 20% of the time spent in this zone, respectively. For Z3, ≥2.5%, ≥7.5% and ≥15% was spent in this zone in connection with 90% (n=157), 41% (n=72) and 19% (n=33) of the TIDs, respectively.

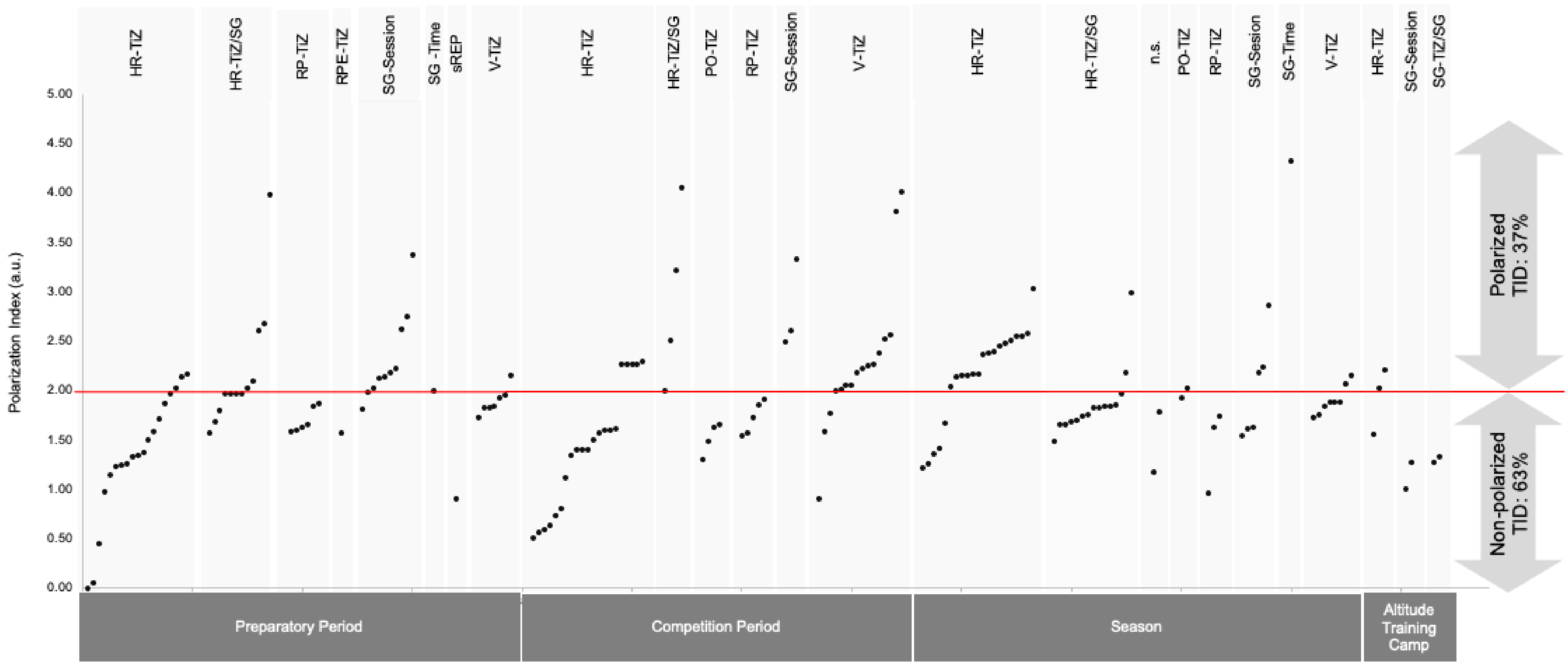


Figure 5. The Polarization Index derived from the articles analyzed and categorized on the basis of (1) phase of the season and (2) method of quantification.

Discussion

The major findings of the present analysis were as follows:

i) Most of the TIDs summarized here concerned skiing (cross-country and biathlon; n=69, 39%) or running (from 800/1500 m to the marathon, n=41, 23%)
ii) Quantification of most of the TIDs reported (120 of 175) was based on heart rate, with zone demarcations involving physiological benchmarks. Fewer were based on velocity or power output as extrinsic parameters, with zone demarcations involving physiological benchmarks (V-TiZ n=31; PO-TiZ n=6) or based on racing pace with zones defined by velocity (n=14).
iii) 85 (49%) of the 175 TIDs were obtained from single-case reports, of which 57 (67%) involved cross-country skiing/the biathlon.
iv) The relative amounts of time spent in Z1 (20-96%), Z2 (0-70%) and Z3 (0-41%) varied considerably between sports and different phases of the season. The median amount of time spent in each zone was 85%, 7%, 6% for Z1, Z2, and Z3, respectively (Figure 3).
v) 51% (n=89) of the 175 TIDs were pyramidal; 5% (n=8) threshold; 4% (n=7) with an equal amount of time spent in Z2 and Z3; 1% (n=2) with no distinction between Z2 and Z3; and 2% (n=4) classified as "others".
vi) Overall, 65 TIDs (37%) were associated with a Polarization Index of > 2.0, with 34 (52%) of these being obtained from single-case reports involving cross-country skiing (including the biathlon).
vii) Of the 65 TIDs with a PI > 2.0, 40% were derived from studies that defined zones of exercise intensity on the basis of HR-TiZ, 22% from studies utilizing SG-Session to define zones, 22% involving V-TiZ and 15% HR-TiZ/SG.

Since the first reports on this subject in the 1990s [12, 17, 82, 84, 87], there has been increasing interest in the TID for different sports, as reflected in numerous articles, both peer-reviewed and not, on world-class, elite, and amateur athletes. The initial interest probably arose from the belief that the distribution of training intensity may, at least in part, determine long-term physiological adaptations to exercise and, thereby, successful performance as an endurance athlete.

Traditionally, athletes have employed various combinations of training in Z1, Z2, and Z3, depending on their sport, training procedures (e.g., distance, fartlek, various types of interval training), the terrain and other aspects of the environment, training camps, their schedule of preliminary and actual competitions, and the training strategy/philosophy of their coach. As illustrated in Figures 3a-g, many coaches and/or athletes appear to utilize a high or very high proportion of Z1, with gradually less time being spent in Z2 and Z3. One reason for training primarily in the "fat-consuming" Z1 is that glycogen stores can be replenished during sessions of low-intensity endurance exercise between more intense workouts. Another reason, although not as well investigated, might be that extensive volumes of low-intensity endurance training are required for additional “aerobic” adaptations in the highly oxidative Type I fibers. Already in normally active individuals, these Type I fibers are well supported by O2-delivering capillaries, and they are rich in mitochondria that effectively utilize O2. Thus, highly sustained usage of these fibers might be required to further improve their aerobic capacity in elite endurance athletes, thereby improving their potential to consume the end-product of glycolysis during intense efforts [88]. Indeed, the aerobic contribution to the total amount of energy production is crucial to performance already after as little as one minute of exercise [89].

In fact, the present analysis revealed that 91% (n=160) of all the TIDs involved >60% low-intensity endurance exercise. In some sports this value was even >90%. Unfortunately, we cannot quantify the entire amount of time actually spent in Z1 for each sport, technique or phase of the season, but recent anecdotal reports by, among others, a highly successful speed skater [4], indicates that extensive time (per session, week and phase) is spent in Z1.

Since in connection with certain sports (e.g., marathon running), Z2 may already be close to racing pace, coaches may choose to emphasize training in this zone over, e.g., in Z3. However, because of the extensive variation in TIDs described here, no definitive conclusion about this potential preference can be drawn at present. Training sessions that primarily target Z2 are commonly referred to as "threshold training", because they involve an intensity around which the blood level of lactate begins to rise. One reason for focusing on Z2 may be the belief that this involves an exercise intensity that effectively improves most relevant physiological parameters without inducing excessive fatigue, allowing a rapid pace to be maintained for a long time.

Depending on the stage of the season, as well as their own personal training strategy, coaches may vary the relative amounts of training intensities. During the past two decades, extensive research has examined the distinct physiological responses and adaptations that result from high-intensity interval training, which entails alternating intervals of higher-intensity exercise (i.e., in Z3 or Z2) with periods of lower intensity (i.e., Z1). It is thought that spending more time at or above the anaerobic threshold in Z3 improves a variety of parameters that influence endurance performance [90], including maximum oxygen uptake (VO_{2max}), which is a key determinant of such performance [42, 43, 46, 91, 92]. However, it is important to remember that the optimal TID for each individual athlete will be influenced by individual factors such as training history, genetic characteristics, current level of fitness and many others (for further details, see [93]).

Previous studies have indicated that some elite endurance athletes tend to prioritize greater amounts of Z3 over Z2 during their mid- and long-term preparation, which differs from the traditional pyramidal TID [1, 13, 15, 16, 19, 25, 26, 40]. This distribution has been referred to as polarized TID, since Z1>Z3>Z2. One rationale for this approach is the assumption that more time spent in the high-intensity zone (Z3), with a more pronounced training stimulus, evokes more extensive physiological adaptations (i.e., maximization of adaptive signaling while minimizing hormonal and autonomic stress) that ultimately improve endurance performance [1, 94, 95]. In fact, of the 175 TID analyzed here, 65 had a Polarization Index >2.0, indicating that Z1>Z3>Z2.

However, it is important to highlight that many of the studies we analyzed here are single-case reports and, moreover, 34 (52%) of the 65 TIDs with a Polarization-Index >2.0 were associated with cross-country skiing and the biathlon. Single-case analysis allows in-depth monitoring of the individual athlete's response to training over time, which can provide valuable insights. However, since individual responses may vary greatly, the findings of single-case studies may not be generally applicable to other athletes participating in the same or other sports. In addition, we assume that in many cases, especially in reports on TIDs during the period of competition, the high-intensity exercise involved in preparation for competition and the competition itself was also included in these distributions. Since competitions are much more frequent in some sports, such as swimming or cycling, than in others, e.g., marathon running, there will be a tendency in the case of the former to report more time spent in Z3. Unfortunately, most studies do not report the type, amount and intensity of exercise during competitions, probably in part because in the case of some sports, chest belts or watches cannot be worn during competition.

Retroactive quantification of TID is descriptive, rather than explanatory

To more accurately understand the relationship between the TID and adaptations that improve performance, other factors, such as genetic characteristics, training history, and environmental conditions, must be taken into consideration. In particular, unfavorable ambient conditions, (rain, wind, high or low temperature) may lead to modification or cancelation of training sessions, thereby influencing the actual, as opposed to the planned TID. Clearly, it would be desirable to describe both the planned and actual TID.

Although retroactive quantification of TID reveals the relative amounts of time spent in different intensity zones during training, this analysis does not explain in detail the reasons for this distribution, which can limit its utility for practical decision-making. For instance, during the four-year training cycle of an elite female swimmer prior to the 2008 Olympics in Beijing (where she took fourth place in the 200-m butterfly competition), she actually performed only 84.8% of the pre-planned training volume [96]. In this case it remains unclear whether and/or how this influenced the overall TID and decisions about training.

Furthermore, it is questionable whether subsequent utilization of the same TID by the same athlete would result in the same adaptations as the first time around [97], as well as whether the TIDs of different athletes and athletes participating in different sports can be compared. Thus, training is now more often regarded as a dynamic and complex process, in contrast to the traditional linear and predictable "cause-effect" model [98].

Furthermore, the theory of periodization, like the dose-response relationship, is based on reductionistic models, e.g., the general assumption that a given stressor will lead to a predictable physiological response [98], even though, as mentioned above, the response of different individuals to the same stressor varies considerably [99]. Several studies have highlighted this extensive variability [100-104].

Improving analysis of the TID by taking all daily activities into consideration

It is clear that adaptation to structured training procedures can be either enhanced or attenuated by other, “off-training” daily activities [105], including, among many other things, unstructured free-time activities, nutritional strategies, recovery procedures, and sleep [105, 106]. For example, Treff and co-workers [106] have demonstrated that both the training and off-training activities of elite rowers significantly influenced their total training volume and TID. At the same time, under some circumstances, such as during stays in training camps at elevated altitude, the daily lives of athletes are more standardized, perhaps allowing more reliable evaluation of certain dose-response or cause-effect relationships. Rapid developments in the field of wearable sensor technology along with the application of diverse analytical frameworks [107, 108] have enabled more accurate analysis of both training load and off-training activities, potentially providing a more holistic understanding of the relationship between training and endurance performance.

Variations in the TID between different sports

The TID has been found to be influenced by a variety of sport-specific features, including the muscle mass (lower-, upper-, or whole-body) primarily involved in locomotion [68], the most frequent type of muscle contraction (concentric, concentric-eccentric) [109, 110], overall biomechanical loading (weight-bearing or non-weight-bearing) [93, 110], environmental conditions (such as hypoxia, hyperoxia, or heat) [105], incorporation of strength training [68], and the relative amounts of moderate- (blood lactate level 2-4 mmol/L) and high-intensity exercise (>3-4 mmol/L) [93]. Since different endurance sports differ with respect to many of these features, comparisons should be avoided. For instance, particularly during the preparatory phase athletes in endurance sports such as rowing, kayaking, and swimming perform a substantial proportion of strength training, with as much as 50-60% of their total training being non-specific [10-12, 17, 72, 75, 84, 106].

In addition, the short- and medium-term fatigue induced by strength training of different intensity and duration influences the recovery from preceding sessions, as well as the intensity and volume of sport-specific training [111]. Indeed, the need for recovery from extensive strength training may explain, at least in part, the differences in time spent in Z1 between sports and phases of the season. This may be why many endurance athletes perform very high proportions of Z1, which induces less fatigue than exercise in Z2 or Z3.

For example, a recent seasonal analysis of the TID of canoeists/kayakers focused only on the 53% of the total training time spent on-water [11], leaving the 25% strength training and 17% non-specific endurance training unexamined. Similarly, other investigators have characterized only the intensity of specific training, which accounted for approximately only 52% of total training time [10]. The reports on TID including both specific and non-specific endurance training reveal that the proportions of these vary between different sports [12, 15, 16, 106].

At present, there is no framework for integrating the intensity of strength, power and speed training and (un)specific endurance training into TID analysis [68], which means that the TIDs presented here do not reflect the actual distribution of training intensity. It is desirable that future prospective investigations encompass all aspects of training.

The method of quantification

Clearly, the TID obtained is strongly dependent on the quantitative parameters on which it is based, as shown in studies on, e.g., running [9, 21, 22], cross-country skiing [15, 16, 53, 81], cycling [20, 24, 58], swimming [49], and kayaking/canoeing [23]. Therefore, it is crucial that practitioners and researchers evaluate which methodological approach is appropriate and optimal for their specific purposes. For instance, when the primary goal is to elicit certain physiological adaptations, heart rate or blood lactate kinetics may be a suitable basis on which to define the zones of exercise intensity, albeit only for prolonged sessions of exercise at lower-to-moderate intensity (Z1, Z2). Quantification of higher-intensity exercise, which aims to enhance neuromuscular capabilities (e.g., maximal or constant speed and/or power output) should be based on velocity and/or output.

In particular, planning and analyzing training sessions on the basis of actual race performance would appear to be appropriate for the development of event-specific racing pace. At the same time, since race performance depends on the coordinated utilization of an individual´s capacities, the specific type of training required, even for the same event, might differ considerably between two athletes. In this context, measurement of physiological parameters as well might provide valuable information concerning an individual athlete´s potential for improvement.

Interestingly, even though the available wearable technology already allows automated quantitative monitoring of training, many analyses of TID involve the use of diaries and interviews [13, 15, 16, 18, 25, 26, 39, 41, 80, 85], i.e., self-reporting with all its limitations (e.g., recall bias, inaccuracy, incompleteness). Such self-reporting by elite cross-country skiers was recently shown to have acceptable accuracy, but, at the same time, it was recommended that accuracy be improved by providing strict guidelines in this connection [112]. Clearly, automated analysis of TID, perhaps in combination with self-reporting could provide more accurate and reliable information. However, in our experience not all athletes are comfortable wearing, e.g., chest straps that monitor heart rate and, furthermore, current wearable technology may not have the level of accuracy required for monitoring load [113].

Stage of the season

In order to achieve their peak performance at the right time, endurance athletes usually divide their training into micro-, meso- and macro-cycles (preparatory phases, the period of competition including tapering phases) [99]. Depending on the athlete and his/her aims, sport, and upcoming event, the TIDs at different time-points in these cycles may differ significantly, as has been reported for a variety of endurance sports, including rowing [10, 60], kayaking [11], cross-country skiing [15, 19, 54], running [87], and cycling [57]. For example, the pyramidal TID of kayak/canoe sprint athletes as determined over an entire season differed markedly when two preparatory phases and the period of competition were analyzed separately [11].

Altering the TID in an appropriate manner during the training season has been shown to be superior to adhering rigidly to a single pattern [114]. However, even though such adjustments are common in practice, little is presently known about them.

Therefore, comparisons of TIDs are meaningful only if similar periods of training are involved. However, even such comparisons are meaningful only if the primary goal of training, the adaptations achieved, and strategy behind the changes are known. In addition, individual factors such as level of fatigue, emotional state, and general health, as well as unexpected changes in environmental conditions can lead to unplanned adjustments in TID, even on a weekly basis. Unfortunately, the periods analyzed in the articles reviewed here vary considerably, making it impossible to identify patterns of TID associated with any given sport.

The total training volume versus relative distribution of training intensity

Development of key components of endurance performance requires extensive training for several years [115], during which a gradual and injury-free increase in training volume is crucial for long-term success. However, the TID does not take the total training volume, one of the primary training variables, into consideration [110].

Above a certain threshold, more and/or more frequent sessions of high-intensity training may lead to symptoms of overtraining, as well as stagnation and even (if executed for longer periods) a worsening of performance [116]. For example, in connection with sports that involve extensive impact on the musculoskeletal system, such as running, excessive mileage can easily lead to injury from overuse [110]. On the other hand, cyclists can manage a higher total volume of training.

In additional, even in connection with one and the same sport, the demand for high-intensity training depends on the specific schedule and types of competition. For instance, athletes who focus on longer-distance events that are less intense tend to perform more overall training with a lower proportion of high-intensity exercise, whereas the average training intensity of athletes who focus on shorter distances is higher. Moreover, personal preferences differ. For example, some marathon runners cover 130-150 km•wk-1, 25-30% of which is at or close to their marathon pace; whereas others run 220-240 km•wk-1 with only about 15-20% at or close to their marathon pace [2]. Such “personal signatures” of coaches and/or athletes question the concept of an “optimal” TID.

Future directions and perspectives

Hopefully, our present analysis will be of value in connection with the intricate process of making decisions about TID. However, current research in this area is somewhat reductionist (i.e., based simply on the relative amounts of time spent in the three zones of exercise intensity) and does not take into account the volume and frequency of training, as well as other factors of importance to training by tier 4 and 5 athletes.

Based on our current findings, we would like to make the following suggestions for future research in this area:

i) The analysis of TIDs should be more precise, especially with respect to reporting absolute volumes (kilometers, time, power, etc.) of pre-planned versus actual training in relationship to the nature of the individual sport, phase of the season, and mode of training (e.g., on water versus on an ergometer (rowing/kayaking), breaststroke versus butterfly (swimming), the different skiing techniques utilized in cross-country skiing and the biathlon).

ii) Additional contextual information on, for example, ambient conditions during training, the number and type of competitions and training camps, team versus individual training (e.g., drafting in cycling and kayaking influences the intensity of exercise) and any special diets would provide a more holistic perspective on the training process and clarify the reasons for changes in TID in greater detail.

iii) Different types and duration of strength, power and speed training elicit pronounced physiological perturbation, but this type of training is not included in current approaches to quantifying TID. Accordingly, inclusion of the adaptations evoked by these unspecific training stimuli is required.

iv) Our current perspective is that the TID focuses on physiological (i.e., cardio-respiratory and/or metabolic) training, whereas in certain sports, such as running, biomechanical loading on the body is also a key concern. Therefore, future research should aim to develop TID models incorporating e.g., biomechanical aspects of training.

v) Current methods for quantifying TID do not take variations in intensity over the course of a season or more extensive periods of time, especially variations in loading and unloading, into consideration. Thus, future research should examine the interplay between work and recovery in considerably greater detail. In general, optimization of the TID requires careful consideration of the characteristics of each individual athlete and of the season-specific demands associated with his/her sport, as well as regular monitoring and adjustment of the volume and intensity of training to ensure that the overall training load is appropriate.

vi) Analysis of the TID requires considerable time and resources. To reduce these costs at least somewhat, we recommend employing reliable sensor technology to automatically collect useful data, instead of relying solely on diaries. Sensors also allow monitoring of unstructured exercise and activities of daily living (e.g., sleep, nutrition, ambient conditions), thereby providing a broader perspective of “confounding” factors.

vii) Only 12 of the 34 articles analyzed here focused on the TID of female athletes (2 of which were single-case studies), who accounted for no more than 15% of the total number of subjects. In light of the sex differences in hormonal status, body composition, strength, ability to recovery, and demands placed on performance, the TID of female athletes may differ from those of men and should be characterized separately in detail.

Conclusion

The majority of retrospective studies of TID employ different methods of quantification, which makes comparisons between sports problematic. The relative amounts of time spent in all zones of exercise intensity by level 4 and 5 endurance athletes vary considerably between sports and at different stages of the season, i.e., there is no one TID that is appropriate for all nor was any particular TID predominant. At the same time, all methods of quantification have revealed that athletes participating in all endurance sports perform relatively large amounts of time training in Z1.

In our present analysis, 49% of the TIDs retrieved were based on single-case observations (of which 67% involved cross-country skiing/the biathlon), which makes drawing generalized conclusions for elite athletes participating in different endurance sports impossible. This analysis also reveals that, in general, determination of the TID does not take contextual information on, e.g., strength training, mode of exercise (e.g., the various classical vs skating techniques in cross-country skiing), environmental conditions, biomechanical loading, and activities of daily living into consideration. In particular, the lack of information concerning absolute values mentioned above makes a reliable comparison between different sports or the phases of a season impossible. Therefore, to avoid oversimplification of the dose-response relationship, we recommend strongly that future investigations in this area take a more holistic approach.

REFERENCES

[1] Seiler, S., What is best practice for training intensity and duration distribution in endurance athletes? Int J Sports Physiol Perform, 2010. 5(3): p. 276-91.

[2] Haugen, T., et al., The training characteristics of world-class distance runners: An integration of scientific literature and results-proven practice. Sports Med Open, 2022. 8(1): p. 46.

[3] Svendsen, I.S., et al., Training, performance, and physiological predictors of a successful elite senior career in junior competitive road cyclists. Int J Sports Physiol Perform, 2018: p. 1-6.

[4] van der Poel, N. How to skate a 10k and also half a 10k. 2022; Available from: https://www.howtoskate.se/.

[5] Stoggl, T.L. and B. Sperlich, The training intensity distribution among well-trained and elite endurance athletes. Front Physiol, 2015. 6: p. 295.

[6] Johansen, J.M., et al., No change - no gain; the effect of age, sex, selected genes and training on physiological and performance adaptations in cross-Country skiing. Front Physiol, 2020. 11: p. 581339.

[7] Johansen, J.M., et al., Effects of individual changes in training distribution on maximal aerobic capacity in well-trained cross-country skiers: A follow-up study. Front Physiol, 2021. 12: p. 675273.

[8] Sandbakk, O., et al., Effects of intensity and duration in aerobic high-intensity interval training in highly trained junior cross-country skiers. J Strength Cond Res, 2013. 27(7): p. 1974-80.

[9] Bellinger, P., B. Arnold, and C. Minahan, Quantifying the training intensity distribution in middle-distance runners: The influence of different methods of training intensity quantification. Int J Sports Physiol Perform, 2019: p. 1-5.

[10] Guellich, A., S. Seiler, and E. Emrich, Training methods and intensity distribution of young world-class rowers. Int J Sports Physiol Perform, 2009. 4(4): p. 448-60.

[11] Matzka, M., et al., The relationship between the distribution of training intensity and performance of kayak and canoe Sprinters: A retrospective observational analysis of one season of competition. Front Sports Act Living, 2021. 3: p. 788108.

[12] Mujika, I., et al., Effects of training on performance in competitive swimming. Can J Appl Physiol, 1995. 20(4): p. 395-406.

[13] Schmitt, L., S. Bouthiaux, and G.P. Millet, Eleven years' monitoring of the world's most successful male biathlete of the last decade. Int J Sports Physiol Perform, 2021. 16(6): p. 900-905.

[14] Schumacher, Y.O. and P. Mueller, The 4000-m team pursuit cycling world record: theoretical and practical aspects. Med Sci Sports Exerc, 2002. 34(6): p. 1029-36.

[15] Solli, G.S., E. Tonnessen, and O. Sandbakk, The training characteristics of the world's most successful female cross-country skier. Front Physiol, 2017. 8: p. 1069.

[16] Solli, G.S., E. Tonnessen, and O. Sandbakk, Block vs. traditional periodization of HIT: Two different paths to success for the world's best cross-country skier. Front Physiol, 2019. 10: p. 375.
[17] Steinacker, J.M., et al., Training of junior rowers before world championships. Effects on performance, mood state and selected hormonal and metabolic responses. J Sports Med Phys Fitness, 2000. 40(4): p. 327-35.
[18] Tjelta, L.I., A longitudinal case study of the training of the 2012 european 1500 m track champion. International Journal of Applied Sports Sciences, 2013. 25: p. 11-18.
[19] Tonnessen, E., et al., The road to gold: training and peaking characteristics in the year prior to a gold medal endurance performance. PLoS One, 2014. 9(7): p. e101796.
[20] Rothschild, J.A., et al., Racing and training physiology of an elite ultra-endurance cyclist: case study of 2 record-setting performances. Int J Sports Physiol Perform, 2021. 16(5): p. 739-743.
[21] Kenneally, M., et al., Training intensity distribution analysis by race pace vs. physiological approach in world-class middle- and long-distance runners. Eur J Sport Sci, 2021. 21(6): p. 819-826.
[22] Kenneally, M., et al., Training characteristics of a world championship 5000-m Finalist and multiple continental record holder over the year leading to a world championship final. Int J Sports Physiol Perform, 2022. 17(1): p. 142-146.
[23] Matzka, M., et al., Retrospective analysis of Ttaining intensity distribution based on race pace versus physiological benchmarks in highly trained sprint kayakers. Sports Med Open, 2022. 8(1): p. 1.
[24] van Erp, T., D. Sanders, and J.J. de Koning, Training characteristics of male and female professional road cyclists: A 4-year retrospective analysis. Int J Sports Physiol Perform, 2019: p. 1-7.
[25] Billat, V., et al., Training and bioenergetic characteristics in elite male and female Kenyan runners. Med Sci Sports Exerc, 2003. 35(2): p. 297-304; discussion 305-6.
[26] Billat, V.L., et al., Physical and training characteristics of top-class marathon runners. Med Sci Sports Exerc, 2001. 33(12): p. 2089-97.
[27] Leo, P., et al., Training characteristics and power profile of professional U23 cyclists throughout a competitive season. Sports (Basel), 2020. 8(12).
[28] Spragg, J., P. Leo, and J. Swart, The relationship between training characteristics and durability in professional cyclists across a competitive season. Eur J Sport Sci, 2022: p. 1-10.
[29] Wasserman, K. and M.B. McIlroy, Detecting the Threshold of Anaerobic Metabolism in Cardiac Patients during Exercise. Am J Cardiol, 1964. 14: p. 844-52.
[30] Beaver, W.L., K. Wasserman, and B.J. Whipp, A new method for detecting anaerobic threshold by gas exchange. J Appl Physiol, 1986. 60(6): p. 2020-7.
[31] Sjodin, B. and I. Jacobs, Onset of blood lactate accumulation and marathon running performance. Int J Sports Med, 1981. 2(1): p. 23-6.

[32] Urhausen, A., et al., Individual anaerobic threshold and maximum lactate steady state. Int J Sports Med, 1993. 14(3): p. 134-9.

[33] Mader, A. and H. Heck, A theory of the metabolic origin of "anaerobic threshold". Int J Sports Med, 1986. 7 Suppl 1: p. 45-65.

[34] Stegmann, H., W. Kindermann, and A. Schnabel, Lactate kinetics and individual anaerobic threshold. Int J Sports Med, 1981. 2(3): p. 160-5.

[35] Kindermann, W., G. Simon, and J. Keul, The significance of the aerobic-anaerobic transition for the determination of work load intensities during endurance training. Eur J Appl Physiol Occup Physiol, 1979. 42(1): p. 25-34.

[36] Davis, J.A., et al., Anaerobic threshold and maximal aerobic power for three modes of exercise. J Appl Physiol, 1976. 41(4): p. 544-50.

[37] Coyle, E.F., et al., Physiological and biomechanical factors associated with elite endurance cycling performance. Med Sci Sports Exerc, 1991. 23(1): p. 93-107.

[38] Conconi, F., et al., Determination of the anaerobic threshold by a noninvasive field test in runners. J Appl Physiol, 1982. 52(4): p. 869-73.

[39] Orie, J., et al., Thirty-eight years of training distribution in Olympic speed skaters. Int J Sports Physiol Perform, 2014. 9(1): p. 93-9.

[40] Seiler, K.S. and G.O. Kjerland, Quantifying training intensity distribution in elite endurance athletes: is there evidence for an "optimal" distribution? Scand J Med Sci Sports, 2006. 16(1): p. 49-56.

[41] Fiskerstrand, A. and K.S. Seiler, Training and performance characteristics among Norwegian international rowers 1970-2001. Scand J Med Sci Sports, 2004. 14(5): p. 303-10.

[42] Daussin, F.N., et al., Improvement of VO2max by cardiac output and oxygen extraction adaptation during intermittent versus continuous endurance training. Eur J Appl Physiol, 2007. 101(3): p. 377-83.

[43] Helgerud, J., et al., Aerobic high-intensity intervals improve VO2max more than moderate training. Med Sci Sports Exerc, 2007. 39(4): p. 665-71.

[44] Jones, A.M. and H. Carter, The effect of endurance training on parameters of aerobic fitness. Sports Med, 2000. 29(6): p. 373-86.

[45] McKay, B.R., D.H. Paterson, and J.M. Kowalchuk, Effect of short-term high-intensity interval training vs. continuous training on O2 uptake kinetics, muscle deoxygenation, and exercise performance. J Appl Physiol (1985), 2009. 107(1): p. 128-38.

[46] Midgley, A.W., L.R. McNaughton, and M. Wilkinson, Is there an optimal training intensity for enhancing the maximal oxygen uptake of distance runners?: empirical research findings, current opinions, physiological rationale and practical recommendations. Sports Med, 2006. 36(2): p. 117-32.

[47] Romijn, J.A., et al., Regulation of endogenous fat and carbohydrate metabolism in relation to exercise intensity and duration. Am J Physiol, 1993. 265(3 Pt 1): p. E380-91.

[48] Foster, C., et al., A new approach to monitoring exercise training. J Strength Cond Res, 2001. 15(1): p. 109-15.

[49] Ieno, C., et al., Monitoring rating of perceived exertion time in zone: A novel method to quantify training load in elite open-water swimmers? Int J Sports Physiol Perform, 2021. 16(10): p. 1551-1555.

[50] Jamnick, N.A., et al., An examination and critique of current methods to determine exercise intensity. Sports Med, 2020. 50(10): p. 1729-1756.

[51] Kenneally, M., A. Casado, and J. Santos-Concejero, The effect of periodization and training intensity distribution on middle- and long-distance running performance: A systematic review. Int J Sports Physiol Perform, 2018. 13(9): p. 1114-1121.

[52] Treff, G., et al., The Polarization-Index: A simple calculation to distinguish polarized from non-polarized training intensity distributions. Front Physiol, 2019. 10: p. 707.

[53] Sylta, O., E. Tonnessen, and S. Seiler, From heart-rate data to training quantification: a comparison of 3 methods of training-intensity analysis. Int J Sports Physiol Perform, 2014. 9(1): p. 100-7.

[54] Sandbakk, O., et al., The physiology of world-class sprint skiers. Scand J Med Sci Sports, 2011. 21(6): p. e9-16.

[55] Gallo, G., et al., How do world class top 5 Giro d'Italia finishers train? A qualitative multiple case study. Scand J Med Sci Sports, 2022. 32(12): p. 1738-1746.

[56] Esteve-Lanao, J., et al., How do endurance runners actually train? Relationship with competition performance. Med Sci Sports Exerc, 2005. 37(3): p. 496-504.

[57] Lucia, A., et al., Metabolic and neuromuscular adaptations to endurance training in professional cyclists: a longitudinal study. Jpn J Physiol, 2000. 50(3): p. 381-8.

[58] Sanders, D., T. Myers, and I. Akubat, Training intensity distribution in road cyclists: Objective versus subjective measures. Int J Sports Physiol Perform, 2017. 12(9): p. 1232-1237.

[59] Zapico, A.G., et al., Evolution of physiological and haematological parameters with training load in elite male road cyclists: a longitudinal study. J Sports Med Phys Fitness, 2007. 47(2): p. 191-6.

[60] Plews, D.J., et al., Heart-rate variability and training-intensity distribution in elite rowers. Int J Sports Physiol Perform, 2014. 9(6): p. 1026-32.

[61] Buchheit, M. and P.B. Laursen, High-intensity interval training, solutions to the programming puzzle: Part I: cardiopulmonary emphasis. Sports Med, 2013. 43(5): p. 313-38.

[62] Hogan, C., et al., Heart rate and stroke rate misrepresent supramaximal sprint kayak training as quantified by power. Eur J Sport Sci, 2021. 21(5): p. 656-665.

[63] Cerezuela-Espejo, V., et al., The relationship between lactate and ventilatory thresholds in runners: Validity and reliability of exercise test performance parameters. Front Physiol, 2018. 9: p. 1320.

[64] Pallares, J.G., et al., Validity and reliability of ventilatory and blood lactate thresholds in well-trained cyclists. PLoS One, 2016. 11(9): p. e0163389.

[65] Warr-di Piero, D., et al., Effects of work-interval duration and sport specificity on blood lactate concentration, heart rate and perceptual responses during high intensity interval training. PLoS One, 2018. 13(7): p. e0200690.

[66] Burnley, M., S.E. Bearden, and A.M. Jones, Polarized training is not optimal for endurance athletes. Med Sci Sports Exerc, 2022. 54(6): p. 1032-1034.

[67] Foster, C., et al., Polarized training is optimal for endurance athletes. Med Sci Sports Exerc, 2022. 54(6): p. 1028-1031.

[68] Sperlich, B., G. Treff, and J. Boone, Training intensity distribution in endurance sports: Time to consider sport specificity and waking hour activity. Med Sci Sports Exerc, 2022. 54(7): p. 1227-1228.

[69] Cejuela, R. and S. Selles-Perez, Road to Tokyo 2020 Olympic Games: Training characteristics of a world class male triathlete. Front Physiol, 2022. 13: p. 835705.

[70] Zeller, S., T. Abel, and H.K. Strueder, Monitoring training load in handcycling: A case study. J Strength Cond Res, 2017. 31(11): p. 3094-3100.

[71] McKay, A.K.A., et al., Defining training and performance caliber: A participant classification framework. Int J Sports Physiol Perform, 2022. 17(2): p. 317-331.

[72] Garcia-Pallares, J., et al., Performance changes in world-class kayakers following two different training periodization models. Eur J Appl Physiol, 2010. 110(1): p. 99-107.

[73] Kim, T.H., et al., The effect of polarized training on the athletic performance of male and female cross-country skiers during the general preparation period. Healthcare (Basel), 2021. 9(7).

[74] Pla, R., et al., Effects of a 6-week period of polarized or threshold training on performance and fatigue in elite swimmers. Int J Sports Physiol Perform, 2019. 14(2): p. 183-189.

[75] Treff, G., et al., Eleven-week preparation involving polarized intensity distribution is not superior to pyramidal distribution in national elite rowers. Front Physiol, 2017. 8: p. 515.

[76] Yu, H., et al., A quasi-experimental study of Chinese top-level speed skaters' training load: threshold versus polarized model. Int J Sports Physiol Perform, 2012. 7(2): p. 103-12.

[77] Drevon, D., S.R. Fursa, and A.L. Malcolm, Intercoder Reliability and Validity of WebPlotDigitizer in Extracting Graphed Data. Behavior Modification, 2017. 41(2): p. 323-339.

[78] Bompa, T.O. and C. Buzzichelli, Periodization: theory and methodology of training. 2019: Human kinetics.

[79] Boone, J., et al., Physical preparation of a world-class lightweight men's double sculls team for the Tokyo 2020 Olympics. Int J Sports Physiol Perform, 2022. 17(12): p. 1741-1747.

[80] Ingham, S.A., B.W. Fudge, and J.S. Pringle, Training distribution, physiological profile, and performance for a male international 1500-m runner. Int J Sports Physiol Perform, 2012. 7(2): p. 193-5.

[81] Talsnes, R.K., et al., The return from underperformance to sustainable world-class level: A case study of a male cross-country skier. Front Physiol, 2022. 13: p. 1089867.

[82] Secher, N.H., Physiological and biomechanical aspects of rowing. Implications for training. Sports Med, 1993. 15(1): p. 24-42.

[83] Guellich, A. and S. Seiler, Lactate profile changes in relation to training characteristics in junior elite cyclists. Int J Sports Physiol Perform, 2010. 5(3): p. 316-27.

[84] Hartmann, U., A. Mader, and W. Hollmann, Heart rate and lactate during endurance training programs in rowing and its relation to the duration of exercise by top elite rowers, in FISA Coaching Development Programme Course - Level III. 1990, www.worldrowing.com.

[85] Torvik, P.O., G.S. Solli, and O. Sandbakk, The training characteristics of world-class male long-distance cross-country skiers. Front Sports Act Living, 2021. 3: p. 641389.

[86] Mujika, I., Olympic preparation of a world-class female triathlete. Int J Sports Physiol Perform, 2014. 9(4): p. 727-31.

[87] Robinson, D.M., et al., Training intensity of elite male distance runners. Med Sci Sports Exerc, 1991. 23(9): p. 1078-82.

[88] Mader, A., Glycolysis and oxidative phosphorylation as a function of cytosolic phosphorylation state and power output of the muscle cell. Eur J Appl Physiol, 2003. 88(4-5): p. 317-38.

[89] Craig, N.P. and K.I. Norton, Characteristics of track cycling. Sports Med, 2001. 31(7): p. 457-68.

[90] Laursen, P.B., Training for intense exercise performance: high-intensity or high-volume training? Scand J Med Sci Sports, 2010. 20 Suppl 2: p. 1-10.

[91] Gibala, M.J., et al., Short-term sprint interval versus traditional endurance training: similar initial adaptations in human skeletal muscle and exercise performance. The Journal of Physiology, 2006. 575(3): p. 901-911.

[92] Laursen, P.B. and D.G. Jenkins, The scientific basis for high-intensity interval training: optimising training programmes and maximising performance in highly trained endurance athletes. Sports Med, 2002. 32(1): p. 53-73.

[93] Bourgois, J.G., G. Bourgois, and J. Boone, Perspectives and determinants for training intensity distribution in elite endurance athletes. Int J Sports Physiol Perform, 2019. 14(8): p. 1151-1156.

[94] Stöggl, T. and B. Sperlich, Polarized training has greater impact on key endurance variables than threshold, high intensity, or high volume training. Front Physiol, 2014. 5: p. 33.

[95] Esteve-Lanao, J., et al., Impact of training intensity distribution on performance in endurance athletes. J Strength Cond Res, 2007. 21(3): p. 943-9.

[96] Slominski, P. and A. Nowacka, Swimming – The structure and volume of training loads in the four-year training cycle of an elite olympic athlete. Polish Journal of Sport and Tourism, 2017. 24(3): p. 162-169.

[97] Del Giudice, M., et al., Investigating the reproducibility of maximal oxygen uptake responses to high-intensity interval training. J Sci Med Sport, 2020. 23(1): p. 94-99.

[98] Pol, R., et al., Training or synergizing? Complex systems principles change the understanding of sport processes. Sports Med Open, 2020. 6(1): p. 28.

[99] Kiely, J., Periodization theory: Confronting an inconvenient truth. Sports Med, 2018. 48(4): p. 753-764.

[100] Zinner, C., D. Schäfer Olstad, and B. Sperlich, Mesocycles with different training intensity distribution in recreational runners. Medicine & Science in Sports & Exercise, 2018. 50(8): p. 1641-1648.

[101] McPhee, J.S., et al., Variability in the magnitude of response of metabolic enzymes reveals patterns of co-ordinated expression following endurance training in women. Exp Physiol, 2011. 96(7): p. 699-707.

[102] Raleigh, J.P., et al., Contribution of central and peripheral adaptations to changes in maximal oxygen uptake following 4 weeks of sprint interval training. Appl Physiol Nutr Metab, 2018. 43(10): p. 1059-1068.

[103] Simoneau, J.A., et al., Inheritance of human skeletal muscle and anaerobic capacity adaptation to high-intensity intermittent training. Int J Sports Med, 1986. 7(3): p. 167-71.

[104] Yan, X., et al., The gene SMART study: method, study design, and preliminary findings. BMC Genomics, 2017. 18(Suppl 8): p. 821.

[105] Sperlich, B. and H.C. Holmberg, The responses of elite athletes to exercise: An all-day, 24-h integrative view is required! Front Physiol, 2017. 8: p. 564.

[106] Treff, G., et al., The integration of training and off-training activities substantially alters training volume and load analysis in elite rowers. Sci Rep, 2021. 11(1): p. 17218.

[107] Duking, P., et al., Integrated Framework of Load Monitoring by a Combination of Smartphone Applications, Wearables and Point-of-Care Testing Provides Feedback that Allows Individual Responsive Adjustments to Activities of Daily Living. Sensors (Basel), 2018. 18(5).

[108] Sperlich, B., et al., Editorial: Wearable sensor technology for monitoring training load and health in the athletic population. Front Physiol, 2019. 10: p. 1520.

[109] Brownstein, C.G., et al., Disparate mechanisms of fatigability in response to prolonged running versus cycling of matched intensity and duration. Med Sci Sports Exerc, 2022. 54(5): p. 872-882.

[110] Sandbakk, O., T. Haugen, and G. Ettema, The influence of exercise modality on training load management. Int J Sports Physiol Perform, 2021. 16(4): p. 605-608.

[111] Buitrago, S., et al., Effects of load and training modes on physiological and metabolic responses in resistance exercise. Eur J Appl Physiol, 2012. 112(7): p. 2739-48.

[112] Sylta, O., E. Tonnessen, and S. Seiler, Do elite endurance athletes report their training accurately? Int J Sports Physiol Perform, 2014. 9(1): p. 85-92.

[113] Sperlich, B. and H.C. Holmberg, Wearable, yes, but able...?: it is time for evidence-based marketing claims! Br J Sports Med, 2017. 51(16): p. 1240.

[114] Filipas, L., et al., Effects of 16 weeks of pyramidal and polarized training intensity distributions in well-trained endurance runners. Scand J Med Sci Sports, 2022. 32(3): p. 498-511.

[115] Jones, A.M., The physiology of the world record holder for the women's marathon. International Journal of Sports Science & Coaching, 2006. 1(2): p. 101-116.

[116] Billat, V.L., et al., Interval training at VO2max: effects on aerobic performance and overtraining markers. Med Sci Sports Exerc, 1999. 31(1): p. 156-63.