JYU DISSERTATIONS 588

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Monitoring Recovery and Training Responses From Different Types of Endurance Exercises and Training Protocols in Recreational Runners

Implications for Individual Training Prescription

UNIVERSITY OF JYVÄSKYLÄ
FACULTY OF SPORT AND HEALTH SCIENCES

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ABSTRACT

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This thesis examined physiological, perceptual, and performance responses to endurance training sessions differing in intensity (study I) and endurance training periods of either increased volume or intensity (studies II and III). In addition, the thesis explored whether individualized endurance training based on recovery would provide superior training adaptations compared to predefined training (study IV). A total of 114 recreationally endurance-trained males (study I) or males and females (II-IV) were examined in four separate data collections. In all studies, recovery was assessed by markers monitored during submaximal running, resting heart rate variability (HRV), neuromuscular performance, and perceived recovery. Endurance performance was assessed by an incremental treadmill test (studies I-IV) and by 3000-m (study III) or 10-km (study IV) running tests. It was found that single exercise sessions rarely impaired the state of recovery significantly 24 hours afterwards. On the other hand, the recovery kinetics differed between neuromuscular, perceptual, and HR-based markers. After the 10-week (study II) and 2-week (study III) training interventions, similar improvements in the maximal treadmill test speed (study II) and 3000-m running time (study III) were observed in the volume and intensity groups. In the monitoring variables, responses were also consistent between the groups during the 10-week training period. Meanwhile, during the 2-week block, negative trends were observed in the intensity group compared to the volume group in nocturnal HRV and muscle soreness. In the last study, the predefined (PD) and individualized (IND) training groups improved their performance in the incremental treadmill test and 10-km test after the 12-week intervention. However, the IND improved their 10-km time twice as much as the PD. The IND also had fewer low-responders when the magnitude of change in maximal treadmill and 10-km performance was analyzed. The results of this thesis suggest that monitoring multiple aspects of recovery and combining objective and subjective data can provide useful information that could be utilized in the individualization of endurance training. Individualized training seems to lead to more consistent training adaptations compared to predefined training.

Keywords: endurance training, endurance performance, recovery monitoring, heart rate variability, perceived recovery, individualized training

TIIVISTELMÄ (ABSTRACT IN FINNISH)

Nuuttila, Olli-Pekka
Palautumisen ja harjoitusvasteiden seuranta erilaisista kestävyysharjoituksista ja kestävyysharjoitusjaksoista kuntoliikkujilla: sovellukset yksilölliseen harjoittelun ohjelmointiin
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Tässä väitöskirjassa tutkittiin eri intensiteetin kestävyysharjoitusten (osa 1) sekä kestävyysharjoittelun määrää tai intensiteettiä kasvattaneiden harjoitusjaksojen (osat 2 ja 3) aikaansaamia vasteita palautumisen ja suorituskyvyn näkökulmista. Lisäksi väitöskirjassa tutkittiin, kyetäänkö yksilöllisesti palautumistilan perusteella mukautuvalla harjoitusohjelmalla kehittämään kestävyyssuorituskykyä enemmän kuin ennalta määrätyllä ohjelmalla (osa 4). Yhteensä 114 20–45-vuotiasta mies- tai naispuolista kuntoliikkujaa osallistui neljään erilliseen aineistonkeruuseen. Osatutkimuksissa mitattiin maksimaalista kestävyyssuorituskykyä, submaksimaalisen juoksun vasteita, leposykevälivaihtelua, hermolihasjärjestelmän suorituskykyä sekä koettua palautumista. Tutkimuksessa havaittiin, että yksittäiset kestävyysharjoitukset eivät juurikaan vaikuttaneet palautumistilaan 24 tunnin kuluttua. Toisaalta palautumisen nopeus erosi yksilöiden välillä ja sisällä riippuen siitä, mitä muuttujaa tarkasteltiin. Intensiteetti- ja määräryhmissä havaittiin samanlaisia positiivisia muutoksia mattotestin maksiminopeudessa 10 viikon harjoitusjakson jälkeen (osa 2) ja 3000 metrin juoksuajassa kahden viikon harjoitusjakson jälkeen (osa 3). Myös palautumismuuttujat reagoivat yhdenmukaisesti ryhmien välillä 10 viikon harjoitusjakson aikana. Sen sijaan kahden viikon blokkiharjoitusjakson aikana intensiteettiryhmässä lihasarkuus lisääntyi ja yön aikainen sykevälivaihtelu pieneni verrattuna määräryhmään. Viimeisessä osatutkimuksessa ennalta määrätyllä ohjelmalla harjoitellut ryhmä (EM) ja yksilöllisesti mukautuneen ohjelman perusteella harjoitellut ryhmä (YM) paransivat mattotestin maksiminopeuttaan ja 10 km:n juoksuaikaansa 12 viikon harjoitusjakson jälkeen. Ryhmien välillä havaittiin kuitenkin merkitsevä ero 10 km:n testissä, jossa YM-ryhmä paransi aikaansa kaksinkertaisesti verrattuna EM-ryhmään. Lisäksi YM-ryhmässä oli vähemmän matalan harjoitusvasteen yksilöitä. Tämän väitöskirjan tulosten perusteella palautumistilan arvioinnissa tulisi yhdistää sekä objektiivisia että subjektiivisia näkökulmia. Palautumismuuttujia voi hyödyntää harjoituskuorman yksilöllisessä hienosäädössä, mikä vaikuttaisi tuottavan johdonmukaisempia adaptaatioita ennalta määrättyyn harjoitusohjelmaan verrattuna.

Avainsanat: kestävyysharjoittelu, kestävyyssuorituskyky, palautumisen seuranta, sykevälivaihtelu, koettu palautuminen, yksilöllinen harjoittelu

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ORIGINAL PUBLICATIONS AND AUTHOR CONTRIBUTION

The present thesis is based on the following original research articles, which are referred to in the text by their Roman numerals:

I Nuuttila, O-P., Kyröläinen, H., Häkkinen, K., & Nummela, A. (2021). Acute physiological responses to four running sessions performed at different intensity zones. *International Journal of Sports Medicine,* 42(6), 513–522.

II Nuuttila, O-P., Nummela, A., Häkkinen K., Seipäjärvi S., Kyröläinen, H. (2021). Monitoring Training and Recovery during a Period of Increased Intensity or Volume in Recreational Endurance Athletes. *International Journal of Environmental Research and Public Health*, 18(5), 2401.

III Nuuttila, O-P., Nummela A., Kyröläinen H., Laukkanen J., Häkkinen K. (2022). Physiological, Perceptual, and Performance Responses to the 2-wk Block of High- versus Low-Intensity Endurance Training. *Medicine and Science in Sports and Exercise*, 54(5), 851–860.

IV Nuuttila, O-P., Nummela, A., Korhonen, E., Häkkinen, K., Kyröläinen, H. (2022). Individualized Endurance Training Based on Recovery and Training Status in Recreational Runners. *Medicine and Science in Sports and Exercise*, 54(10), 1690-1701.

The author of this thesis, who is the first author of the above-mentioned original publications, was mainly responsible for drafting the study design, collecting the data, performing statistical analysis, interpreting the results and writing of the manuscripts in all four studies.

ABBREVIATIONS

1RM	One repetition maximum
10 km	Ten-kilometer running test
3000 m	3000-meter running test
ANS	Autonomic nervous system
CK	Creatine kinase
CMJ	Countermovement jump
CV	Coefficient of variation
ECG	Electrocardiography
GPS	Global positioning system
HF	High-frequency power
HIT	High-intensity training
HIIT	High-intensity interval training
HR	Heart rate
HRV	Heart rate variability
HR-RS	Heart rate-running speed index
INT	Intensity training group
INT-P	Interval training period
IND	Individualized training group
LF	Low-frequency power
LIT	Low-intensity training
LT	Lactate threshold
MIT	Moderate-intensity training
MVC	Maximal voluntary contraction
PD	Predefined training group
PREP	Preparatory period
RER	Respiratory exchange ratio
RPE	Rating of perceived exertion
RMSSD	Root mean square of successive differences
SMIT	Supramaximal-intensity interval training
SRT	Submaximal running test
SWC	Smallest worthwhile change
TID	Training intensity distribution
TRIMP	Training impulse
VAS	Visual analogue scale
vMax	Maximal running speed on treadmill test
VO_{2max}	Maximal oxygen uptake
VOL	Volume training group
VOL-P	Volume training period

CONTENTS

1 INTRODUCTION

Endurance training is a process consisting of the manipulation of exercise frequency, intensity, and volume to induce desirable training adaptations. Although the main determinants of successful endurance performance are quite well known (Bassett & Howley, 2000; Joyner & Coyle, 2008), the best training methods to induce the greatest adaptations and improvements in these determinants are still under debate (Burnley et al., 2022; Foster et al., 2022). Numerous studies have looked for the optimal model to prescribe endurance training via training interventions (Düking et al., 2020; Muñoz et al., 2014; Stöggl & Sperlich, 2014; Zinner et al., 2018) as well as retrospectively from the training of successful endurance athletes (Haugen et al., 2022; Stöggl & Sperlich, 2015; Tønnessen et al., 2014). Although there are some principles that have been recognized, such as the necessity for high-volume of low-intensity training (Haugen et al., 2022; Stöggl & Sperlich, 2015; Tønnessen et al., 2014), it seems that training adaptations to standardized programs are highly individual regardless of the model utilized (Düking et al., 2020; Vesterinen et al., 2016a; Zinner et al., 2018). Interestingly, it has been found that even in the same individuals, the training adaptations would not be similar after same types of training periods separated by a wash-out period (Del Giudice et al., 2020; Islam et al., 2021). Therefore, it seems unlikely that there would exist only one optimal training method providing the best results across individuals and times.

When looking for possible reasons behind the interindividual differences in the responses and adaptations to training, it has been found that there are multiple potential factors not related to the actual exercise dose (Mann et al., 2014). On the other hand, whether an individual could be regarded as a responder that has adapted to the training or a low-responder lacking significant adaptations may also depend on the marker being analyzed (Scharhag-Rosenberger et al., 2012). Genetics has been suggested to influence the trainability of especially VO_{2max} (Bouchard et al., 1999). In addition, the training status, sleep, and psychological stress may all alter the capability to restore homeostasis and to recover from the exercise load the individual is exposed to (Mann et al., 2014), highlighting the importance of finding the proper balance between the training load and recovery for each individual.

While general recommendations may provide a suitable starting point for the exercise prescription, monitoring training and recovery would help to consider differences between individuals (Halson, 2014). Furthermore, monitoring the responses to training would allow modifications if undesirable or unexpected responses were detected. The evolution of wearable technology has provided feasible methods for monitoring, for example, options to record heart rate (HR) and heart rate variability (HRV) via a ring (Cao et al., 2022) or a wrist-worn watch (Nuuttila et al., 2021), even 24/7 if desired. Wearable technology has been ranked in the top three of the annual fitness trends in the ACSM annual survey for seven years in a row (Thompson, 2022), demonstrating the interest of implementing monitoring devices also into practice. Although new monitoring opportunities could provide lots of data, it is also important to acknowledge the limitations of such devices (Sperlich & Holmberg, 2017) and to understand which aspects provide relevant and reliable information and how this information can be transformed into actions.

Probably the most typical internal variables that are being monitored at rest or during exercise in endurance sports are HR and HRV (Buchheit, 2014). HR can be used in the discrimination of the training intensity zones and the prescription of the training (Seiler, 2010). Furthermore, submaximal HR and changes in it can also be used as an indirect marker of the current performance level (Vesterinen et al., 2014; Vesterinen et al., 2016b). HRV, in turn, is primarily a marker of the current cardiac parasympathetic nervous system activity and cardiovascular homeostasis (Stanley et al., 2013), and for monitoring purposes it is most typically assessed at resting conditions (Buchheit, 2014). Resting HRV also appears to be a potential marker to assist the individual training prescription – when to load and when to recover. Studies that have compared individually adjusted endurance training based on resting HRV to predefined training programs have induced beneficial effects in terms of endurance performance in untrained (da Silva et al., 2019), recreationally trained (Kiviniemi et al., 2007; Nuuttila et al., 2017; Vesterinen et al., 2016c), and well-trained individuals (Carrasco-Poyatos et al., 2022; Javaloyes et al., 2019).

Although HRV-guided training has induced promising results, the limitations of a single-marker view of the recovery state should also be understood. It has been argued, for example, that neuromuscular recovery or muscle glycogen resynthesis would not follow similar recovery kinetics compared to HRV (Buchheit, 2014; Stanley et al., 2013). Furthermore, in all HR-based markers, there are situations where responses are paradoxical compared to the performance or the actual recovery state (Bellenger et al., 2016; Le Meur et al., 2013b). Despite negative changes in performance, HR may actually decrease and HRV in turn increase during periods of high training load. These dilemmas call for additional parameters, such as subjective markers of recovery (Bellenger et al., 2016; ten Haaf et al., 2017) that would help to assess the responses in the right context. Therefore, a multidisciplinary approach for monitoring would potentially provide the most comprehensive information about the training-recovery state of an individual.

The purpose of this thesis was to examine the physiological, perceptual, and performance responses to different types of endurance training sessions and endurance training periods. Furthermore, this thesis aimed to investigate whether the measured internal responses could be used in individualizing endurance training prescription, and whether this approach would lead to greater adaptations and a smaller number of low-responders compared to a predefined program.

2 REVIEW OF THE LITERATURE

2.1 Basis of endurance training and performance

2.1.1 Determinants of endurance performance

Endurance could be defined as the ability to maintain performance and resist fatigue for a prolonged time. Endurance training is often described as aerobic, which illustrates the metabolic basis of endurance. During short high-intensity activities intramuscular adenosine triphosphate (ATP), phosphocreatine stores and anaerobic glycolysis ensure sufficient ATP supplies, while aerobic metabolism through oxidative phosphorylation of carbohydrates and fats is the main pathway for ATP resynthesis for maximal activities exceeding about 90 s (Gastin, 2001; Hargreaves & Spriet, 2020; Hill, 1999; Lacour et al., 1990). Since aerobic metabolism requires oxygen, the amount of oxygen that can be delivered and utilized in the working muscles, i.e., the maximal oxygen uptake (VO_{2max}), is an important determinant of maximal endurance performance and is a widely used marker of cardiorespiratory fitness (Bassett & Howley, 2000). Significant correlations have been found between VO_{2max} and running performance in a wide range of events from 3000 m to the marathon (Grant et al., 1997; Lourenço et al., 2018; Noakes et al., 1990). VO_{2max} does not seem to rely on endurance training only, and it has been suggested that the trainability of VO_{2max} is fairly heritable (Bouchard et al., 1999).

There exists interindividual variation in the ability to sustain the intensity of VO_{2max} (Billat et al., 1994), and on average, that intensity cannot be maintained for more than six minutes (Billat et al., 1994; Billat et al., 1999). Therefore, the ability to sustain intensity close to the individual maximum is of importance in most endurance events. Prolonged performance is strongly linked to metabolic thresholds which are typically divided into the first (aerobic) and second (anaerobic) thresholds (Seiler, 2010). Thresholds could be determined based on changes in blood lactate, ventilation/gas exchange, or a combination of both during an incremental test (Meyer et al., 2005). The anaerobic threshold refers basically to the intensity that can be sustained for a certain period of time (e.g. 45-60 minutes) without an accumulation of lactate (Faude et al., 2009; Meyer et al., 2005). Also, critical speed or power has been suggested to demonstrate practically the same phenomenon (Jones & Vanhatalo, 2017). High correlations between the anaerobic threshold and 3000-m running performance have been found in several studies (Grant et al., 1997; Lourenço et al., 2018; Santos-Concejero et al., 2014), but the importance of the threshold performance seems to even grow with increasing distance up to marathons (Noakes et al., 1990; Roecker et al., 1998). Recently, it has been argued that determinants of endurance performance should be expanded to include "durability" which describes the ability to maintain a steady state and resist fatigue during prolonged events (Maunder et al., 2021). It has been observed that thresholds are not perhaps as locked as often thought, and for example, critical power could be altered due to fatigue during prolonged high-intensity activities (Clark et al., 2018).

Economy of the movement, which refers to the amount of energy a certain activity requires (Barnes & Kilding, 2015), is often regarded as one of the big three determinants of distance running performance (Bassett & Howley, 2000; Joyner & Coyle, 2008). For example, in a group of well-trained athletes (VO_{2max} 71.7 ± 2.8 $ml \cdot kg^{-1} \cdot min^{-1}$), the economy was reported to be a significant contributor to 10-km running performance (Conley & Krahenbuhl, 1980). Furthermore, changes in economy could also translate into improved distance running performance (di Prampero et al., 1993; Paavolainen et al., 1999a). While in elite athletes, it is challenging to induce further increases in VO_{2max} (Legaz Arrese et al., 2005), economy is a capability that could still be improved (Jones, 2006). Despite the relative importance, in studies with heterogeneous samples, correlations between economy and performance in events from 3000 m to marathon have been smaller than for VO_{2max} or anaerobic threshold (Grant et al., 1997; Noakes et al., 1990; Paavolainen et al., 1999b; Stratton et al., 2009). Interestingly, it has been found that VO_{2max} and economy are not very significantly associated even in well-trained athletes (Shaw et al., 2015), illustrating the distinctness of these capabilities. While there are multiple potential contributors to the differences in running economy, in well-trained middle-distance runners the muscle fiber type (Kyröläinen et al., 2003) and running technique (e.g. magnitude of braking forces) (Kyröläinen et al., 2001) could explain at least a slight portion of the interindividual variation.

In addition to traditional endurance-related parameters, neuromuscular and anaerobic capacity have been proposed to play an essential role in endurance performance (Nummela et al., 2006; Paavolainen et al., 2000; Paavolainen et al., 1999b). These peripheral capabilities can also be described as "muscle power" which Paavolainen et al. (1999b) defined "as an ability of the neuromuscular system to produce power during maximal exercise when glycolytic and oxidative energy production is high, and muscle contractility may be limited". Neuromuscular characteristics are also associated with economy of the movement and thus could affect performance indirectly (Nummela et al., 2006). The summary of distance running performance determinants is illustrated in FIGURE 1. Factors related to these determinants are discussed in more detail in chapter 2.3.1. Physiological adaptations to endurance training.

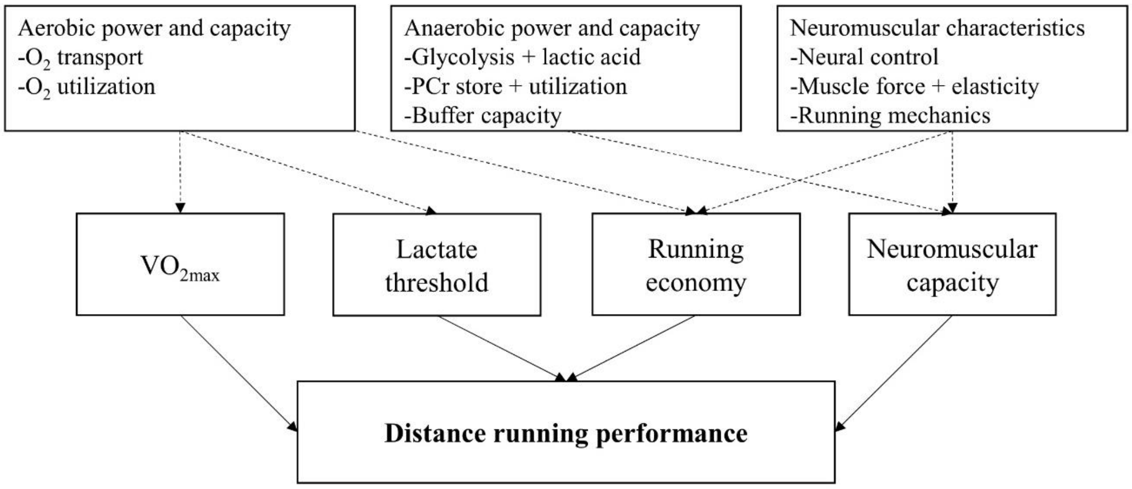

FIGURE 1 Determinants of distance running performance, modified from Paavolainen et al. (1999a) model.

Di Prampero (2003) summarized that performance at any given running distance could be predicted somewhat accurately when VO_{2max}, the energy cost of running, and the maximal anaerobic capacity are known. When considering the single best predictor of distance running performance, results have slightly varied depending on the level/heterogeneity of the participants and how the parameters have been defined. It is also important to acknowledge the interdependency between many of the parameters (Nummela et al., 2006; Paavolainen et al., 2000). Conclusively, maximal velocity achieved during the treadmill test (vMax), which in a way combines multiple aspects of performance such as VO_{2max}, neuromuscular capacity, and economy, is suggested to be the best predictor (Noakes et al., 1990) together with the anaerobic threshold (Roecker et al., 1998) in a wide range of events up to the marathon.

2.1.2 Defining endurance training intensity zones

While the aim of endurance training is to induce acute responses and chronic adaptations that would in the long term lead to improved performance, it requires proper manipulation of training intensity, duration, and frequency. The intensity of the exercise plays a fundamental role since it has a significant effect on the cardiovascular, neuromuscular, and metabolic demands of the activity (Seiler & Tønnessen, 2009). Endurance training intensities are typically divided into distinct zones that illustrate the nature of the session. There exist multiple methods and models to define the zones (Bellinger et al., 2020a; Sylta et al., 2014), and the number of zones can vary between 3, 5 and even 8 zones if extended to anaerobic training (Seiler & Tønnessen, 2009). Probably the most justifiable way is to divide intensity zones into low-, moderate-, and high-intensity zones according to the threshold performance at lactate and/or ventilatory thresholds (FIGURE 2) (Seiler & Tønnessen, 2009). In this way, the actual training process can be guided by setting a determined HR or speed/power range for each zone.

Low-intensity training (LIT) zone is associated with low (baseline level) lactate values, an HR between approximately 60-80%/max, and low perceived effort (1-4/10) (Seiler & Kjerland, 2006; Seiler & Tønnessen, 2009). This type of training represents the bulk of endurance training in athletes (Haugen et al., 2022; Seiler, 2010; Stöggl & Sperlich, 2015). Typical low-intensity sessions are continuous basic sessions of > 40 min or specific long-distance sessions up to several hours (Haugen et al., 2022; Seiler & Tønnessen, 2009). The training mode also significantly affects the duration of such sessions. While cyclists could train for many hours (van Erp et al., 2020), runners perform shorter sessions and lower total volume, most likely due to higher musculoskeletal demands of the activity (Haugen et al., 2022).

Moderate intensity training (MIT) or threshold training is typically performed between two metabolic thresholds. MIT zone is associated with a slight increase in blood lactate values (2-4 mmol$\cdot$l^{-1}), an HR of about 80-90% of max, and increased perceived effort (5-6/10) (Seiler & Kjerland, 2006; Seiler & Tønnessen, 2009). In endurance athletes, the sessions are performed typically as continuous (20-60 min) or intervals (1-15 min) with short recovery periods and accumulated time of >30 min (Haugen et al., 2022; Seiler & Tønnessen, 2009). Moderate intensity exercise could be sustained for hours, and it is possible to cover e.g., a marathon at an intensity above the first lactate threshold in recreational (Myrkos et al., 2020) and elite athletes (Joyner & Coyle, 2008).

High-intensity training (HIT) zone refers to the intensity above the second metabolic threshold, and on most occasions, below the intensity of VO_{2max}. HIT is typically performed as long intervals (1-6 min) (Seiler & Tønnessen, 2009) or as shorter "micro-intervals" (e.g. 30 s/15 s, Rønnestad et al., 2020). Longer work period compared to the recovery period is often used to maximize time at high oxygen consumption which is thought to be a relevant aspect during HIT (Buchheit & Laursen, 2013a). Interestingly, microintervals (3 × 13 × 30 s/15 s) seem to allow achieving higher working time above 90% of VO_{2max} compared to effort-matched long (4 × 5 min/2.5 min) intervals (Almquist et al., 2020). In athletes, the accumulated time in the HIT zone varies typically between 15-30 min (Haugen et al., 2022; Seiler & Tønnessen, 2009). Intensity is associated with increased blood lactate levels (4-10 mmol$\cdot$l^{-1}), an HR of 90-100%/max, and high perceived effort (7-10/10) (Seiler & Kjerland, 2006; Seiler & Tønnessen, 2009). During the LIT and MIT sessions a steady state can be achieved, while in the HIT sessions blood lactate values and VO_2 will not stabilize but will hypothetically keep increasing until reaching maximum values (Burnley & Jones, 2007). At high (supramaximal) intensities, VO_2 could also start to decrease before exhaustion (Hawkins et al., 2007). There is an overlap in the way HIT and HIIT definitions are used in the literature. However, in this thesis HIT is used to describe the high-intensity training zone and training in that zone generally, while HIIT refers specifically to the high-intensity interval training session type.

In addition, there are supramaximal intensity intervals (SMIT) that are performed between the maximal aerobic intensity (vVO2max) and maximal sprinting speed or power (Buchheit & Laursen, 2013a). There also exists a wide range of sessions from short 10-15-s sprints to all-out 30-s intervals (Billat, 2001; Rosenblat et al., 2022). In general, it can be concluded that anaerobic intervals are shorter, and a longer recovery period in relation to work duration is typically used compared to intervals below vVO_{2max} (Billat, 2001; Rosenblat et al., 2022). Blood lactate values and perceived exertion are typically high (Buchheit & Laursen, 2013b) due to the nature of the almost maximal effort, but cardiovascular responses are milder compared to longer intervals (Buchheit & Laursen, 2013a). Interestingly, SMIT seems to induce quite similar adaptations as would be expected after traditional endurance training (Rosenblat et al., 2020; 2022).

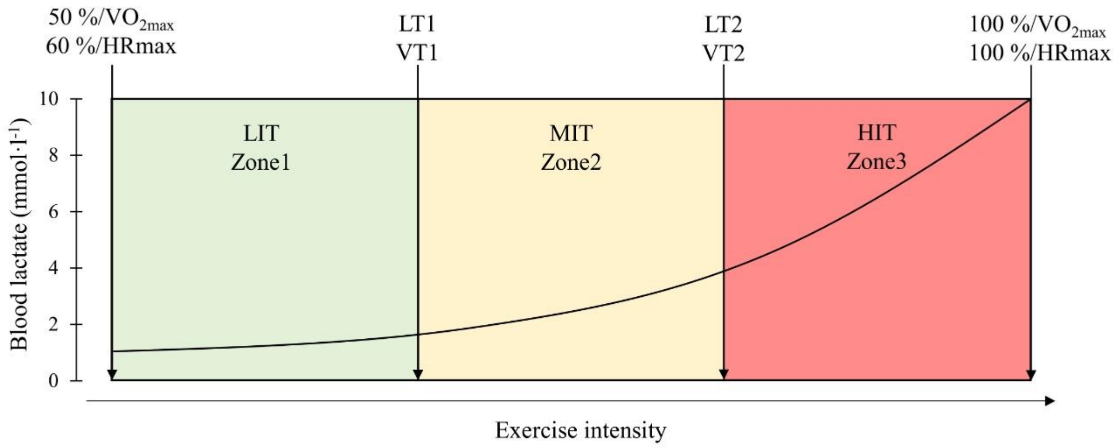

FIGURE 2 Endurance training intensity zones. Modified from Seiler (2010) and Seiler and Tønnessen (2009). Above the intensity of VO_{2max} begins the "supramaximal intensity zone". LT, lactate threshold; VT, ventilatory threshold.

2.2 Acute responses to endurance exercises

2.2.1 Cardiorespiratory and metabolic responses

After the onset of exercise, the body starts to adjust its functions to respond to the demands of an activity. In endurance exercise, this means e.g., increasing ventilation, cardiac output, and oxygen utilization in the active muscle groups. The autonomic nervous system (ANS) has a central role in regulating cardiovascular functions via its two branches, the sympathetic and parasympathetic nervous systems (Freeman et al., 2006). The ANS responds to exercise by increasing the sympathetic drive and catecholamine secretion (Le Meur et al., 2014; Mazzeo, 1991), while the cardiac parasympathetic activity diminishes (Kaikkonen et al., 2007; Kaikkonen et al., 2010). Cardiac output is the outcome of HR and stroke volume, and it can be manipulated by increasing either one or both markers through the sympathetic nervous system. While the increase in the cardiac output occurs rapidly at the beginning of the exercise, the interaction between stroke volume and the HR is more debated. It has historically been suggested that the stroke volume would plateau already at low intensities (50%/VO_{2max}) (Åstrand et al., 1964), and at higher intensities, the increase in cardiac output is achieved mainly via HR. However, later on, it was observed that at least in endurance-trained athletes, the stroke volume may increase until the intensity of VO_{2max} (Gledhill et al., 1994; Zhou et al., 2001).

If exercise is performed below the first lactate threshold, VO_2 stabilizes quite rapidly in a few minutes to match the demands of the work (Xu & Rhodes, 1999). If exercise is performed above the first lactate threshold, the so-called slow component of VO_2 delays the achievement of a steady state or even prevents it at intensities close to VO_{2max} (Pringle et al., 2003; Xu & Rhodes, 1999). While aerobic metabolism can produce ATP from fats and carbohydrates, exercise intensity affects the respiratory exchange ratio (RER), the ratio between VCO_2 and VO_2, which can be used to estimate the relation between fat and carbohydrate oxidation (Holloszy, 1998). The higher the intensity of the exercise, the higher the RER and the proportion of carbohydrate oxidation (De Feo et al., 2003; Holloszy, 1998). On the other hand, increased duration of the session and depletion of muscle glycogen stores leads to an increased proportion of fat oxidation (Holloszy, 1998; Sproule, 1998).

Blood lactate, as an end product of anaerobic glycolysis (Rogatzki et al., 2015), is often used as a marker of exercise intensity; the balance between lactate production and clearance during incremental tests is also used in multiple threshold estimations (Faude et al., 2009). While LIT should not increase lactate values from the resting level significantly, blood lactate starts to increase in the MIT zone, and a steady state cannot be achieved in the HIT zone (Faude et al., 2009). Although often thought otherwise, it has been argued that blood lactate is not the main contributor to fatigue-induced impairment in performance (Gladden, 2004). Instead, it could even be used in the re-production of glucose and used as a substrate, especially in the cardiac muscle (Ferguson et al., 2018). For example, Brooks et al. (2022) have discussed in detail how "lactate shuttles" fulfil at least three purposes by being a major source of energy, a gluconeogenic precursor and a signaling molecule also under fully aerobic conditions. From a metabolic point of view, it is more likely that muscle fatigue relates to the increased levels of acidosis and inorganic phosphates in working muscles (Sundberg et al. 2018).

During prolonged activities, cardiorespiratory functions could be altered, even if a steady state had been achieved earlier. The so-called cardiac drift is a typical phenomenon meaning increases in HR despite maintained training intensity (Souissi et al., 2021). The drift is probably related to multiple factors such as increased core temperature, sympathetic nervous system activity, dehydration, and decreased blood volume (Coyle & Gonzalez-Alonso, 2001). In addition, neuromuscular fatigue leading to increased muscle activation could contribute to cardiac uncoupling (Kounalakis et al. 2008). At the same time, and probably partly for the same reasons, the oxygen consumption may also increase (Xu & Montgomery, 1995; Zavorsky et al., 1998).

The timeframe to recover cardiac functions back to resting levels depends on the exercise intensity and duration. Also, well-trained athletes may have the ability to recover and restore homeostasis faster compared to lower-caliber athletes (Seiler et al., 2007). HR has previously returned to baseline in 30 minutes after HIIT in well-trained athletes (Seiler et al., 2007), while in sedentary individuals, it has remained increased at the same time point even after LIT (Kaikkonen et al., 2007). In the same studies, HRV returned to baseline in 30 minutes after a LIT in sedentary individuals (Kaikkonen et al., 2007), but in well-trained athletes, it was recovered already in 5 minutes (Seiler et al., 2007). On the other hand, it has been suggested that it may take as long as 24-48 hours after a moderate-to-high-intensity session for HRV values to return to pre-exercise levels (Stanley et al., 2013). In general, it seems that parasympathetic reactivation is diminished most by the intensity of the preceding exercise instead of the duration (Kaikkonen et al., 2007, 2010; Seiler et al., 2007).

Metabolic factors such as blood lactate concentration (Menzies et al., 2010) or oxygen consumption (Smith & Naughton, 1993) seem to recover quite rapidly. Both can return to resting levels already in 30 minutes (Menzies et al., 2010; Smith & Naughton, 1993), although after demanding exercises, the excess post-exercise oxygen consumption (EPOC) can be apparent from a few hours to 24 hours (Børsheim & Bahr, 2003). Like HRV, EPOC is affected more by the intensity than the duration of the preceding exercise (Børsheim & Bahr, 2003). Regarding the physiological responses during exercise, the studies have reported unaltered running economy 24 hours after high-intensity (Morgan et al., 1990) and moderate-intensity exercises (Quinn & Manley, 2012) or two days after a marathon (Kyröläinen et al., 2000). Petersen et al. (2007) found even improvements in running economy two and five days after a marathon. Similarly, in submaximal HR lowered values have been reported two days after a supramaximal exercise (Buchheit et al., 2009) or ultramarathon race (Siegl et al., 2017), possibly partly due to acute plasma volume expansion (Buchheit et al., 2009).

2.2.2 Neuromuscular responses

Endurance exercises require a prolonged period of submaximal muscle work, which may cause fatigue in the neuromuscular system. Fatigue induced by exercise can have central and peripheral origins. Central fatigue relates to mechanisms that decrease the voluntary activation of the muscle, while peripheral fatigue is associated with decreased capability for muscle contractions despite similar central activation (Carroll et al., 2017). Both mechanisms may lead to a similar outcome: acutely impaired neuromuscular performance. Neuromuscular fatigue caused by high-intensity or prolonged duration of endurance exercise can relate to peripheral contractile mechanism's disturbances (Carroll et al., 2017; Škof & Strojnik, 2005) as well as decreased voluntary activation (Carroll et al., 2017) or changes in stretch-reflex sensitivity and muscle stiffness (Avela & Komi, 1998).

The notion of one distinct root cause for fatigue has been challenged, and as a consequence, the recruitment (or lack of) of motor units could rather be affected by multiple concurrent mechanisms (Lambert et al. 2005).

From a neuromuscular performance point of view, acute decrements in the maximal voluntary contraction (MVC) have been reported in leg press after a 5-km time trial (Nummela et al., 2008), in knee extension after a 30-km trail-running race (Millet et al., 2003), and in knee extension and plantar flexion after a marathon (Petersen et al., 2007). Nummela et al. (2008) also found that the muscle activity in the running muscles, as well as the maximal sprinting speed, decreased during a maximal 5-km time trial in well-trained distance runners. Finni et al. (2003), in turn, discovered that the running economy or kinematics were not significantly altered by a 10-km run, whereas the maximal sprinting speed was impaired in untrained males. Millet and Lepers (2004) have suggested that after running exercises longer than 2 hours, the strength loss would increase in a non-linear way with the exercise duration. This could possibly relate to the stretch-shortening nature of running, which could lead to impairment in the contractile properties of the muscle (Avela et al. 1999). It should be noted that most protocols have examined neuromuscular fatigue after extensive/maximal sessions, while responses to more typical low- or moderate-intensity exercises are not similarly known.

Although impaired neuromuscular performance has been observed in MVC and maximal sprints after several endurance exercises, also improved performance has been found in endurance-trained athletes, especially in rapid force movements, such as countermovement jump (CMJ) (Boullosa & Tuimil, 2009; Vuorimaa et al., 2006). These responses are suggested to relate to post-activation potentiation (PAP) which is defined as acute improved muscular performance as a result of their contractile history (Tillin & Bishop, 2009). This phenomenon seems to concern especially high-intensity exercises since Vuorimaa et al. (2006) found improved CMJ performance after a 40-min continuous run at 80% vVO_{2max} and 10 × 2-min intervals at 100% vVO_{2max}; and additionally, Boullosa and Tuimil (2009) detected similar improvements after two different maximal field running tests in endurance-trained athletes. Due to this potentiation effect, it has been suggested that the CMJ may not be an optimal marker to describe neuromuscular load/fatigue during endurance exercise sessions (García-Pinillos et al., 2021).

Regarding the neuromuscular responses and recovery, also the training mode might have a significant effect (Brownstein et al., 2022). While cycling involves mainly concentric muscle work, running is associated with a repeated stretch-shortening cycle, as mentioned earlier. Therefore, running exercises such as high-intensity intervals (Wiewelhove et al., 2016), long-distance sessions (Quinn & Manley, 2012), or marathons (Avela et al., 1999; Kyröläinen et al., 2000) may induce muscle damage that could take several days to recover. Moreover, neuromuscular performance may remain impaired after intensive or prolonged exercise for at least 24-48 hours (Gómez et al., 2002; Petersen et al., 2007; Wiewelhove et al., 2016).

2.2.3 Perceptual responses

The psychobiological aspects of endurance performance (Marcora, 2010) may sometimes be overlooked by physiology. However, the perceptual effort during prolonged endurance events could affect the pacing and, eventually, the outcome measured as performance (de Koning et al., 2011; Joseph et al., 2008). The perceived effort could also be utilized in the training prescription, for example, via intervals that are performed with the maximal sustainable effort (Rønnestad et al., 2020; Seiler et al., 2013). The typical method to assess perceptual responses during exercise is via the rating of perceived exertion (RPE). A few different types of models have been established, and the most common ones are probably the 0-10 and 6-20 scales (Borg, 1982) that are used to estimate current perceptual effort during the exercise. Also a slightly different modification, the session RPE, has been adapted from the original model to estimate the training load of the preceding session by multiplying the number (0-10) by the duration (minutes) (Foster et al., 1996). Typically, the perceived effort increases during endurance activities regardless of the maintained power or speed (Crewe et al., 2008; Steed et al., 1994), even at low intensities (Steed et al., 1994). Changes in the RPE seem to be quite well aligned with the changes in the HR and blood lactate (Borg et al., 1987).

In addition to the estimations made during the activity, recovery from the exercise is typically assessed at resting conditions from perceptual aspects such as fatigue and muscle soreness (Hooper et al., 1995). After prolonged or intensive endurance exercise, it is typical that perceived exertion and muscle soreness would remain increased for more than 24 hours, especially after running of long distances (Quinn & Manley, 2012; Siegl et al., 2017). Interestingly, the perceptual responses could also counteract the physiological responses such as the submaximal HR (Siegl et al., 2017) during the recovery phase after exercise. Although muscle soreness or increased perceived effort does not necessarily indicate compromised performance, Marcora and Bosio (2007) have illustrated that high muscle soreness could lead to impaired performance via increased perceived effort during time-trial.

2.3 Adaptations to endurance training

2.3.1 Physiological adaptations to endurance training

When endurance exercises are repeated with adequate frequency, physiological adaptations occur to improve the body's capability to function when encountering similar physical challenges again. Most of the physiological adaptations are related to either enhanced capacity to deliver oxygen to the working muscle groups (central adaptations) or improved capacity to utilize delivered oxygen in the active muscles (peripheral adaptations) (Bassett & Howley, 2000).

In terms of central adaptations, the pulmonary system function is not typically regarded to be significantly limiting endurance performance. It has been observed that in normal conditions, there is no significant change in the arterial oxygen content even at high intensities (Scroop & Shipp, 2010). However, in specific groups, such as well-trained endurance athletes with high metabolic and ventilatory demands, also the pulmonary capacity could limit the endurance performance (Amann, 2012). The most important adaptations that are possibly occurring in the pulmonary system include the increased fatigue resistance of ventilatory muscles (Boutellier et al., 1992) and the improved pulmonary diffusing capacity (Dridi et al., 2021).

Cardiac adaptations are perhaps one of the key factors improving endurance performance and VO_{2max} after endurance training. Strong associations have been observed between the maximal cardiac output and the VO_{2max} (Bassett & Howley, 2000). Since the maximum HR is not significantly affected by endurance training, or it may even decrease, the only way to increase cardiac output is by increasing the volume of pumped blood by each stroke. The stroke volume could be improved by increasing the size of the (left) ventricle and by increasing the muscle mass of the left ventricle (Arbab-Zadeh et al., 2014; Scharhag et al., 2002). Increased stroke volume has been observed after endurance training (Astorino et al., 2017; Hatle et al., 2014; Helgerud et al., 2007) and in a cross-sectional analysis of endurance athletes (Pluim et al., 2000). Although it has originally been suggested that the stroke volume would plateau at low intensity (Åstrand et al., 1964), in endurance-trained athletes, it may continue to increase until achieving the VO_{2max} (Gledhill et al., 1994; Wang et al., 2012), which relates possibly to another important adaptation.

The blood's capacity to deliver oxygen is mainly determined by the hemoglobin (Hb) mass (Mairbäurl, 2013). Hb is delivered in the red cells, and although Hb concentration/l or hematocrit (% fraction of red cells in the blood) are highly used standard markers, the absolute Hb and the red cell mass are better indicators for oxygen transport capacity, especially in endurance-trained athletes (Schmidt et al., 2002). Regarding relative Hb, endurance athletes may even have lowered values due to athletes' anemia (Mairbäurl, 2013) which is caused by increased plasma volume - another typical adaptation followed by endurance training (Sawka et al., 2000). The increase in plasma and blood volume is an important adaptation which has an indirect impact by increasing venous return to the heart and thus affecting the cardiac stroke volume by the Frank-Starling mechanism (Grant et al., 1997; Hopper et al., 1988). Whether blood oxygen-carrying capacity could be affected significantly by endurance training is not as clear as is its strong association to the VO_{2max} (Eastwood et al., 2009; Schmidt & Prommer, 2008). For example, Steiner and Wehrlin (2011) found no changes in blood oxygen-carrying capacity in top endurance athletes between the ages of 21 and 28, suggesting changes to be rather minor at the highest. However, methods such as high-altitude training in a real environment or simulated environment have increased Hb and red cell mass at least acutely (Nummela et al., 2021).

Peripheral adaptations occur locally in the muscles that are used during exercise. Adaptations are basically related to the increased ability to oxidize fats and carbohydrates aerobically. Although peripheral factors are typically suggested not to limit endurance performance, it is possible in activities of small muscle groups (Saltin et al., 1976). Regarding circulation in the muscles, the capillary density could be increased by endurance training (Denis et al., 1986; Liu et al., 2022; Shono et al., 2002), and endurance-trained individuals have higher capillary density compared to untrained individuals (Brodal et al., 1977). In addition, mitochondrial density (Jacobs & Lundby, 2013; Lundby & Jacobs, 2016; MacInnis et al., 2017) and enzyme activities related to aerobic metabolism, such as citrate synthase, increase after endurance training (Carter et al., 2001; Jacobs & Lundby, 2013; Taylor & Bachman, 1999), leading to higher muscular oxidative capacity. Especially in longer endurance events, the capacity to oxidize fat and maintain high rates of fat oxidation at higher intensities is a relevant training adaptation (Hetlelid et al., 2015; Lindsay et al., 1996).

2.3.2 Neuromuscular adaptations to endurance and combined strength and endurance training

Although the focus of endurance training adaptations may have traditionally been on the metabolic and cardiovascular system, the importance of the neuromuscular system has been understood during the last decades (Nummela et al., 2006; Paavolainen et al., 2000; Paavolainen et al., 1999b). From a neuromuscular point of view, a typical endurance exercise consists of thousands of submaximal contractions. Therefore, the adaptations mainly relate to the increased ability to sustain the submaximal load and resist fatigue, specifically in the muscle groups involved. It has been found that endurance-trained athletes have a high proportion of type I slow-twitch (ST) muscle fibers that could be described as fatigue-resistant (Saltin et al., 1977). Although training years have been reported to be associated with the percentage of type I fibers (Coyle et al., 1991), it remains debated, whether muscle fibers could shift from less fatigue-resistant fast-twitch (FT) type II fibers to ST type I fibers. At least within subtypes, this type of transformation from type IIb to type IIa has been suggested to occur (Saltin et al., 1977).

While increased maximal strength, muscle fiber cross-sectional area (CSA), and rapid force development (RFD) are typical adaptations after the strength training period (Häkkinen et al., 2003; Mikkola et al., 2012; Rønnestad et al., 2012), pure endurance training is not likely to improve neuromuscular performance or increase muscle CSA to the same extent (Mikkola et al., 2012; Vikmoen et al., 2016a; 2016b). However, when endurance training is combined with strength training, it is possible to achieve similar adaptations in maximal strength (Häkkinen et al., 2003; Mikkola et al., 2012; Vikmoen et al., 2020). Interestingly, RFD seems to be a capability that may be more challenging to improve if endurance training is being performed along with strength training (Häkkinen et al., 2003; Mikkola et al., 2012; Rønnestad et al., 2012).

The neuromuscular adaptations have been suggested to enhance endurance performance via improved muscle power (Paavolainen et al., 1999a), economy of movement (Millet et al., 2002; Paavolainen et al., 1999a; Vikmoen et al., 2016b), and fractional utilization of VO_{2max} (Vikmoen et al., 2016b). In their review, Rønnestad and Mujika (2014) suggested that the main adaptations contributing to improved performance are delayed activation of type II fibers, improved neuromuscular efficiency, shift from IIb to IIa fibers, and improved musculotendinous stiffness.

2.3.3 Effects of intensity and volume on training adaptations

While adaptations associated with endurance training and superior performance are quite well known, the interaction between training intensity and volume to induce such adaptations have remained more controversial. It has been frequently observed that endurance athletes tend to perform quite a high proportion of training as LIT (70-90%) and a smaller proportion at the intensities of MIT or HIT (10-30%) (Seiler, 2010; Stöggl & Sperlich, 2015). Based on these findings, it seems that both types of training methods (LIT, MIT-HIT) are needed to optimize training adaptations.

Training protocols that have examined the effects of HIT have typically incorporated 2-3 HIIT sessions into the weekly program of participants (Cicioni-Kolsky et al., 2013; Helgerud et al., 2007; Seiler et al., 2013). Another method that has been applied is block periodization which consists of a momentary (e.g., 1-week) high proportion of HIIT sessions, followed by a period focusing on LIT (Rønnestad et al., 2014; 2016). In turn, protocols that have focused on increasing training volume have mostly been either a few weeks' overload periods of a sudden increase in volume (Bellenger et al., 2016; Le Meur et al., 2013b; Lehmann et al., 1992) or slightly longer periods with a more moderate progression of training volume (e.g., 10% per week) (Bellinger et al., 2020b; Düking et al., 2020; Vesterinen et al., 2016a). A certain challenge is that training interventions generally will not last more than 8-12 weeks, leaving the long-term effects of different training methods more questionable. Since athletes typically achieve progression in training volume from junior to elite years while keeping training intensity distribution (TID) quite constant (Schmitt et al., 2021; Tjelta, 2019), the importance of volume and LIT may not fully emerge during short interventions.

Studies that have compared either increased volume or intensity of training have typically focused on performance-related parameters. A relatively consistent finding has been that HIT improves maximal performance (vMax, VO_{2max}), submaximal performance (velocity/power at thresholds), and time-trial performance (Nuuttila et al., 2017; Rønnestad et al., 2020; Stöggl & Sperlich, 2015; Vesterinen et al., 2016a). It has also been suggested that polarized training, mixing LIT and HIT, or a period focusing only on HIT would induce greater adaptations compared to high-volume LIT (Stöggl & Sperlich, 2015). On the other hand, Talsnes et al. (2022) or Vesterinen et al. (2016a) found no significant differences between groups that increased either volume or intensity of endurance training. Somewhat contrary to most studies, Ingham et al. (2008) even found that both maximal and submaximal performance were improved by 10 weeks of exclusive LIT, and a program mixing LIT, MIT and HIT improved only maximal performance. Contradictions may, at least partly, relate to the period preceding the intervention. For example, in the case of Ingham et al. (2008), the training period was started after off season. Also, the TID of volume groups has varied. One interesting aspect related to adaptations is that especially after HIT they could be reclaimed quite rapidly (Sylta et al., 2017).

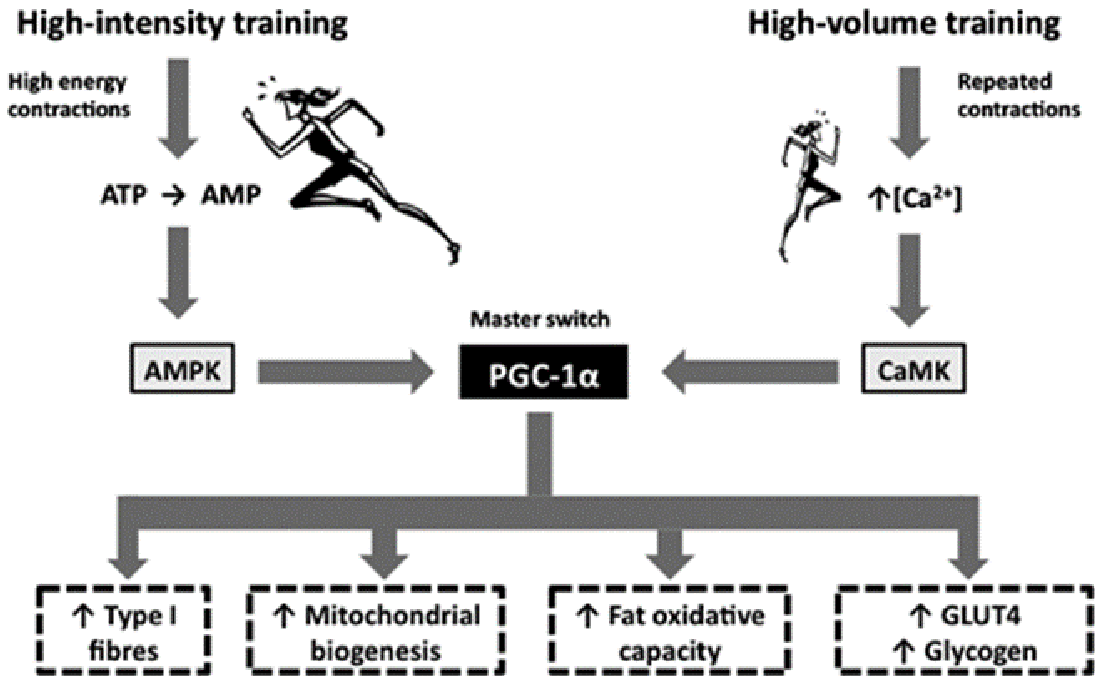

FIGURE 3 Simplified model of signaling pathways following high-intensity or high-volume training. From Laursen (2010), reproduced with permission from John Wiley & Sons A/S.

Regarding the physiological adaptations, it seems that HIT could have significant effect at a central level. For example, cardiac stroke volume has increased in many HIT interventions (Astorino et al., 2017; Hatle et al., 2014; Helgerud et al., 2007). Also, several peripheral adaptations have been suggested, such as potential mitochondrial biogenesis (Gibala, 2009; Little et al., 2010) and increased oxidative enzyme activities (Hoshino et al., 2016; Little et al., 2010). One speculative factor relating to HIT adaptations is that they may affect specifically type II muscle fibers (Gibala & McGee, 2008; Kohn et al., 2011) and improve their oxidative capacity since they would not be similarly activated at low intensities. Another HIT-specific adaptation is increased buffer capacity (Edge et al., 2006; Weston et al., 1996) which would be advantageous, especially in shorter endurance events. LIT, in turn, is suggested to induce mostly peripheral adaptations, such as increased capillary density (Nybo et al., 2010; Shono et al. 2002) and enzyme activity of aerobic pathways (Carter et al., 2001; Gillen et al., 2016). The volume of (LIT) training may also have a significant positive effect on plasma volume expansion (Green et al., 1991). As can be noticed, there is currently no conclusive evidence that the main adaptations followed by high-volume or -intensity training would differ dramatically. Laursen (2010) speculated that these somewhat similar adaptations would be driven through different signaling mechanisms (FIGURE 3), which highlights the possible advantages of combining LIT and HIT.

2.3.4 Interindividual variation in the training adaptation

In endurance training interventions, participants are typically exposed to a similar types of predetermined endurance training programs. The training programs can be scaled based on the individuals' background and previous training, for example, by increasing volume compared to the typical level of an individual, or by replacing a certain number of sessions with an unused training method (e.g., HIIT) (Vesterinen et al., 2016a). Another important way to take into account individual differences is to lock training intensity of sessions on individually defined training zones based on measured thresholds, instead of a fixed proportion of maximum HR (Mann et al., 2014). Although training would have been standardized with the aforementioned methods, it is typical to observe quite a large variation in the training adaptations measured as performance or physiological parameters. For example, Vollaard et al. (2009) reported changes in aerobic capacity ranging from a 2% decrease to > 30% improvement after a 6-week period in sedentary men. In turn, in recreational runners, changes in vMax have varied from slightly negative up to 10% improvements after 14-week basic or intense training periods (Vesterinen et al., 2013). In the same study, the mean increase for vMax was 4.1% after the basic training period and 3.3% after the intense training period.

When reasons behind interindividual differences have been analyzed, genetics seem to play a certain role. Bouchard et al. (1999) argued that even 50% of the training response in VO_{2max} could be explained by genetic components. However, there also exist multiple other reasons that an individual can influence. For example, training status/baseline fitness level, nutritional status, sleep, and general stress are all possible contributors to the adaptations (Mann et al., 2014). In the long term, also training compliance and training days missed due to injury or illness are most likely contributing to the high adaptation or the lack of it (Talsnes et al., 2020). Interestingly, it has been observed that the ANS function assessed indirectly via resting HRV could also relate to the training adaptation after HIT and LIT training. Vesterinen et al. (2016a) reported positive associations between HIT and HRV, as well as negative association between HRV and LIT. The authors speculated that individuals with higher vagal (parasympathetic nervous system) activity may have a better capacity to cope with intensified training. This theory has been supported by several studies that have observed associations between baseline HRV and training adaptation to HIT (Nuuttila et al., 2017; Vesterinen et al., 2013). In addition to the training process itself, also several external stressors may be reflected in HRV, and it is relevant to notice that high stress outside of training can translate into diminished training adaptations (Bartholomew et al., 2008; Otter et al., 2015; Ruuska et al., 2012).

While multiple aspects may affect how an individual adapts to a specific training program, also the training method (intensity/volume) itself may have an effect. For example, some studies have suggested that LIT induces fewer low-responders (Zinner et al., 2018) and more high-responders (Düking et al., 2020) compared to HIT. On the other hand, it has been argued that such a phenomenon as non-/low-responders would not exist, and the issue would rather be associated with improper training stimulus for an individual. This has been supported by studies where such individuals have disappeared after intensifying training (Gaskill et al., 1999) or increasing training dose (Montero & Lundby, 2017). Another aspect to acknowledge is that despite not being a responder to a certain parameter, the same individual could possibly be regarded as a responder in another marker (Scharhag-Rosenberger et al., 2012). Increasing the likelihood of positive training adaptations is probably the main rationale behind individualized training prescriptions (Düking et al., 2021).

2.4 Training and recovery monitoring

When there is a major increase in training load, there is also an increased risk of injuries (Maupin et al., 2020) and maladaptation or overreaching (Bellinger, 2020), leading to impaired performance. To avoid such consequences, it would be beneficial to recognize early signs that may predict a compromised state of recovery and negative training adaptations. Since responses to similar external and internal training loads can vary between individuals (Neumann et al., 2022), the training load on its own does not necessarily provide sufficient information. Monitoring of training and recovery typically consists of regular assessments of physiological, perceptual, or performance-related markers that are estimated to provide valuable information about the recovery-training state of an athlete (Halson, 2014). On one end of the monitoring tool spectrum there are extensive laboratory tests, such as hormonal or biochemical examinations from blood or urine (Cadegiani & Kater, 2017; Lehmann et al., 1992), whereas perceptual markers such as subjective surveys (Hooper et al., 1995; ten Haaf et al., 2017) or session RPE (Foster et al., 1996) represent the other end of the spectrum. In addition, non-invasive assessments of physiological markers, like HRV recordings at rest (Vesterinen et al., 2016c), HR during exercise (Capostagno et al., 2014), and performance-related markers, such as various jumping tests (Claudino et al., 2016) can be utilized in monitoring. The purpose of the monitoring process is to follow whether an athlete is adapting to the stimulus as expected and to influence decisions for the forthcoming training load (Claudino et al., 2016) or session intensity (Capostagno et al., 2014; Vesterinen et al., 2016c). While it may even be desirable to induce acute fatigue by single exercises, prolonged excessive fatigue should be avoided, because it can be regarded as a sign of non-functional overreaching which in the most serious cases could develop into an overtraining syndrome (FIGURE 4). Although sometimes even desired by athletes, Bellinger (2020) recently argued that functional overreaching would not be necessary for the training process nor would it lead to greater improvements compared to training resulting in acute fatigue only.

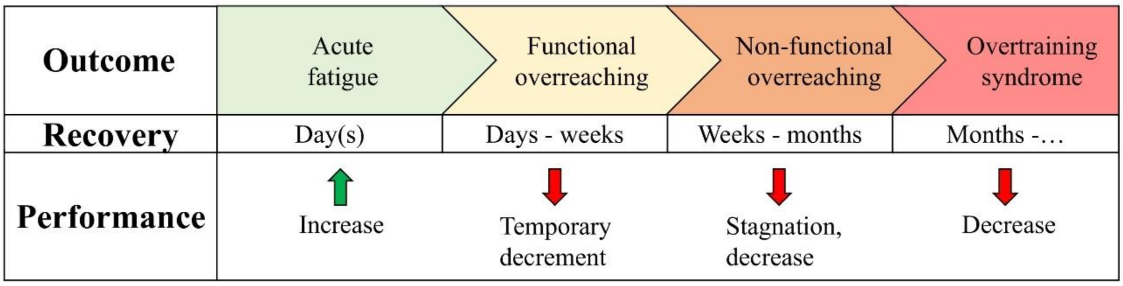

FIGURE 4 States of fatigue. Modified from Meeusen et al. (2013).

2.4.1 Indirect performance estimations

Maximal endurance tests are challenging to incorporate into day-to-day monitoring of an athlete since they always interfere with training and recovery. Therefore, endurance performance is more often evaluated indirectly, based on submaximal tests (Decroix et al., 2018; Vesterinen et al., 2016b) or data collected from normal training sessions (Vesterinen et al., 2014). Since submaximal tests are only estimations of the current performance level, they have their limitations. The basic logic behind such tests is that they assess the relation between external load (speed, power) and internal response (HR, blood lactate, RPE) the load induces. When the internal load decreases in relation to the external load, it could be taken as a sign of positive training adaptation and improved performance (Vesterinen et al., 2014; Vesterinen et al., 2016b), while the opposite may relate to impaired performance and increased fatigue. Despite the fact that these assumptions are in general correct, some contradictions make interpretations of the results more challenging. It has been found that internal markers such as blood lactate (Bosquet et al., 2001; Le Meur et al., 2013a) or HR (Le Meur et al., 2013a; Roete et al., 2021) could also decrease during submaximal exercise as a sign of high training load and cumulative fatigue, which in that case may relate to overreaching. Another challenge relating to submaximal tests is the daily variation in HR which could be as high as 7-9 bpm (Lamberts & Lambert, 2009). One option to overcome the aforementioned issues would be to standardize the submaximal test intensity based on perceived effort instead of physiological markers (Sangan et al., 2021), or at least support the submaximal HR response with perceived exertion (Capostagno et al., 2014; Roete et al., 2021). Recently, one interesting HRV marker (DFA-a1) has been introduced (Gronwald et al., 2020), and it has been suggested to have certain advantages compared to the traditional HR markers. However, despite some preliminary findings related to the detection of aerobic threshold (Rogers et al., 2021; 2022), the actual usefulness as well as repeatability of the marker across different training modes and populations are yet to be confirmed. Heart rate recovery (HRR) is a marker that combines exercise and resting conditions. Basically, HRR is analyzed by calculating short-term (e.g., 60 s) decrease in HR after exercise cessation. HRR is thought to relate to sympathetic withdrawal and parasympathetic reactivation (Buchheit, 2014). There are certain limitations in the application of HRR which are the same as in other HR-based markers:

identical changes can be associated with both positive (Stöggl & Björklund, 2017) and negative (Aubry et al., 2015) changes in performance. However, it has been suggested that HRR could be a useful marker in the detection of functional over-reaching when it is combined with supportive information, such as submaximal RPE (Roete et al., 2021).

In addition to endurance performance itself, also some specific aspects such as neuromuscular performance could be monitored to gain a more comprehensive picture of the current recovery state. Especially in running, which induces high stress in the musculoskeletal tissues of the lower limbs, mechanical fatigue caused by training may also relate to overuse injuries (Edwards, 2018). Therefore, maintenance or even improvements in neuromuscular performance could be regarded as desirable in endurance athletes. Similar to endurance tests, frequent monitoring favors simple tests that are possible to perform also at field conditions. CMJ is quite a widely used test that measures the explosive force production of the lower limbs and can be easily assessed e.g., via a mobile phone application (Balsalobre-Fernández et al., 2015a). The flight-time based (contact mat) CMJ test was originally developed by Bosco et al. (1983) for a simple and feasible assessment of maximal explosive power and mechanical power in a ballistic motion. In the context of endurance training monitoring, the potential usefulness of the test has been supported by Balsalobre-Fernández et al. (2014) who found that increased training load and running volume were associated with impaired CMJ during a 39-week follow-up study. Furthermore, the authors discovered that better CMJ performance was accompanied by better performance in running competitions. Also Marco-Contreras et al. (2021) reported in their case study significant correlations between training load and CMJ performance. In turn, Bachero-Mena et al. (2017) found that during the competitive season, positive trends in both CMJ and running performance were observed in middle-distance runners. In addition to CMJ, there exists also some other options for neuromuscular performance testing such as the 5-jump test (Paavolainen et al., 1999a) or sprint tests (Balsalobre-Fernández et al., 2015b). However, especially in recreational runners, the reliability of the test as well as the risk of injuries should be taken into account when considering the appropriate tests.

2.4.2 Resting heart rate and heart rate variability

Different types of HR measures are widely used in endurance training monitoring, and resting HRV in particular is stated to be a useful marker when assessing the state of recovery of an individual (Buchheit, 2014; Stanley et al., 2013). In general, it is suggested that HRV provides information on the regulation of ANS, and HRV could be used as an indirect marker of cardiac parasympathetic nervous system activity (Martinmäki et al., 2006) and cardiovascular homeostasis (Stanley et al., 2013). While multiple analysis methods and parameters exist for HRV (Task Force, 1996), high frequency power (HF) (Martinmäki et al., 2006; Thomas et al., 2019) and root mean square of successive differences (RMMSD) (Thomas et al., 2019) seem to be the most valid opportunities for noninvasive assessment of parasympathetic nervous system activity. Although it has also been suggested that low-frequency power (LF) or the ratio between LF and HF would provide information about the sympathetic nervous system activity or the sympathovagal balance, it is quite debated to which extent such simplification could be made (Billman, 2013; Shaffer et al., 2014). Recently, Altini and Plews (2021) illustrated how resting HRV might provide additional insights compared to mere HR on responses to different types of stressors. In the training context, daily resting HRV recordings have been used in the endurance training prescription of untrained (da Silva et al., 2019), recreationally trained (Vesterinen et al., 2016c), and well-trained (Javaloyes et al., 2019) participants, inducing greater improvements in endurance performance compared to predefined training.

Previously, various time frames (nocturnal, morning) to analyze resting HR and HRV have been introduced, but all HRV-guided training protocols, for example, have utilized morning or day-time recordings (Düking et al., 2021). Although sleep is not necessarily a stable period in terms of the ANS function and HRV (Herzig et al., 2018), when data is being averaged for a sufficient period (e.g., 4 h), very good day-to-day reliability has been reported in nocturnal HRV (Nuuttila et al., 2022), and within-week variation could be even lower compared to morning recordings (Mishica et al., 2022). Furthermore, nocturnal HRV seems to be sensitive and demonstrate internal responses to the training load (Nuuttila et al., 2022). While nocturnal recordings may have been challenging to implement frequently (Buchheit, 2014), the current technology provides validated and feasible opportunities to record HR and HRV through the night (Cao et al., 2022; Nuuttila et al., 2021; Vesterinen et al., 2020). Recently, it was found that nocturnal HRV and morning HRV correlated significantly (Mishica et al., 2022). However, Ruiz-Alias et al. (2022) reported that week-to-week changes would not be necessarily aligned. Until proven otherwise, the best period to monitor HRV is probably the most feasible one that would allow frequent high-quality monitoring for an individual.

There exist some contradictions that should be taken into account when considering resting HR or HRV results. First of all, responses can sometimes be paradoxical like the results of HR-based submaximal exercise tests (Bellenger et al., 2016; Le Meur et al., 2013a). In addition, acute changes in HRV may relate to the shifts in plasma volume, regardless of the recovery state (Buchheit et al., 2009). During periods of high training load, contradictory changes may relate to decreased activity of the sympathetic nervous system via a reduced adrenergic response during exercise (Le Meur et al., 2014) or down-regulation of β-adrenoreceptors (Lehmann et al., 1998) leading to parasympathetic hyperactivity. Finally, it should be acknowledged that HRV does not necessarily reflect the recovery of the neuromuscular system (Flatt et al., 2019; Thamm et al., 2019), which potentially should have implications on the training prescription.

2.4.3 Basal hormonal levels

Endogenous hormones play a crucial role in the physiological responses and adaptations to training via anabolic and catabolic processes (Urhausen et al., 1995). Therefore, it has been suggested that the basal levels of certain hormones would provide information about the recovery state of an individual. Among the different markers, testosterone or free testosterone and cortisol are functionally somewhat contradictory hormones that are thought to reflect anabolic and catabolic processes in the body (Urhausen et al., 1995). Interestingly, it has been observed that endurance training, in general, tends to decrease testosterone levels (Hackney & Lane, 2018; 2020), but this decrement is not a direct sign of impaired performance (Hackney & Hooper, 2019). In long-term monitoring, the greatest changes in hormonal levels may occur at the beginning of the training year, but in well-trained athletes variations remain somewhat minor (Alves et al., 2020; Häkkinen et al., 1989), at least when the training load is appropriate. Regarding changes in basal testosterone levels, previous studies have been contradictory: after endurance training periods that have led to improved performance, basal levels have remained similar (Vesterinen et al., 2016a), increased (Nuuttila et al., 2017; Zinner et al., 2013), or decreased (Sylta et al., 2017). Also, changes in the stress hormone cortisol (Nuuttila et al., 2017; Sylta et al., 2017; Vesterinen et al., 2016a) or the ratio between testosterone and cortisol (Nuuttila et al., 2017; Sylta et al., 2017) have remained rather trivial. In the state of overtraining, resting testosterone (Lehmann et al., 1992; Uusitalo et al., 1998) and cortisol levels (Hynynen et al., 2006; Uusitalo et al., 1998) have been reported as unchanged, and in one study, cortisol has even decreased (Lehmann et al., 1992). In well-trained rowers, Mäestu et al. (2005) reported decreased resting free testosterone levels as well as diminished response to maximal exercise after a heavy increase in the training load.

Other hormones that may be useful in the detection of overtraining are catecholamines (Urhausen et al., 1995). Catecholamines, adrenaline, and noradrenaline are responsible for sympathetic nervous system effects in the organs (Axelrod & Weinshilboum, 1972). Resting catecholamine levels have typically been analyzed through nocturnal urine collections to illustrate the long-term activity of the sympathetic nervous system (Hynynen et al., 2006; Lehmann et al., 1992; Uusitalo et al., 1998). Similar to testosterone and cortisol, the findings regarding catecholamines have been somewhat contradictory, and decreases at rest (Lehmann et al., 1992) and after maximal exercise, (Lehmann et al., 1992; Uusitalo et al., 1998) as well as no change (Le Meur et al., 2014; Lehmann et al., 1992) have been previously observed after intensified training. In general, it seems that hormonal responses to exercise may be better and more sensitive in terms of overtraining detection than basal levels (Cadegiani & Kater, 2017). Furthermore, Meeusen et al. (2004) have suggested that the protocol assessing hormonal responses to two maximal exercises on the same day would be especially useful in detecting differences in the training status. Contradictions in the hormonal values could also relate to the differences in the protocols (increased volume, intensity, or both) as well as the level of fatigue/overreaching at the moment of hormonal assessments. However, it seems likely that in the overtraining detection, it is challenging to detect meaningful changes from one single assessment only (Snyder & Hackney, 2013).

2.4.4 Perceptual markers

In addition to performance and physiological markers, recovery and training state could be assessed from a subjective perspective. In the systematic review of Saw et al. (2016), subjective/perceptual markers were suggested to be more sensitive than objective measures to acute and chronic changes in the training load. Furthermore, Saw et al. (2016) found that subjective and objective markers of recovery correlated poorly in general. Regarding the usefulness of perceptual markers in monitoring recovery, ten Haaf et al. (2017) have even suggested that perceived fatigue and readiness to train could predict the overreaching state after a few days of an intensive cycling event. It has also been found that increases in markers reflecting perceptual fatigue and muscle soreness could be associated with an increased risk of staleness (Hooper et al., 1995).

Options for the evaluation of perceived recovery include detailed surveys (Kellmann, 2010), single-item assessments (Laurent et al., 2011), or a hybrid model containing a few aspects of recovery such as fatigue, muscle soreness, sleep quality, and stress (Hooper et al., 1995). In the simple scales, it is typical to use a combination of words and numbers such as 0-10 (Laurent et al., 2011) or 1-7 (Hooper et al., 1995). Another option is to use a visual analogue scale (VAS), containing negative and positive extremities for the aspect in question (ten Haaf et al., 2017). Session RPE is a marker of internal training load (Foster et al., 1996) that may also provide information regarding the recovery state. Increases in session RPE without the change in other training load parameters could be related to accumulated training fatigue (Fusco et al., 2020; Pind et al., 2021). As discussed earlier, perceptual markers may also help to contextualize changes in HR-based markers (Bellenger et al., 2016). Although comprehensive surveys could provide precise information about the recovery status of an athlete, an advantage of simple scales is that they allow monitoring on a daily basis (Schäfer Olstad et al., 2019).

2.4.5 Interpretation of the changes in monitoring variables

Once training and/or recovery-related data has been collected, the following interpretations and steps of action define the actual benefits of the monitoring. What type of change could be regarded as worthwhile or meaningful in a certain marker, would be the central question at this phase. Methods to set such boundaries are typically based on within- and/or between-subject variability of the monitored marker. Basically, the main idea is to differentiate meaningful change from a normal day-to-day variation. Hopkins et al., (1999) have been the pioneers of this type of statistics. In 1999, they suggested that 0.3 × coefficient of variation (CV) in performance would allow an extra medal to be taken per 10 competitions and defined this change as the smallest worthwhile change (SWC). While between-subject comparisons may work in a homogenous group of athletes, in heterogeneous groups, or in markers that may substantially differ between individuals, the within-subject variation based on previous results could be more useful (Buchheit, 2014). Proper reference values would require a sufficient period in a normal training state. In HRV, for example, most studies have applied a baseline period of regular training (7-28 days), after which measurement results have been compared to the baseline values with an SWC of ± 0.5-1.0 × standard deviation (SD) (da Silva et al., 2019; Javaloyes et al., 2019; Vesterinen et al., 2016c). Especially in HRV, it has also been suggested to use averages (3-7 days) instead of isolated values to have a valid assessment (Plews et al., 2014b). FIGURE 5 demonstrates how the SWC has been used in the interpretation of the recovery state and decisions on training intensity in Vesterinen et al. (2016c) study.

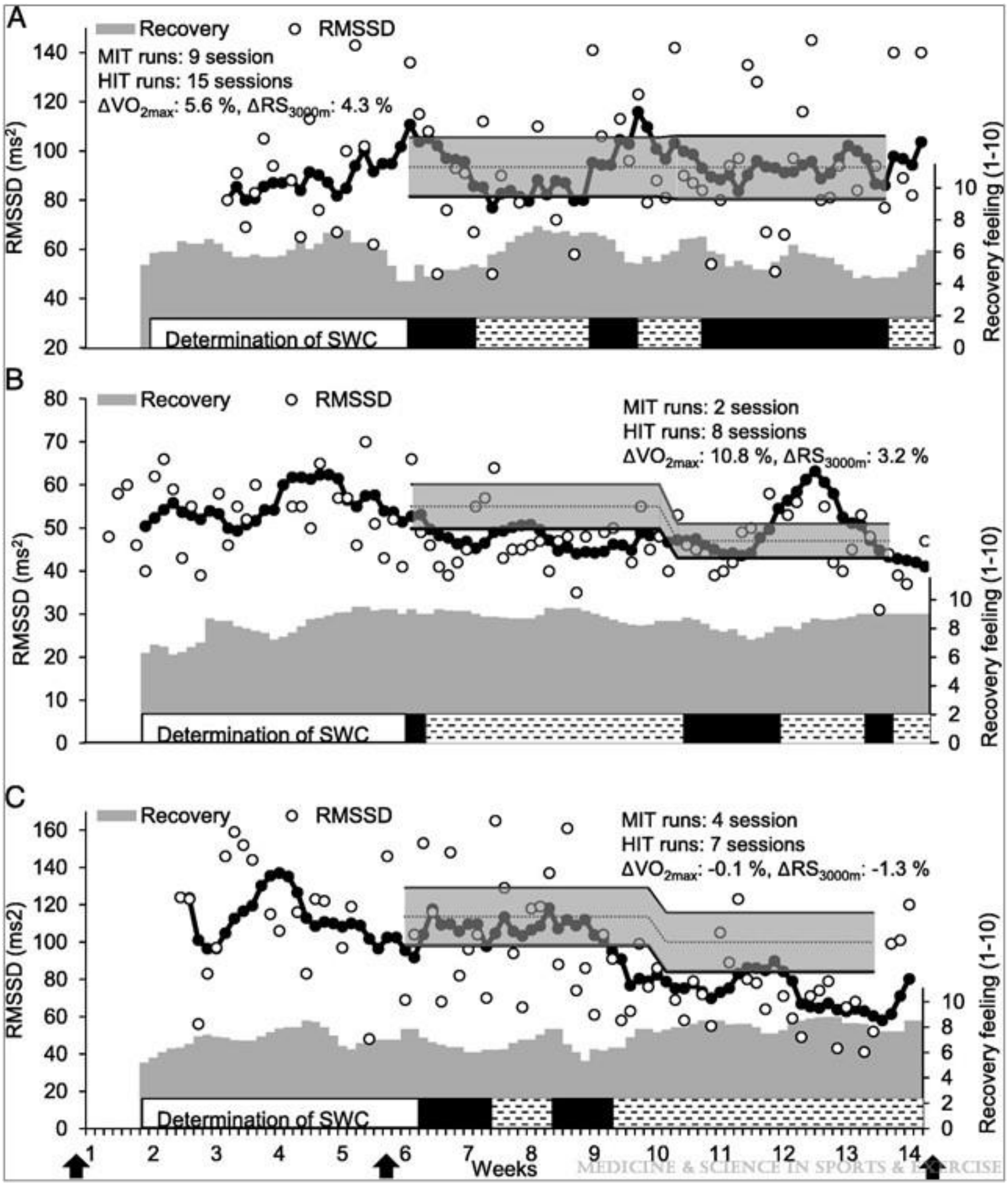

FIGURE 5 An example of execution of HRV-guided endurance prescription. From Vesterinen et al. (2016c), reproduced with permission from American College of Sports Medicine.

When considering the usefulness of certain markers for monitoring, it would be important to consider the signal (expected change in the marker) and the noise (typical error of the marker) (Buchheit, 2014). For example, Rabbani et al. (2019) suggested that subjective markers (Hooper index) may have a greater signal-to-noise ratio compared to resting HRV. Basically, the higher the ratio, the more sensitive the marker and easier to find meaningful changes. Signal-to-noise ratio also takes into account the reliability of the marker which is one of the most important characteristics of a useful monitoring tool.

2.5 Periodization of endurance training

2.5.1 Intensity distribution and periodization in endurance training

While about 80/20 division between LIT and MIT to HIT seems to be followed by most endurance athletes (Seiler, 2010), there remains a lot of room for speculations on how to optimally periodize these intensities from microcycle to training season level. Also, the proper division between MIT and HIT is somewhat debated (Burnley et al., 2022; Foster et al., 2022). Several training organization models have been identified, such as pyramidal, threshold, polarized, and block models (Mølmen et al., 2019; Rosenblat et al., 2019; Stöggl & Sperlich, 2015). In brief, pyramidal and polarized models include a high proportion of training at low intensities (~80%), but polarized favors HIT over MIT, while in the pyramidal model it is vice versa (Stöggl & Sperlich, 2015). The threshold model, in turn, puts high emphasis on MIT (35-55%) while decreasing the volume of LIT (45-55%) compared to previous models (Rosenblat et al., 2019). Block periodization refers to the model where instead of a consistent mix of LIT, MIT and HIT, it focuses only on one intensity zone for a certain period of time (block) (Mølmen et al., 2019). When comparing different types of models, it should be acknowledged that the method of training intensity definition could have a significant effect on the outcome of the analysis (Bellinger et al., 2020a; Sylta et al., 2014). For example, HR-based divisions may underestimate the amount of training at high intensities, because during interval sessions the HR does not increase immediately to the level corresponding to the workload. In this regard, the session goal approach, defining intensity distribution based on each session's target intensity (low, moderate, high) (Sylta et al., 2014), or the running speed-derived approach (Bellinger et al., 2020a) could have some advantages over the HR-based divisions. Other challenges in the TID analyses relate to the inclusion/exclusion of strength training and the ignorance of off-training activities, both of which could potentially alter responses to training and the result of TID analysis (Sperlich et al., 2022).

In the retrospective analysis of elite endurance athletes, it has been observed that TID varies also during the training season. Recently, the training of elite distance runners (track and marathon) was analyzed, and the conclusion was that both athlete groups performed high volumes of LIT (> 80%), and the amount of race pace training increased when the main event approached (Haugen et al., 2022). Successful elite skiers have previously demonstrated quite a similar approach: at the beginning of the season, relatively high training volumes are performed and there is less emphasis on HIT. In turn, when the main event approaches, the training volume starts to decrease, and a higher proportion of training is performed as HIT (Tønnessen et al., 2014). Interestingly, Filipas et al. (2022) demonstrated that this type of switch from pyramidal TID to polarized TID may be superior compared to the opposite or either of the models alone in well-trained runners.

Training interventions that have compared different types of periodization models and TID have induced somewhat controversial results. Perhaps the most typical comparison has been performed between polarized and threshold models. In many cases, the polarized approach has been superior (Esteve-Lanao et al., 2007; Muñoz et al., 2014; Neal et al., 2013; Stöggl & Sperlich, 2014), but some have found no significant differences in the main parameters (Festa et al., 2020; Selles-Perez et al., 2019). It is possible that the threshold model could be more beneficial in athletes of long-duration events, such as half-Ironman triathlons (Selles-Perez et al., 2019). On the other hand, also block periodization has been suggested to be superior compared to "traditional" methods (Mølmen et al., 2019). As mentioned earlier, the periodization models and TID may vary across the training seasons (Haugen et al., 2022; Seiler, 2010; Tønnessen et al., 2014) and even from season to season (Solli et al., 2019). Interestingly, aspects such as monotony vs. variability of the training load could also be important factors to consider when designing training periodization (Foster, 1998). Conclusively, it seems that many methods can induce quite similar outcomes, and it can be argued that there is no single right model for training periodization which would be optimal across individuals and situations.

2.5.2 Individualized training based on recovery status

There is always certain interindividual variation in the training adaptation despite standardizing the TID and the periodization of the training (Düking et al., 2020; Vesterinen et al., 2016a; Vollaard et al., 2009; Zinner et al., 2018). Therefore, instead of utilizing a predefined training program based on general recommendations it has been suggested that individualizing the training based on the ANS status (HRV) would allow proper training prescriptions for individuals by informing whether the individual would be able to adapt to intensive training (Stanley et al., 2013). This type of approach could also potentially lead to more consistent training adaptations by decreasing the interindividual variability in the responses (Vesterinen et al., 2016c). HRV-guided training, during which the training load has been adjusted based on individual HRV values, has been examined in several studies since Kiviniemi et al. (2007). Recent meta-analyses on the topic have found positive effects on submaximal markers of endurance performance (Düking et al., 2021) and VO_{2max} (Granero-Gallegos et al., 2020). Another finding has been that in many cases, HRV-guided training has led to a lower volume of HIT and a lower amount of non-responders (Düking et al., 2021).

The basic idea in all studies has been somewhat similar: Fluctuation in the resting HRV values has been compared to the individually defined normal range. If HRV has remained within desirable limits, HIT or MIT has been performed. If

HRV has been outside of the normal range, LIT or rest has been prescribed. Individual normal range has typically been analyzed as the average of 1-4 weeks preceding the intervention and ± 0.5-1 × SD of the results from that period (da Silva et al., 2019; Javaloyes et al., 2019; Vesterinen et al., 2016c). In some cases, the training adjustments have been made based on a single value only (Kiviniemi et al., 2007), but in recent studies, the averages of 3-7 preceding days have been favored (Javaloyes et al., 2019; Nuuttila et al., 2017; Vesterinen et al., 2016c). HRV recording durations have varied between 1.5 and 15 minutes, and except for da Silva et al. (2019) study, they have been performed during the morning (Düking et al., 2021). Supine position has been the most typical recording position, but also standing recordings and the combination of supine and standing have been used (Düking et al., 2021). Actual protocols and the methods to adjust training have slightly varied between studies, but the main characteristics of previous HRV-guided protocols and their outcomes are presented in TABLE 1.

Although the findings of HRV-guided training look promising (Granero-Gallegos et al., 2020; Düking et al., 2021), a single marker cannot establish all aspects critical to recovery (Buchheit, 2014; Stanley et al., 2013). To the best of my knowledge, only one previous study has considered multiple variables in the training decision scheme by analyzing three separate markers obtained from a submaximal cycling test (Capostagno et al., 2014). While it seems obvious that combining both objective and subjective markers would provide the best quality for the monitoring purposes, there certainly exists a lack of research on how to utilize such an approach in practice. Another aspect yet remaining unanswered is whether a similar type of approach could be used in the adjustment of training volume in addition to training intensity.

TABLE 1 Summary of the previous HRV-guided studies that were included in Düking et al. (2021) meta-analysis.

Study protocol and program in the predefined group	Δ% in performance
Kiviniemi et al. (2007): Recreational runners performed a 4-wk training period which consisted of 4 MIT/HIT-sessions and 2 LIT-sessions per wk. There were no significant variations in the weekly training load.	**vMax** HRV 5.8%*#, PD 3.9%*
Kiviniemi et al. (2010): Recreationally trained participants performed an 8-wk training period which consisted of at least 2 LIT and 3 MIT/HIT-sessions per wk. Possible variations in the weekly training loads were not reported. Training was performed with the modes that participants were accustomed to.	**Wmax (Males)** HRV 11.1%*#, PD 6.5%* **Wmax (Females)** HRV 18.6%*, HRV2 9.6%*, PD 10.6%*
Vesterinen et al. (2016c): Recreational runners performed an 8-wk training period which consisted of 0-3 MIT or HIIT-sessions and 2-5 LIT-sessions per wk. Training load was decreased every fourth week.	**3000 m running speed** HRV 2.1%*, PD 1.1%
Nuuttila et al. (2017): Recreational runners performed an 8-wk block period which consisted of 1-5 HIIT-sessions and 1-5 LIT-sessions. Training load was decreased every other week.	**vMax** HRV 5.1%*#, PD 2.7%* **3000 m running time** HRV -5.2%*, PD -5.2%*
Schmitt et al. (2018): Competitive cross-country skiers performed 15 days of high-altitude training. Training was executed based on the program made by national team coach.	**Roller-skiing TT** HRV -2.7%*, PD -2.5%
da Silva et al. (2019): Untrained participants performed an 8-wk training period which consisted of 1-2 MIT-sessions and 1-2 HIIT-sessions per wk. Training was periodized in a way that 2 HIIT-sessions were performed every other week and 2 MIT-sessions every other week.	**vMax** HRV 10.0%*, PD 8.2%* **5000 m running time** HRV -17.5%*, PD -14.0%*
Javaloyes et al. (2019): Well-trained male cyclists performed an 8-wk training period which consisted of 1-3 MIT/HIT-sessions and 2-5 LIT-sessions. Training load was decreased every fourth week.	**Wmax** HRV 5.1%*, PD 1.4% **40 min cycling TT average W** HRV 7.3%*, PD 4.2%
Javaloyes et al. (2020): Well-trained cyclists performed an 8-wk block period which consisted of weekly1-4 MIT or HIIT-sessions and 2-4 LIT-sessions. Training load was decreased every fourth week.	**Wmax** HRV 7.0%*, PD 4.9% **40 min cycling TT average W** HRV 6.0%*, PD 0.7%

PD, predefined training group; HRV, HRV-guided training group; LIT, low-intensity training; MIT, moderate-intensity training; HIIT, high-intensity interval training; vMax, maximal speed achieved during incremental treadmill test; Wmax, maximal power achieved during incremental cycling test; TT, time trial. *Statistically significant change within-group, #statistically significant difference between groups.

3 PURPOSE OF THE THESIS

The purpose of this thesis was to examine physiological, perceptual, and performance responses to different types of endurance exercises and endurance training periods. Furthermore, this thesis aimed to investigate whether these physiological and perceptual responses could be used in the individualization of endurance training prescription and whether this approach would lead to greater adaptations and fewer low-responders compared to a predefined endurance training program. The specific aims and hypotheses for this thesis were:

1. To analyze how the type and intensity of endurance exercise affects recovery kinetics of ANS, physiological responses to submaximal exercise, and neuromuscular performance. (Study I)

   Hypothesis: Intensity of the session is the main factor affecting ANS recovery (Kaikkonen et al., 2007; Seiler et al., 2007). Perceptual, physiological and neuromuscular recovery differ in their kinetics. (Flatt et al., 2019; Thamm et al., 2019).

2. To compare how the increase in training volume and intensity affects the perceived recovery, resting HRV and neuromuscular performance. (Studies II, III)

   Hypothesis: An increase in training volume will increase resting HRV, while intensity has the opposite effect (Plews et al., 2014a). Increased training load will also impair neuromuscular performance (Balsalobre-Fernández et al., 2014). Subjective markers will be more systematically affected by increased training load than objective markers (Saw et al., 2016).

3. To analyze which monitoring markers would predict adaptations to volume or intensity periods. (Studies II, III)

Hypothesis: The state of recovery (HRV, perceived recovery), stress outside of training (Ruuska et al., 2012) and baseline HRV (Vesterinen et al., 2016a) would be associated with the training adaptation.

4. To examine whether individually adjusted training would lead to greater endurance training adaptations than predefined training. (Study IV)

   Hypothesis: Individualized training would lead to greater improvements (Kiviniemi et al., 2007; Nuuttila et al., 2017) and fewer low-responders (Düking et al., 2021) than predefined endurance training.

4 METHODS

4.1 Participants

A total of 25 (study I), 42 (study II), and 40 (studies III, IV) participants were recruited to four separate data collections. Baseline characteristics of all participants that were involved in the final analyses are presented in TABLE 2.

TABLE 2 Baseline characteristics of the participants.

	Study I	Study II		Study III		Study IV	
		INT	VOL	INT	VOL	IND	PD
	n = 24	n = 13	n = 17	n = 15	n = 15	n = 16	n = 14
Sex (M/F)	24/0	8/5	8/9	9/6	9/6	8/8	7/7
Age (y)	35 ± 6	38 ± 4	36 ± 6	33 ± 7	37 ± 7	37 ± 7	34 ± 7
Height (cm)	180 ± 5	173 ± 11	172 ± 11	172 ± 10	174 ± 11	174 ± 8	173 ± 9
Body mass (kg)	79 ± 9	72 ± 12	70 ± 12	72 ± 14	71 ± 13	69 ± 12	71 ± 14
Fat (%)	15 ± 4	17 ± 7	19 ± 8	19 ± 4	20 ± 7	16 ± 7	18 ± 7
VO_{2max} ($ml \cdot kg^{-1} \cdot min^{-1}$)	52 ± 5	47 ± 6	47 ± 5	50 ± 7	50 ± 6	47 ± 7	46 ± 4

INT, intensity group; VOL, volume group; IND, individualized group; PD, predefined group; M, males; F, females; VO_{2max}, maximal oxygen uptake.

The participants were healthy adults ages 20 to 45 and accustomed to regular running and endurance training. Exclusion criteria, which were screened through a customized questionnaire, included diseases, injuries or use of any medications that could contraindicate strenuous exercise. In addition, a cardiologist checked the electrocardiography of all participants in studies III and IV, where it was deemed necessary because of the demanding nature of the training. Dropouts during the studies occurred due to personal reasons (n = 5), illnesses (n = 7), and musculoskeletal injuries that prevented proper execution of training during control/preparatory (n = 5) or intervention periods (n = 6). In addition, 10 participants were excluded from the final analyses due to inadequate training adherence (< 90% of the main sessions). The participants gave their written consent to participate, and the study protocols were approved by the ethics committee of the University of Jyväskylä.

4.2 Experimental designs

4.2.1 Study I

The study compared acute and post 24-h responses following four different training sessions performed on a treadmill. The order of the sessions was randomized by drawing the sequence for each participant. After a preliminary performance testing week, training sessions were performed during a one-month study period. Before (Pre), immediately after (Post), and 24 h after (Post24) each session, supine HRV, a CMJ test, and a submaximal running test (SRT) were performed. Additionally, perceived recovery and muscle soreness were estimated Pre and Post24. The structure of one training session and the measurements performed are presented in FIGURE 6.

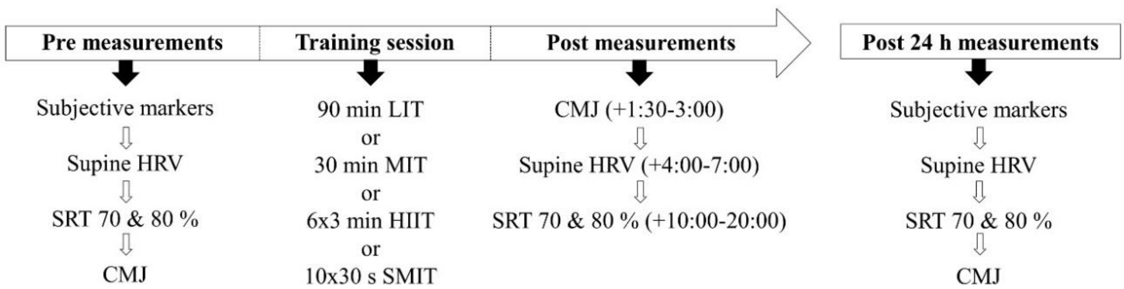

FIGURE 6 Pre, Post, and Post24 measurements around each training session. Supine HRV, supine heart rate variability; SRT, submaximal running test; CMJ, counter-movement jump; LIT, low-intensity training; MIT, moderate-intensity training; HIIT, high-intensity interval training; SMIT, supramaximal intensity interval training.

Participants could continue their regular training during the study period. However, on the day before each training session, no exercise was performed, and two days before only light exercise was permitted. During the recovery phase before Post24 measurements, exercising was not allowed. Participants were advised to avoid heavy meals and caffeine 3−4 h preceding each measurement to avoid any gastrointestinal symptoms or any other possible effects on measured variables.

4.2.2 Study II

The study consisted of two separate 10-week periods. During the first period, participants continued their typical training on their own (control period). After the control period, the participants were matched into pairs based on their background information (treadmill test performance, age, gender) and training characteristics (volume) and randomized into an intensity group (INT) or a volume group (VOL). During the 10-week training period, the INT group increased the proportion of MIT and HIIT sessions, while the VOL group increased the endurance training volume (low-intensity). Laboratory tests, including incremental running tests on a treadmill and resting serum hormone analyses at fasted state, were performed at the beginning of the control period (T_0), between the control and training periods (T_1), and at the end of the training period (T_2), at the same time of the day (± 2 h) within-participant. During the whole study period, the participants recorded weekly nocturnal HR and HRV (control period: 29 ± 3 nights, training period: 29 ± 4 nights), performed CMJ (control period: 8.9 ± 1.1 times, training period: 9.3 ± 1.0 times), collected training data from all endurance exercises (HR and speed), and filled a training log.

4.2.3 Study III

The study consisted of four separate phases similar to the protocol used by Le Meur et al. (2013b): a 2-week preparatory period (PREP, phase 1), the first recovery week (phase 2), a 2-week block training period (phase 3), and the second recovery week (phase 4). Participants were advised to continue their regular training in terms of volume during the PREP and to decrease training volume by 50% in the following recovery week. To match training intensity distribution before the training intervention, the participants were asked to perform only LIT sessions, excluding one HIIT session (6 × 3 min) which was prescribed to familiarize them with the interval protocol. At the end of the PREP, the participants were matched into pairs based on sex, 3000-m running performance, vMax, and baseline HRV and divided into an intensity group (INT) or a volume group (VOL). During the training period, the INT performed a HIIT microcycle (10 HIIT sessions), while the VOL increased training volume by 70% and performed exclusively LIT sessions. After the two-week training period, a similar recovery week as the first was prescribed. Performance in the 3000-m run and CMJ were measured, and fasting blood and urine samples were taken and analyzed before PREP (T_0), in the middle of the first recovery week (T_1), one day after the training period (T_2), and after the second recovery week (T_3), always at the same time of the day (± 2 h) within-participant. An incremental treadmill test was performed once in the same week as the other T_0 tests to analyze lactate thresholds (LT1 and LT2) and individual training intensity zones among the participants. A day of rest was always prescribed before testing days. Training and recovery were monitored daily with multiple markers (HR and speed, nocturnal HR and HRV, perceived recovery) throughout the study.

4.2.4 Study IV

The study period consisted of a three-week PREP, which was followed by a six-week volume (VOL-P) and interval (INT-P) periods. During the PREP, participants were advised to continue their regular training in terms of volume and frequency. However, they were asked to do only LIT except for one weekly predefined MIT. To ensure sufficient recovery before the testing week that preceded the training intervention (T_1), the participants were asked to decrease training volume by 25% during their last week of PREP. After the PREP, the participants were matched into pairs based on sex, endurance performance (maximal treadmill speed, 10 km), and endurance training volume (h); after that, they were randomized into a predefined group (PD) or an individualized group (IND). PD trained according to the predefined program, while the program of IND was adapted twice a week based on measured training and recovery data. All the programmed sessions were performed by running in both groups. Laboratory tests including incremental running tests on a treadmill and resting serum hormone analyses at fasted state and 10-km road running tests were performed four times during a testing week before the PREP (T_0), between the PREP and VOL-P (T_1), between the VOL-P and INT-P (T_2), and after the INT-P (T_3). The testing week included two testing days which were separated by at least 48 hours. The first testing day consisted of fasting measurements (blood samples and anthropometrics) and incremental treadmill tests. On the second day, a 10-km running test was executed. The tests were performed at the same time of the day (± 2 h) within-participant. The last day before the test was a rest day and no HIIT or long-distance sessions were performed on the two days preceding any test. In addition, all participants collected HR and global positioning system (GPS) data from endurance exercises, recorded daily nocturnal HR and HRV, and filled out questionnaires on perceived recovery.

4.3 Data collection

4.3.1 Endurance performance

Maximal incremental treadmill test

An incremental treadmill test was performed on a treadmill (Telineyhtymä Oy, Kotka, Finland). In study I, the starting speed was individually set based on information obtained from previous performance and the training background of the participants. In studies II-IV, the starting speed was set to 7 or 8 $km \cdot h^{-1}$ for women and 8 or 9 $km \cdot h^{-1}$ for men. Three-minute stages and speed increments of

1 km·h^{-1} were used, and the test was continued until volitional exhaustion. After each stage, the treadmill was stopped, and the participants stood still for the fingertip blood lactate samples which took approximately 15-20 s. The incline was kept constant at 0.5 degrees throughout the test. Oxygen consumption was measured breath by breath (Studies I and II: OxygonPro, Jaeger, Hochberg, Germany; Studies III and IV: Jaeger VyntusTM CPX, CareFusion Germany 234 GmbH, Hoechberg, Germany). HR was monitored with Garmin Forerunner 920XT (study I; Garmin Ltd, Schaffhausen, Switzerland), Garmin Forerunner 245M (studies II and III), or Polar Vantage V2 (study IV; Polar Electro Oy, Kempele, Finland). VO_{2max} (ml·kg^{-1}·min^{-1}) was defined as the highest 60-s average of oxygen consumption. Maximal running speed (vMax) of the test was defined as the highest completed speed, or if the stage was not finished, as the speed of the last completed stage (km·h^{-1}) + (running time (s) of the unfinished stage – 30 seconds) / (180 – 30 seconds) × km·h^{-1}. The first lactate threshold (LT1) and the second lactate threshold (LT2) were determined based on lactate values during the test. The LT1 was set at 0.3 mmol·l^{-1} above the lowest lactate value and LT2 at the intersection point between 1) a linear model between LT1 and the next lactate point and 2) a linear model for the lactate points measured after the point when lactate increased at least 0.8 mmol·l^{-1} for the first time. The same treadmill and lactate threshold estimation protocols have been used in previous studies (Nuuttila et al., 2017; Vesterinen et al., 2016a; Vesterinen et al., 2016c). Due to technical issues regarding the gas analyzer in study II, reliable oxygen consumption values were available only at T_0 and T_1, thus post-intervention values are not reported.

Field tests
In study III, a 3000-m running test was performed on a 200-m indoor track, and in study IV, a 10-km road running test was run on a flat 1.6-km asphalt loop (+400 m starting line). Before both tests, a 15-min low-intensity warm-up was performed, including 2-3 × 20-30-s accelerations to target pace at the latter part of the warm-up. Verbal encouragement and split times were given to all participants during the test. Tests were run in small groups (< 7 persons). Running time, average HR, and peak HR were analyzed from the tests.

4.3.2 Neuromuscular performance

20-m flying sprint test
In study I, a 20-m sprint test with a running start was performed on the indoor track. Warm-up before the test included a 10-min low-intensity run, dynamic stretching for the lower limbs, and three submaximal 50-m accelerations. Maximal running speed (v20m) was measured with two photocell gates after 30-m acceleration. Three attempts were performed with a three-minute recovery if no more than 5% improvement was found between the last two attempts. The best result was used in further analysis.

Countermovement jump test
The CMJ test was performed with several different types of protocols and devices. In all studies, CMJ was measured before the performance tests on a contact mat with 30-s (studies I and IV) or 1-min recovery (studies II and III) between the jumps. The participants were advised to keep their hands on their hips and jump as high as possible. The lowest knee angle for the jump was about 90 degrees. Three maximal attempts were performed, and the highest jump was used for the analysis. Jump height (h) was calculated based on the measured flight time with the formula: $h = g \cdot t^2 \cdot 8^{-1}$, where t is the recorded flight time in seconds and g is the acceleration due to gravity ($9.81\ m \cdot s^{-2}$) (Bosco et al., 1983).

In study II, CMJ was additionally measured once per week at home conditions with a validated MyJump2-application (Balsalobre-Fernández et al., 2015a). The jumps were videotaped with a mobile phone which was expected to have a video feature of at least 120 frames per second. The participants were instructed to use a camera angle from the front (about 1.5 m from the jumper) that would allow strict estimation of the first frame in which no foot touches the ground, and the first frame had at least one foot contact again. The videos were sent to the research group, and the jumps were always analyzed by the same person. The average of the two best jumps was used in further analysis. In study III, the CMJ was measured on a contact mat before all supervised sessions, and the best jump was used in the analysis.

Isometric leg press
In study II, maximal isometric force production of the lower extremities was measured in the isometric leg press (Faculty of Sport and Health Sciences, University of Jyväskylä, Finland). The knee angle was determined with a goniometer and set to 107 degrees (Häkkinen et al., 2003). Before the test attempts, participants performed two warm-up efforts at an intensity of 60% and 80%. The participants were advised to push the force plate as fast and maximally as possible. Three attempts with 1-min recovery were performed, and the best result of MVC (N) was used in the analysis.

4.3.3 Blood samples and urine collections

Blood samples were taken after 12 hours of fasting and individually at the same time of the day (7:00-9:15 am). Blood samples were taken in a seated position from the antecubital vein into 6 ml (studies III and IV) or 7 ml (study II) serum tubes using standard laboratory procedures. Whole blood was centrifuged at 2000 (study II) or 2250 G (studies III and IV) (Megafuge 1.0 R, Heraeus, Hanau, Germany) for 10 min, and the separated serum was removed and frozen at -20 °C until analysis. Serum cortisol concentration was analyzed with a chemical luminescence technique (Immulite 2000 XPi, Siemens, New York City, NY, USA). The sensitivity of the cortisol assay was $5.5\ nmol \cdot l^{-1}$ and the intra-assay CV was 3.6% (study II) and 5.3% (studies III and IV). Free testosterone concentration was analyzed with an enzyme-linked immunoassay method (DYNEX DS 2 ELISA processing system, DYNEX Technologies, Chantilly, VA, USA). The sensitivity of the free testosterone assay was 0.6 pmol·l^{-1} and the intra-assay CV was 3.6% (study II) and 6.0% (studies III and IV). Serum creatine kinase (CK) activity was analyzed with Indiko Plus Clinical Chemistry Analyzer (Thermo Fisher Scientific, Vantaa, Finland). The sensitivity of the creatine kinase assay was 2.2 U·l^{-1} and the intra-assay CV was 0.9%. Hb and hematocrit (Hct) were analyzed with an automated hematology analyzer (Sysmex XP-300TM, Sysmex Inc, Kobe, Japan). Plasma volume changes were estimated from the Hct and Hb values based on the equation of Dill & Costill (1974).

In study III, urine sample collection was performed between 19:00 and 7:00 during the night before the fasting samples were taken. The participants were asked to document the accurate starting and ending times of the collection. After bringing the sample to the laboratory, the urine volume was determined. For the analysis of norepinephrine, a 10-ml sample was frozen at -20 °C. The concentrations of hormones in the sample were assessed by a high-performance liquid chromatography (HPLC) method (Labor Dr. Kramer & Kollegen, Geesthacht, Germany). The intra-assay CV for norepinephrine was 2.0%. Due to slight differences in collection times, the concentration of hormones in the urine sample was multiplied by the volume of the whole urine, then divided by the collection time in hours, and multiplied by 12 to represent an identical 12-h collection time for all participants similar to the method used by Hynynen et al. (2006).

4.3.4 Anthropometrics

In studies I and III, body fat percentage was analyzed at baseline as a sum of four skinfolds (Durnin & Rahaman, 1967). In studies II and IV, body mass and body fat percentage were measured at fasted state with a bioimpedance device (InBody770-analyser, Biospace Co. Ltd., Seoul, Korea).

4.3.5 Training and recovery

Submaximal running test and supine HRV (Study I)

The SRT acted as a warm-up and cool-down for each training session. It consisted of two 5-min stages which were performed at the speeds corresponding individually to 70% (1. stage) and 80% (2. stage) of HRmax during the incremental treadmill test. To allow fair comparison between sessions and conditions, the same individually set speeds, which were calculated from the incremental treadmill test, were used in all measurements despite possible changes in HR. During the SRT, HR was recorded (Garmin Forerunner 920 XT), and oxygen consumption (VO_2) and respiratory exchange ratio (RER) were measured (OxygonPro, Jaeger, Hoechberg, Germany). The average of the last two minutes during the 80% running speed was used in further analysis, as higher intensities reflect better the changes in maximal performance (Vesterinen et al., 2017). After the SRT, an RPE was asked using a 6−20 Borg scale (Borg, 1982), and blood lactate values were analyzed from the fingertip sample.

HRV was measured in a supine position using a Garmin Forerunner 920XT monitor. Before starting the three-minute data collection (Bourdillon et al., 2017), a one-minute stabilization period was performed (Krejčí et al., 2018). Participants were able to breathe at their natural rhythm. LnRMSSD (the natural logarithm of the square root of the mean sum of the squared differences) was calculated from the three-minute measurement period. Because the measurements were performed in the lab and not right after awakening, baseline values in each participant were derived from pooled pre-exercise data for the four test sessions comparable to Seiler et al. (2007).

Training data

The training was monitored with HR monitors in all studies: Garmin Forerunner 920XT (study I), Garmin Forerunner 245M (studies II and III), and Polar Vantage V2 (study IV). HR and GPS data (distance covered, running speed) were analyzed from all endurance training sessions. In studies III and IV, which utilized 6 × 3-min interval sessions, the average running speed and HR were also calculated separately for each interval and the entire session. Training intensity distribution was analyzed with a time in zone model (HRzone1, HR < LT1; HRzone2, HR = LT1-LT2; HRzone3, HR > LT2). In addition, the participants estimated the session RPE on a 0-10 scale (Foster et al., 1996) in studies II and III.

The HR-RS index (Vesterinen et al., 2014) was analyzed from all continuous-type running exercises (studies II and III). The sessions that were run on trails or in the forest were excluded from the analysis (study II). In study IV, to establish a fair comparison between the sessions of varying duration and terrain, the HR-RS index was primarily calculated from the beginning of running sessions (5:00-10:00). The participants were advised to run the first 10 min of each session as a warm-up on flat terrain at an intensity of LIT. The data was manually analyzed in Polar Flow software (Polar Electro Oy, Kempele, Finland) to ensure sufficient data quality and flat terrain requirements (not more than 5-m ascent or descent). In cases where the criteria were not met in the original 5:00-10:00 segment, the 5-min segment was either moved until fulfilling the criteria (continuous sessions), or the longest possible segment (of at least 2 min) meeting the criteria was used (interval sessions) instead. In all studies, the HR-RS index was calculated based on the average running speed (Savg) and HR (HRavg) with the following equation:

$$\text{HR-RS index} = S_{avg} - (HR_{avg} - HR_{standing})/k$$
$$k = (HR_{max} - HR_{standing})/S_{peak}$$

HRstanding was estimated by adding 26 bpm to the resting HR (average nocturnal HR during the PREP or control period) similar to Vesterinen et al. (2014). Peak running speed (Speak) and HRmax were determined based on the incremental treadmill test results at T_0 (study III) or T_1 (studies II and IV).

Nocturnal HR and HRV recordings

In studies II and III, nocturnal HR and HRV were recorded with the Firstbeat Bodyguard 2 device (Firstbeat Technologies LTD, Jyväskylä, Finland) three nights a week (study II) or every night from Pre to Week3 (study III). The participants were advised to start recording when going to sleep by attaching the device as instructed and stop the recording right after awakening by detaching the device. Recorded RR-intervals were edited by an artifact detection filter within the Firstbeat Sports software which excluded all falsely detected, missed, and pre-mature heartbeats. If the error percentage representing the number of corrected interbeat intervals shown by the software was higher than 33%, the recordings were excluded from the analysis, as suggested by Vesterinen et al. (2016a). Average HR, LnHF, and LnRMSSD were analyzed from the sleep period of 0:30-4:30 after going to bed. Regarding the 4-h analysis segment, intraclass correlation coefficients of 0.97, 0.96 and 0.94 have been reported in HR, LnRMSSD and LnHF, respectively, when two consecutive nights after a similar training day have been compared (Nuuttila et al., 2022). In study III, one participant in the VOL group had a high amount of erroneous data (error percentage > 33% more than 50% of the recorded nights) and was therefore excluded from the nocturnal analysis.

In study IV, nocturnal HR and HRV were recorded every night via wrist-based photoplethysmography (Polar Vantage V2). The validity of the device has been reported previously (Nuuttila et al., 2021). Automatically formed results from a 4-hour period starting half an hour after the beginning of the detected sleep onset were used in the analysis. Values provided by the watch included the average HR and the average RMSSD which was log-transformed (LnRMSSD) for the analysis.

Perceptual markers

In studies I and II, daily perceived recovery was estimated on a 0−10 scale (Laurent et al., 2011). Additionally, in study I, perceived muscle soreness of the lower limbs was estimated on a 10-cm visual analogue scale (VAS) where 0 represented no soreness at all and 10 represented the highest possible soreness (Ahtiainen et al., 2003). In study III, participants filled out daily questionnaires on the 0-10 VAS regarding estimated readiness to train, sleep quality of the previous night, general fatigue, muscle soreness of lower limbs, and perceived stressfulness during the day. Questionnaires were modified from previous studies (Hooper et al., 1995; ten Haaf et al., 2017). In study IV, perceived recovery was estimated daily on a 1-7 scale which was modified from the questionnaires of Hooper et al. (1995), and Schäfer Olstad et al. (2019). Muscle soreness of the lower limbs, fatigue, sleep quality, and stress were ranked from 1 (very much below/better than normal) to 7 (very much above/worse than normal), while 4 represented normal perception. The items were analyzed separately and as a sum index which was defined as the "staleness score". Recovery was estimated in the morning before any exercise via the Coach4Pro mobile application (Coach4Pro Oy, Espoo, Finland).

4.4 Exercise protocols and training programs

4.4.1 Study I

The duration and intensity of the training sessions were defined so that they represented typical training of each intensity zone (low, moderate, high, and supramaximal intensity) and were possible for each participant to perform. Previous studies (Cicioni-Kolsky et al., 2013; Kaikkonen et al., 2010; Seiler et al., 2007) have also utilized similar types of training. The running speeds of the sessions were set individually based on the LT and vMax during the incremental treadmill test and the v20m. A LIT session was a 90-min run performed at 80% of the speed of the LT1. A MIT session was a 30-min run performed at the average speed of the LT1 and LT2 ((vLT1 + vLT2)/2). A HIIT session was 6 × 3-min with a 2-min recovery performed between the LT2 and vMax speeds (vLT2+(vMax-vLT2)/3). A SMIT session was 10 × 30 s with a 2.5-min recovery performed at 75% of the v20m (v20m·0.75). During the recovery, the treadmill speed was set at 5 $km \cdot h^{-1}$ in both interval sessions. The submaximal running test acted as a warm-up and cool-down for the sessions. Before SMIT, one short acceleration (15 s) to the speed of the upcoming session was performed to familiarize the participants to the running speed, but the actual session started after a 2.5-min recovery. An RPE (6-20) was asked, and average HR, peak HR, training impulse (TRIMP) (Edwards, 1993), and blood lactate were measured in all sessions.

4.4.2 Study II

During the 10-week training period, the participants of the INT and VOL groups utilized distinct individually scaled training programs (FIGURE 7). The aim of the training period was to progressively increase training load via intensity or volume. Individual references for the recovery measurements and training characteristics (intensity and volume) were analyzed as an average of the control period. Weeks including illnesses were excluded from the analysis to avoid distorting the results. After the first week of the training period, during which the participants were familiarized with the predefined training, the program was periodized into three-week mesocycles of two intensive weeks followed by one recovery week (70% volume of the preceding week, only one MIT). The INT group progressively increased the proportion of MIT and HIIT sessions compared to the average of the control period while maintaining the total endurance training volume the same. Progression started from one additional session and led to three additional sessions during the intensive training weeks, accounting for 10 sessions in total. Furthermore, the intensity of these sessions progressed from MIT towards HIIT. The VOL group progressively increased the volume of LIT compared to the control period from 20% to 50% during the intensive weeks while maintaining the volume of MIT and HIIT the same. The volume was increased primarily by adding duration to each training session, and the weekly training frequency was kept similar. The progression logic for both protocols was modified from the study of Vesterinen et al. (2016a).

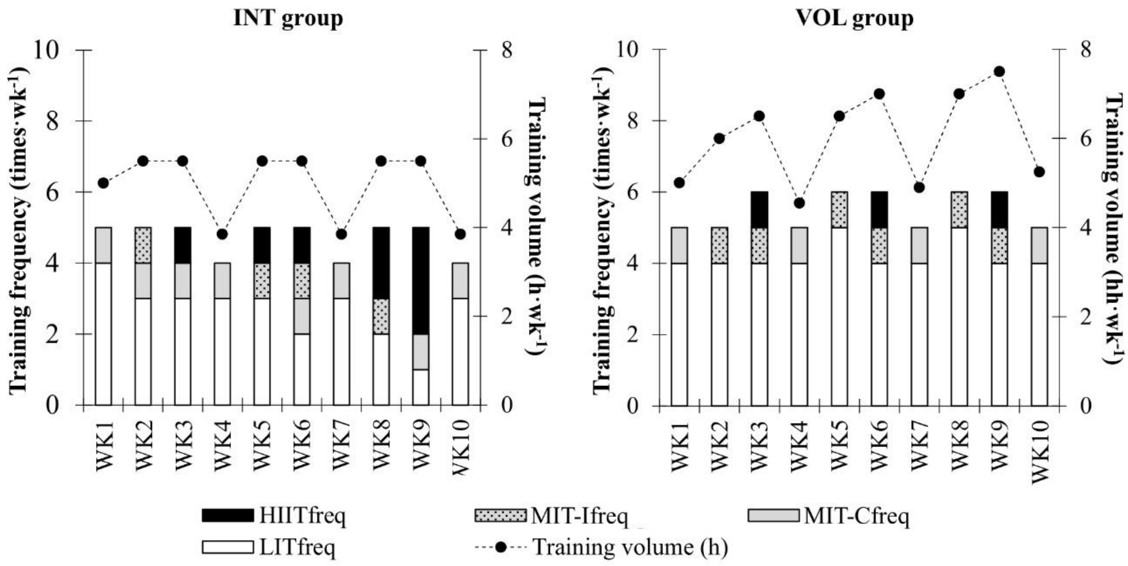

FIGURE 7 Training program progression of a representative participant in the INT and VOL groups. INT, Intensity group; VOL, Volume group; HIITfreq, frequency of high-intensity interval training; MIT-Ifreq, frequency of moderate-intensity interval training; MIT-Cfreq, frequency of moderate-intensity continuous training; LITfreq, frequency of low-intensity training.

The training program included LIT below LT1, MIT between LT1 and LT2, and HIIT above LT2. The session intensity was controlled by HR. The duration of the training sessions was individually determined in accordance with typical sessions performed during the control period. LIT sessions consisted of basic sessions (30–75 min) and long sessions (> 75 min). MIT sessions consisted of long intervals (2–4 × 10–15 min) or continuous running (20–60 min). HIIT sessions consisted of 3–6 min intervals with 2:1 work: relief-ratio and 15–30 min accumulated time in the high-intensity zone during the session. Interval sessions always included low-intensity warm-up and cool-down. The training was performed mainly by running. To reduce the risk of overuse injuries, alternative training modes (cycling, roller-skiing, swimming) were allowed with volumes similar to the control period. Participants were advised not to change the amount or content of their typical strength training during the study period (control period: 0.3 ± 0.3 sessions·week^{-1}, training period: 0.2 ± 0.3 sessions·week^{-1}).

4.4.3 Study III

During the 2-week block training period, the INT group performed a total of 10, 6 × 3 min HIIT sessions (5 sessions·wk^{-1}), while the VOL group increased their LIT volume (hours) by 70%. Proper training load for the INT and VOL protocols was estimated based on previous studies examining HIIT shock microcycles (Dolci et al., 2020) or volume-based overload periods (Le Meur et al., 2013b;

Lehmann et al., 1992; Uusitalo et al., 1998). Both groups had five main sessions per week, and they were supervised and performed individually at the same time of the day (± 2 h) during the morning or afternoon and at the same outdoor road/track which was tight gravel (INT) or about 50/50 combination of gravel and asphalt (VOL). The INT group performed all these sessions at 6 × 3-min intervals, while the VOL group performed only LIT below LT1. If participants performed more than five sessions during PREP, these sessions were also incorporated into the training period as LIT with the same duration (INT) or with increased duration (VOL) to match the requirement of the volume increment. In case the participants were accustomed to alternative endurance training modes such as cycling, these modes were incorporated as part of the additional sessions with a similar proportion to PREP.

HIIT-session was a 6 × 3-min interval with 2-min active recovery (walking). Intervals were performed at the maximal sustainable effort (Seiler & Hetlelid, 2005). Before the session, a 15-min warm-up, including three 30-s accelerations to the target speed, was performed. After the session, a 10-min cool-down was prescribed.

The VOL group performed four similar basic sessions (85-95%/HR of the LT1) and one long-distance session (75-90%/HR of the LT1) in a week. The aim was to increase the duration of running sessions compared to PREP. The basic session was planned to be approximately 1.50 × the average session duration during PREP (1:22 ± 0:10 h:min), while the long-distance session was 1.66 × duration of the basic session (2:16 ± 0:16 h:min).

4.4.4 Study IV

After a 3-week PREP, the PD and IND groups trained according to their own programs. The first 6-week VOL-P focused on the progression of LIT volume, while the second 6-week INT-P focused on HIIT. The training program of PD was individually scaled based on the training frequency and volume during PREP. The basic structure of the program is presented in TABLE 3. The training sessions during VOL-P included LIT sessions where HR was below LT1 (HRzone1) and continuous MIT sessions where HR was between LT1 and LT2 (HRzone2). The training was periodized in a way that two intensive weeks were followed by one recovery week. The training volume progression was similar to previous studies (Bellinger et al., 2020b; Düking et al., 2020): during intensive weeks, it increased by 10% compared to the baseline level (2 first weeks of PREP). To ensure sufficient recovery, the training volume was always decreased by 25% after two intensive weeks (Bosquet et al., 2007). During INT-P, the weekly main session was 6 × 3 min performed at the maximal sustainable effort (Seiler & Hetlelid, 2005) with 2-min recovery intervals in between. Basically, the running speed during the intervals was between LT2 and vMax, and at the end of the intervals, the HR reached values above LT2 (HRzone3). Other endurance training sessions were executed as LIT where the HR was below LT1 (HRzone1). The duration of these sessions was individually defined based on the basic sessions' average values during PREP. Similar to VOL-P, the training was periodized into two intensive weeks (3 HIIT sessions) followed by one recovery week (1 HIIT session and 25% decreased training volume). The weekly HIIT frequency was based on previous studies using 2-3 weekly HIIT sessions (Helgerud et al., 2007; Seiler et al., 2013).

TABLE 3 The training program of the PD group during the preparatory (PREP1-3), volume (VOL1-6), and interval (INT1-6) training periods.

Week	**LIT (basic)** 30-90 min	**LIT (long)** >90 min	**MIT** 30 min	**HIIT** 6x3 min	**Tests** VO_{2max}, 10 km
T_0	1-3 x				x
PREP1	2-4x	1x	1x		
PREP2	2-4x	1x	1x		
PREP3	1-3x	1x	1x		
T_1	1-3 x				x
VOL1	2-4x	1x	1x		
VOL2	2-4x	1x	1x		
VOL3	1-3x	1x	1x		
VOL4	2-4x	1x	1x		
VOL5	2-4x	1x	1x		
VOL6	1-3x	1x	1x		
T_2	1-3 x				x
INT1	1-3x			3x	
INT2	1-3x			3x	
INT3	2-4x			1x	
INT4	1-3x			3x	
INT5	1-3x			3x	
INT6	2-4x			1x	
T_3	1-3 x				x

All MIT and HIIT sessions also included low-intensity warm-up and cool-down. PREP, preparatory period; VOL, volume period; INT, interval period; T_0, familiarization tests; T_1, pre-tests; T_2, mid-tests; T_3 post-tests; LIT, low-intensity training (HRzone1); MIT, moderate-intensity training (HRzone2); HIIT, high-intensity interval training (maximal sustainable effort); VO_{2max}, incremental treadmill test.

In the IND group, the training frequency and timing of different types of sessions within a week were determined according to similar principles as in the PD group. Only the duration of the sessions (VOL-P) or the number of HIIT sessions (INT-P) were adjusted based on the training and recovery state. The execution of the training was individually adjusted twice a week on evaluation days (Monday and Thursday) which were always recovery days (rest or active recovery) as well. Basically, the training load of the following 3-4 days block was either increased, maintained, or decreased from the current level set for the individual. During VOL-P, the current level referred to the coefficient of the session duration compared to baseline, and similar to PD, it started from +10% (1.10 × baseline duration). During INT-P, the current level referred to the number of HIIT sessions performed within a block and started from one HIIT. The adjustment logic for the training load is illustrated in FIGURE 8 and FIGURE 9. The participants were not informed about the exact model behind the training modification to avoid manipulation of the results in a way that would not be related to the actual recovery and training state.

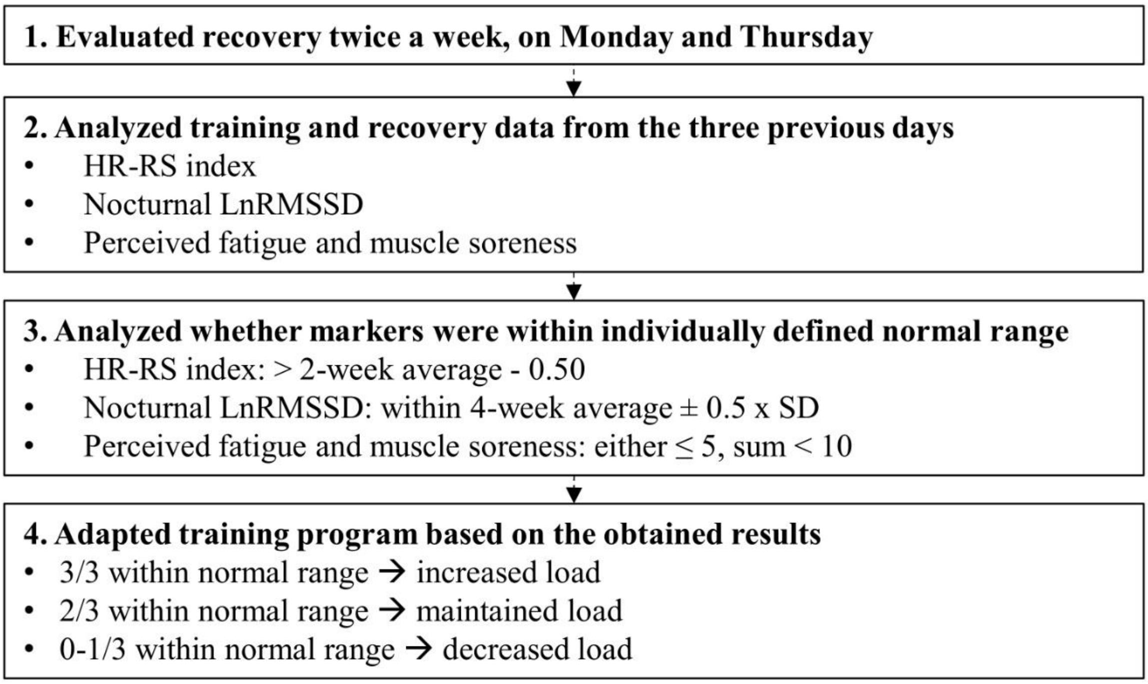

FIGURE 8 Evaluation process and analyses of recovery status.

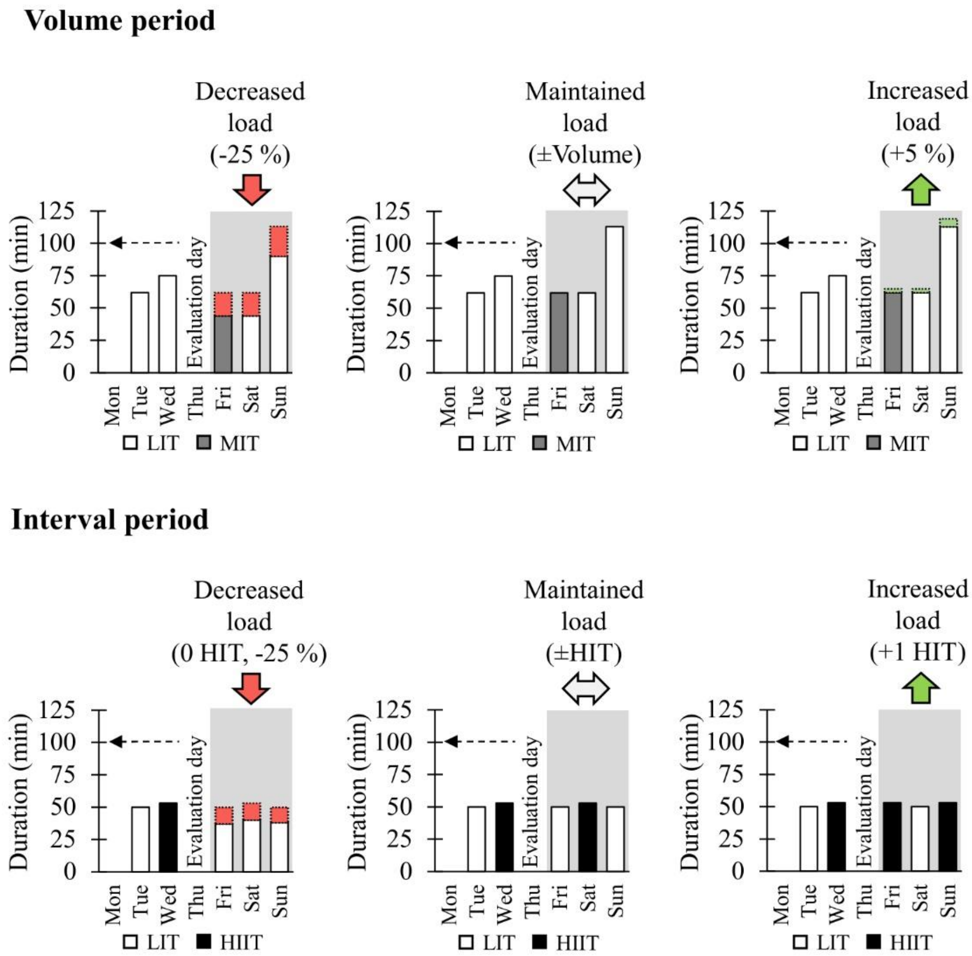

FIGURE 9 Determination logic of the training load in the individualized group. Training load was adjusted twice a week on evaluation days (Mon and Thu). If the training load was maintained, no modifications were made compared to the current level. The training load was increased via adding volume (VOL-P) by 5% (e.g., 1.10 × baseline level to 1.15 × baseline level) or via increasing the number of HIIT sessions (INT-P). The training load was decreased via reducing volume by 25% compared to the current level (VOL-P), or via reducing volume by 25% from the current level and excluding HIIT sessions (INT-P). After the recovery block, the training continued from the level preceding the recovery block (2/3 of the markers within normal range) or the next level (VOL-P). During INT, the progression always started from one HIIT. After reaching a maximum number of HIIT sessions within a block (2 or 3 sessions), no additional sessions were performed. After the last evaluation day of INT-P, a maximum of one HIIT session was performed to ensure sufficient recovery before the final tests.

The variables affecting the training load and their desirable ranges were determined in conformity with previous studies. In the nocturnal HRV, a 4-week rolling average ± 0.5 × SD was chosen, which meant that the values above or below the range were regarded as negative. Similar cut-off values have been used in studies utilizing HRV-guided training (Javaloyes et al., 2019; Vesterinen et al., 2016c). Fatigue was expected to be sensitive for the (too high) changes in the training load (Bellenger et al., 2016; Le Meur et al., 2013b) and to increase as a sign of possible overreaching (Hooper et al., 1995; ten Haaf et al., 2017). Muscle soreness has also increased following periods of intensified training (Bellenger et al., 2016; Schäfer Olstad et al., 2019), and high values may relate to overtraining (Hooper et al., 1995). Hooper et al. (1995) suggested that in a 1-7 scale, values > 5 would be associated with staleness. Since the present study used a similar scale, the respective value was chosen as a cut-off for normal value. HR-RS index was chosen as the third factor affecting the training load, because it is not straightforward how the state of recovery itself translates into training adaptation, and changes in this marker have previously correlated with the change in maximal running performance measured in the laboratory (Vesterinen et al., 2014). Since HR-RS index was not measured in laboratory conditions, and exercise HR has a certain natural day-to-day variation (Lamberts & Lambert, 2009), the maximum decrement of 0.50 compared to the previous 2-week average, equivalent to 3-4 bpm increase in HR at the same running speed, was defined as normal.

4.5 Statistical analyses

All values are expressed as mean and SD. Normal distribution of the data was assessed with the Shapiro-Wilk test. A paired or unpaired samples t-test (two time points) or repeated measures ANOVA (multiple time points) were used to examine differences between time points and groups. In cases where significant main effect or interaction was observed in ANOVA, a Bonferroni post hoc test was used for within-group comparison, while between-group differences were analyzed using either relative changes and paired samples t-test with Bonferroni correction (studies I and II) or using simple contrasts (studies III and IV). In study IV, to exclude any possible effects of different baseline levels in performance parameters (treadmill test, 10-km test), a T_0 test result was used as a covariant (ANCOVA) in the between-group analysis. For not normally distributed variables, the Wilcoxon signed-rank test was used for within-group comparisons and the Mann-Whitney U-test for between-group comparisons. SWC for the monitoring variables was calculated by multiplying the within-participant CV or SD during the laboratory sessions (study I), the control period (study II), or PREP (study III) by 0.5, similar to the logic used in HRV-guided training (Javaloyes et al., 2019; Vesterinen et al., 2016c). Agreement between changes in HRV and other monitoring variables were examined in studies I-III by analyzing whether responses at the end of the training period were over, within, or below individual SWC.

The magnitude of improvements in the main parameters (vMax, 3000 m, 10 km) were also analyzed based on the CV between T_0 and T_1 tests in studies III and IV, and the magnitude was stated as trivial (< 0.5 × CV), moderate (0.5-2 × CV) or high (> 2 × CV). Since only a relatively short period of regular training was performed between the T_0 and T_1, CV was expected to illustrate the typical error of the test caused by day-to-day variation in performance and/or environmental factors. The present division for magnitudes was adapted from Düking et al. (2020), but as an exception, SWC was defined as 0.5 × CV (Hopkins, 2005) similar to the cut-off values used in the recovery variables.

Factors related to interindividual differences in the training adaptation were examined via Pearson correlation coefficient analyses, and by comparing low (magnitude of change in performance trivial) and high (magnitude of change in performance high) responders with the Mann-Whitney U-test. The effect size (ES) of observed changes in the main variables was calculated as Cohen's *d* (difference of the means divided by the pooled SD). As an exception in study IV, between-group differences were calculated by dividing the difference of the means by SD of the mean difference. For the not normally distributed variables ES was calculated with a formula: $ES = Z/ \sqrt{n}$ where Z is the Z-score and n is the number of observations on which Z is based. An ES of < 0.20 was considered trivial, ≥ 0.20 small, ≥ 0.50 medium, and ≥ 0.80 large. Statistical significance level was set at $p < 0.05$. Analyses were performed with IBM SPSS Statistics v.26 or v.28 programs (SPSS Inc, Chicago, IL, USA) and Microsoft Excel 2010 or 2016 (Microsoft Corporation, WA, USA).

5 RESULTS

In the first phase (study I), physiological, perceptual and performance responses were compared in four running sessions differing in intensity. In the second phase (studies II and III), comparisons between increased volume and intensity of endurance training were performed via training interventions, and possible contributors explaining interindividual differences in the training adaptation were analyzed. In the final phase (study IV), individualized endurance training prescription was compared to predefined endurance training.

5.1 Acute responses to endurance exercises

5.1.1 Characteristics of training sessions

Distance covered and TRIMP was the greatest in LIT and the smallest in SMIT. Blood lactate increased after all sessions, reaching the highest values after SMIT and the lowest values after LIT and MIT. RPE was the lowest after LIT, while HIIT and SMIT induced the highest values. Average HR was similar in LIT and SMIT, and highest in MIT and HIIT. Detailed characteristics of the four training sessions performed in the laboratory are presented in TABLE 4.

TABLE 4 Results of four running sessions performed. Values are presented as means ± SD.

	LIT	MIT	HIIT	SMIT
Speed ($km \cdot h^{-1}$)	8.8 ± 1.1[bcd]	12.3 ± 1.4[acd]	14.7 ± 1.3[abd]	21.0 ± 1.3[abc]
Speed (%/vMax)	52 ± 4[bcd]	73 ± 4[acd]	87 ± 3[abd]	126 ± 11[abc]
Distance (km)	13.2 ± 1.7[bcd]	6.2 ± 0.7[acd]	5.7 ± 0.4[abd]	3.6 ± 0.1[abc]
AvgHR (%max)	70 ± 5[bc]	84 ± 4[ad]	81 ± 3[ad]	69 ± 7[bc]
PeakHR (%max)	76 ± 5[bcd]	89 ± 4[ac]	94 ± 3[abd]	88 ± 5[ac]
TRIMP	226 ± 48[bcd]	118 ± 12[ad]	101 ± 12[ad]	68 ± 20[abc]
Blood lactate ($mmol \cdot l^{-1}$)	3.4 ± 2.0[cd]	4.1 ± 1.5[cd]	6.4 ± 1.5[abd]	8.3 ± 3.2[abc]
RPE (6-20)	12.0 ± 1.8[bcd]	15.5 ± 1.4[ac]	16.5 ± 1.2[a]	15.9 ± 1.8[a]

AvgHR, average heart rate; PeakHR, peak heart rate; TRIMP, training impulse; RPE, rating of perceived exertion; LIT, low-intensity session; MIT, moderate-intensity session; HIIT, high-intensity interval session; SMIT, supramaximal intensity interval session. Differences between the training sessions ($p < 0.05$): [a]=LIT, [b]=MIT, [c]=HIIT, [d]=SMIT

5.1.2 Supine HRV

A main effect for the session type ($p < 0.001$) and time ($p < 0.001$) as well as session type × time interaction ($p < 0.001$) was found in LnRMSSD. LnRMSSD decreased at post ($p < 0.001$) after LIT (3.8 ± 0.5 ms vs. 2.9 ± 0.7 ms, ES = -1.83), MIT (4.0 ± 0.5 ms vs. 1.9 ± 0.8 ms, ES = -3.13), HIIT (3.9 ± 0.4 ms vs. 2.1 ± 0.7 ms, ES = -3.12), and SMIT (3.9 ± 0.5 ms vs. 2.5 ± 0.6 ms, ES = -2.55). The relative decrease was smaller after LIT when compared to MIT ($p < 0.001$) or HIIT ($p = 0.001$) (FIGURE 10). A smaller decrease was also observed after SMIT than MIT ($p = 0.009$). LnRMSSD returned to baseline after all sessions at 24 h, with no differences compared to baseline within or between sessions.

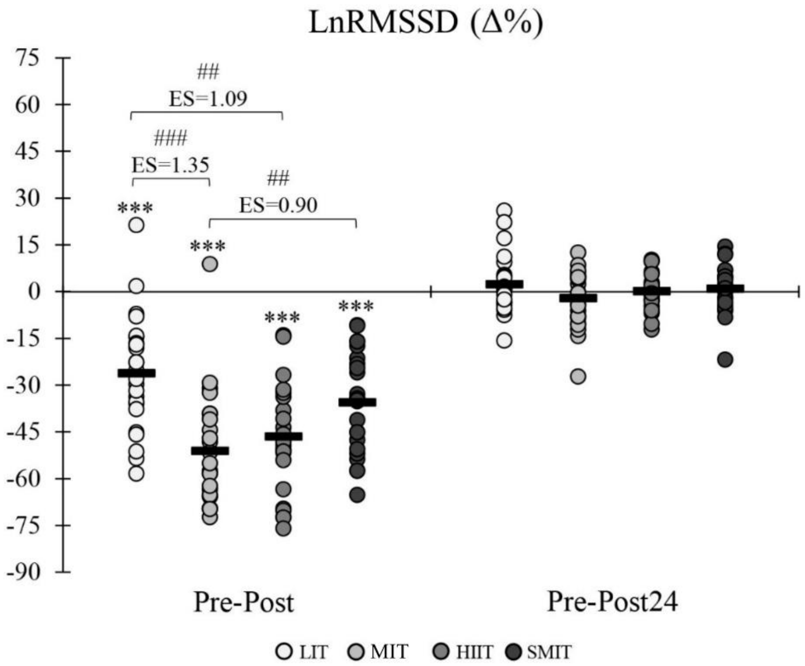

FIGURE 10 Mean (black line) and individual values (dots) in the relative changes compared to Pre in supine LnRMMSD. ***p < 0.001, **p < 0.01, *p < 0.05 difference compared to Pre within session. ###p < 0.001, ##p < 0.01, #p < 0.05 difference in the relative change from Pre between sessions. LnRMSSD, the natural logarithm of the square root of the mean sum of the squared differences. LIT, low-intensity session; MIT, moderate-intensity session; HIIT, high-intensity interval session; SMIT, supramaximal intensity interval session.

5.1.3 CMJ performance

A session type × time interaction (p < 0.001) was observed in CMJ. The CMJ height decreased after LIT (35.8 ± 4.7 cm vs. 34.2 ± 4.9 cm, p = 0.001, ES = -0.34) and SMIT (36.1 ± 4.7 cm vs. 34.4 ± 4.1cm, p < 0.001, ES = -0.37) while no difference compared to baseline was observed after MIT (35.3 ± 5.8 cm vs. 35.8 ± 5.3 cm, ES = 0.09) or HIIT (35.7 ± 5.5 cm vs. 36.4 ± 5.0 cm, ES = 0.13). The relative changes after LIT and SMIT were also different compared to MIT (LIT, p < 0.001; SMIT, p = 0.002) and HIIT (p < 0.001) (FIGURE 11). The CMJ remained decreased after SMIT 24 h after the session (p = 0.018, ES = -0.19) while no difference was observed after other sessions.

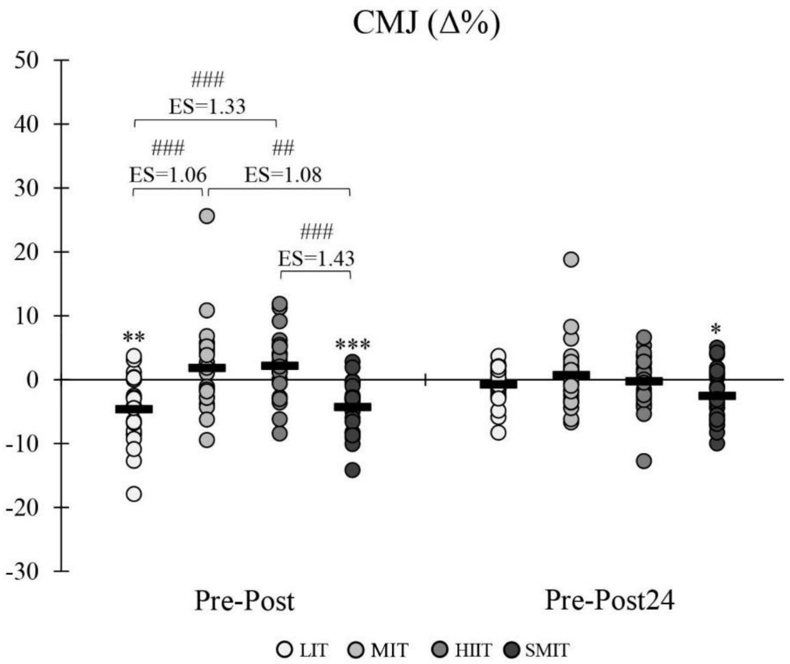

FIGURE 11 Mean (black line) and individual values (dots) in the relative changes compared to Pre in CMJ. p < 0.001, **p < 0.01, *p < 0.05 difference compared to the Pre within session. ###p<0.001, ##p < 0.01, #p < 0.05 difference in the relative change from Pre between sessions. CMJ, countermovement jump; LIT, low-intensity session; MIT, moderate-intensity session; HIIT, high-intensity interval session; SMIT, supramaximal intensity interval session.

5.1.4 Submaximal running test

A main effect for time ($p < 0.01$) was observed in all variables measured during SRT. Also, a main effect for the session type was found in blood lactate ($p < 0.001$), and moreover, the session type × time interaction was statistically significant. The HR during the SRT increased after all sessions ($p < 0.001$), followed by a decrease below the baseline at 24 h after LIT ($p = 0.001$), MIT ($p = 0.023$), HIIT ($p = 0.016$), and SMIT ($p = 0.011$). The RPE during the SRT increased after LIT ($p < 0.001$), MIT ($p = 0.004$), HIIT ($p = 0.001$), and SMIT ($p = 0.002$), and it returned to baseline at 24 h after LIT and MIT but remained increased after HIIT ($p = 0.048$) and SMIT ($p = 0.007$). The VO_2 during the SRT increased after LIT ($p = 0.017$) and MIT ($p = 0.002$), while no difference was observed after SMIT or HIIT. The VO_2 returned to baseline after all sessions at Post24. The only between-group difference observed during the SRT was in blood lactate which was higher after SMIT compared to any other session ($p < 0.001$). The absolute values measured during the SRT are presented in TABLE 5.

TABLE 5 Baseline values (Pre), acute responses (Post), post 24-hour recovery (Post24), and effect size of the changes (ES) in submaximal running test. Values are presented as means ± SD.

	LIT	MIT	HIIT	SMIT
HR (bpm)				
Pre	141 ± 8	140 ± 7	141 ± 9	142 ± 9
Post	153 ± 10***	153 ± 8***	153 ± 9***	151 ± 9***
Post24	138 ± 6**	137 ± 7*	138 ± 8*	138 ± 8*
ES (Pre-Post/Pre-Post24)	1.30/-0.50	1.69/-0.41	1.32/-0.40	1.10/-0.39
$\dot{V}O_2$ ($ml \cdot kg^{-1} \cdot min^{-1}$)				
Pre	38.0 ± 4.5	37.5 ± 4.4	37.8 ± 4.7	37.6 ± 4.8
Post	38.7 ± 4.2*	38.1 ± 4.2*	38.0 ± 4.4	38.1 ± 5.0
Post24	37.5 ± 4.4	37.7 ± 5.0	37.8 ± 4.7	37.5 ± 4.8
ES (Pre-Post/Pre-Post24)	0.16/-0.11	0.14/0.05	0.04/0.01	0.10/-0.01
RER (CO_2/O_2-ratio)				
Pre	0.90 ± 0.03	0.89 ± 0.03	0.90 ± 0.03	0.90 ± 0.03
Post	0.86 ± 0.04***	0.85 ± 0.03***	0.86 ± 0.03***	0.85 ± 0.03***
Post24	0.89 ± 0.03	0.89 ± 0.02	0.90 ± 0.03	0.89 ± 0.03
ES (Pre-Post/Pre-Post24)	-0.90/-0.22	-1.34/-0.20	-1.48/-0.18	-1.55/-0.31
BL ($mmol \cdot l^{-1}$)				
Pre	1.7 ± 0.7	1.7 ± 0.5	1.8 ± 0.6	1.8 ± 0.7
Post	1.6 ± 0.4###	1.5 ± 0.7###	1.9 ± 0.7###	2.8 ± 1.3**
Post24	1.5 ± 0.5*	1.7 ± 0.6	1.7 ± 0.5	1.6 ± 0.6
ES (Pre-Post/Pre-Post24)	-0.33/-0.34	-0.19/0.07	0.18/-0.23	0.94/-0.26
RPE (6-20)				
Pre	11.9 ± 1.7	12.0 ± 1.8	11.9 ± 1.5	11.7 ± 2.0
Post	13.3 ± 1.3***	13.0 ± 1.5**	12.9 ± 1.3**	13.2 ± 1.4**
Post24	12.1 ± 1.8	12.1 ± 1.8	12.4 ± 1.3*	12.5 ± 1.6**
ES (Pre-Post/Pre-Post24)	0.93/0.12	0.60/0.07	0.71/0.39	0.83/0.41

***$p < 0.001$, **$p < 0.01$, *$p < 0.05$ different compared to Pre. ### $p < 0.001$, ## $p < 0.01$, the difference in the relative change from Pre compared to SMIT. HR, heart rate; $\dot{V}O_2$, oxygen consumption; RER, respiratory exchange ratio; BL, blood lactate; RPE, rating of perceived exertion. LIT, low-intensity session; MIT, moderate-intensity session; HIIT, high-intensity interval session; SMIT, supramaximal intensity interval session; ES = Effect size as Cohen's *d*.

5.1.5 Perceived recovery

No main effects or interaction were observed in perceived recovery (LIT 7.4 ± 1.5 vs. 6.7 ± 1.7, p = 0.054, ES = - 0.42; MIT 7.0 ± 1.5 vs. 7.0 ± 1.4, ES = -0.03; HIIT 7.3 ± 1.5 vs 7.1 ± 1.7, ES= -0.13; SMIT 7.4 ± 1.4 vs. 6.9 ± 1.6, ES = -0.33). Muscle soreness increased after LIT (1.5 ± 1.3 vs. 2.4 ± 1.7, p = 0.003, ES = 0.41) and SMIT (1.7 ± 1.9 vs. 2.4 ± 1.5, p = 0.042, ES = 0.25), while no change was observed after MIT (1.7 ± 1.5 vs. 2.1 ± 1.2, ES = 0.20) or HIIT (1.6 ± 1.6 vs. 1.9 ± 1.7, ES = 0.19). No significant differences between sessions were observed in changes of perceptual markers.

5.1.6 Agreement between supine HRV and monitoring variables post 24 h

The agreement between within-individual responses of supine HRV (decrease, no change, increase compared to baseline) and other monitoring variables were analyzed to examine if recovery kinetics would differ between markers. The highest agreement with the HRV responses was found for SRTHR (52 ± 6% agreed), while the lowest agreement was observed for CMJ (33 ± 7% agreed). Summary of the responses and their directions are presented in TABLE 6.

TABLE 6 Agreement between responses in supine HRV (LnRMSSD) and other monitoring variables. The numbers indicate participants within each response (- = greater decrease than SWC, ± = change is within SWC, + = greater increase than SWC). Green indicates a similar response, grey indicates a different response, while red indicates an opposing response between variables. In these analyses it was assumed that an increase in HRV would be a positive change and a decrease in HRV a negative change. All sessions were combined in the analyses meaning that there was a total of 94 cases distributed among 24 participants.

		Supine HRV		
		-	±	+
	DOMS	21	44	29
-	4	1	1	2
±	43	8	23	12
+	47	12	20	15
	PRS			
-	44	11	18	15
±	23	7	11	5
+	27	3	15	9
	SRTHR			
-	46	8	18	20
±	41	8	24	9
+	7	5	2	0
	$SRTVO_2$			
-	25	4	13	8
±	46	10	19	17
+	23	7	12	4
	SRTRPE			
-	11	2	6	3
±	44	6	22	16
+	39	13	16	10
	CMJ			
-	30	6	17	7
±	42	9	18	15
+	22	6	9	7

DOMS, delayed onset of muscle soreness; PRS, perceived recovery scale; SRT, submaximal running test; HR, heart rate; VO_2, oxygen consumption; RPE, rating of perceived exertion; CMJ, countermovement jump.

5.2 Training (studies II, III, IV)

Training characteristics during the study periods are presented in TABLE 7. All interventions included control or preparatory periods followed by volume or intensity periods.

TABLE 7 Mean ± SD weekly training characteristics in the intervention studies.

	Volume (h)	Frequency (times)	Distance (km)	HR zone1 (%)	HR zone2 (%)	HR zone3 (%)
10+10 wk (II)						
$CTRL_{INT}$	4.9 ± 1.7	4.6 ± 1.3	31 ± 11	77 ± 17	21 ± 16	2 ± 3
TRA_{INT}	4.8 ± 1.7	5.1 ± 1.7	38 ± 16*	71 ± 12	22 ± 9	7 ± 6**
$CTRL_{VOL}$	4.9 ± 1.4	4.6 ± 1.1	34 ± 13	75 ± 15	22 ± 13	3 ± 3
TRA_{VOL}	5.7 ± 1.8***	4.8 ± 1.1	44 ± 14***	77 ± 12	19 ± 9	4 ± 3
2+2 wk (III)						
$PREP_{INT}$	5.8 ± 1.7	5.6 ± 1.4	46 ± 13	92 ± 6	6 ± 5	2 ± 3
TRA_{INT}	5.2 ± 1.1	5.8 ± 1.3	50 ± 9	62 ± 7**	18 ± 6**	20 ± 5**
$PREP_{VOL}$	5.4 ± 2.1	5.3 ± 1.9	45 ± 15	92 ± 4	6 ± 3	2 ± 2
TRA_{VOL}	9.0 ± 3.4**	5.9 ± 1.8*	77 ± 23**	100 ± 1	0 ± 1**	0 ± 0**
3+6+6 wk (IV)						
$PREP_{IND}$	4.3 ± 0.8	4.2 ± 0.6	42 ± 10	88 ± 9	11 ± 8	1 ± 2
$VOL\text{-}P_{IND}$	5.3 ± 0.9***	4.4 ± 0.6***	52 ± 12***	90 ± 3	9 ± 3	1 ± 1
$INT\text{-}P_{IND}$	3.8 ± 0.6**	4.3 ± 0.6**	38 ± 8**	78 ± 8**	14 ± 6	8 ± 5**
$PREP_{PD}$	4.6 ± 1.0	4.2 ± 0.9	44 ± 13	89 ± 5	10 ± 5	1 ± 1
$VOL\text{-}P_{PD}$	5.7 ± 1.3**	4.5 ± 1.0	53 ± 15**	90 ± 4	9 ± 3	1 ± 1
$INT\text{-}P_{PD}$	3.8 ± 0.9**	4.3 ± 0.9	37 ± 11**	79 ± 6**	16 ± 6*	5 ± 3**

INT, intensity group; VOL, volume group; IND, individualized group; PD, predefined group; CTRL, control period; TRA, training period; PREP, preparatory training period; VOL-P, volume training period; INT-P, interval training period. HRzone1, HR below LT1; HRzone2, HR between LT1 and LT2; HRzone3, HR above LT2. *$p < 0.05$, **$p < 0.01$, ***$p < 0.001$ compared with the control or preparatory period.

In study II, the VOL increased weekly training volume ($p < 0.001$), while the INT increased the proportion of HRzone3 training ($p = 0.004$). In addition, both groups increased ($p < 0.05$) running kilometers compared to the control period. In study III, the INT group increased ($p < 0.01$) the weekly training volume at HRzone2 and HRzone3 from PREP to the training period, whereas the VOL group increased ($p < 0.01$) the training volume and running distances. Both groups performed lower training volume ($p < 0.01$) compared to PREP during the first (INT 2.9 ± 1.1 h; VOL 2.7 ± 1.2 h) and the second recovery weeks (INT 2.9 ± 1.1 h; VOL 2.9 ± 1.5 h), and only LIT, except for the 3000-m running test, was reported during the recovery weeks. In study IV, the training volume was higher during VOL-P and lower during INT-P in both groups ($p < 0.01$) when compared to PREP. The training intensity distribution was similar in both groups across the study. In addition, the proportion of HRzone1 decreased and HRzone3 increased from PREP to INT-P similarly in both groups ($p < 0.01$). The number of HIIT sessions did not differ between the groups during INT-P (PD 13.6 ± 0.5; IND 15.8 ± 4.3 sessions), although the range was greater in IND (PD 13-14 sessions; IND 10-25 sessions).

5.3 Training adaptations to increased intensity versus volume

5.3.1 Performance

In study II, a main effect of time ($p < 0.001$) was found in vMax, vLT1, and vLT2 (TABLE 8). No differences were observed between the T_0 and T_1 tests in any of the laboratory measurements in either of the groups. vMax improved in both groups after the training period (INT 3.4 ± 3.2%, $p < 0.001$; VOL 2.1 ± 1.8%, $p = 0.006$, between-group ES = 0.50). In addition, vLT1 (INT 4.6 ± 6.1%, $p = 0.006$; VOL 8.4 ± 5.5%, $p < 0.001$, between-group ES = 0.65) and vLT2 (INT 3.0 ± 3.1%, $p = 0.007$; VOL 3.7 ± 3.6%, $p < 0.001$, between-group ES = 0.19) increased in both groups. Neuromuscular performance remained unchanged in both groups.

TABLE 8 Performance test results before (T_1) and after (T_2) the 10-wk training period.

Study II		vLT1 ($km \cdot h^{-1}$)	vLT2 ($km \cdot h^{-1}$)	vMax ($km \cdot h^{-1}$)	CMJ (cm)	Leg press (N)
INT	T_1	10.2 ± 1.3	12.7 ± 1.5	15.7 ± 1.4	29.6 ± 6.7	3203 ± 1328
	T_2	10.7 ± 1.2**	13.1 ± 1.4**	16.2 ± 1.4***	29.6 ± 7.2	3227 ± 1292
	ES	0.34	0.29	0.34	0.00	0.02
VOL	T_1	10.1 ± 1.3	12.5 ± 1.6	15.5 ± 1.7	27.9 ± 5.7	2976 ± 894
	T_2	10.9 ± 1.1***	13.0 ± 1.5***	15.8 ± 1.8**	27.8 ± 5.9	3053 ± 961
	ES	0.62	0.27	0.18	-0.03	0.08

INT, intensity-group; VOL, volume-group; vLT1, the speed at the first lactate threshold; vLT2, the speed at the second lactate threshold; vMax, maximal speed of the incremental treadmill test; CMJ, countermovement jump test; ES, effect size as Cohen's *d* for changes from T_1 to T_2. **$p < 0.01$, ***$p < 0.001$ compared with T_1.

In study III, a main effect of time ($p < 0.001$) was observed in the 3000-m running time as well as HRavg ($p = 0.004$) and HRpeak ($p < 0.001$) measured during the test (TABLE 9). In addition, a time × group interaction ($p < 0.001$) was found in

HRavg and HRpeak. Both groups improved the 3000-m running time from T_1 to T_2 (INT -1.8 ± 1.6%, $p = 0.003$; VOL -1.4 ± 1.7%, $p = 0.017$, between-group ES = 0.22) and from T_1 to T_3 (INT -2.5 ± 1.6%, $p < 0.001$; VOL -2.2 ± 1.9%, $p = 0.001$, between-group ES = 0.18). No main effects nor interaction were observed in the CMJ performance which was tested before the 3000-m tests (TABLE 9) or in the tests that were performed before the supervised sessions during the training period (INT, lowest mean = 31.9 ± 5.5 vs. highest mean = 32.4 ± 5.1 cm; VOL, lowest mean = 31.0 ± 5.8 vs. highest mean = 31.6 ± 6.0 cm).

TABLE 9 Mean ± SD average performance test results before the 2-wk training period (T_1), immediately after the training period (T_2), and after a recovery week (T_3).

Study III		3000 m (min:s)	HRavg (%/max)	HRpeak (%/max)	CMJ (cm)
INT	T_1	12:19 ± 1:32	94.3 ± 2.4	99.4 ± 1.9	33.0 ± 6.2
	T_2	12:06 ± 1:32**	92.2 ± 2.6***##	96.6 ± 2.4***###	32.6 ± 5.6
	T_3	12:00 ± 1:27***	93.8 ± 2.2#[b]	98.1 ± 1.7**##[b]	33.5 ± 5.5
	ES	-0.14/-0.21	-0.85/-0.24	-1.29/-0.71	-0.07/0.09
VOL	T_1	12:33 ± 1:33	94.7 ± 2.1	98.9 ± 2.3	32.6 ± 6.4
	T_2	12:22 ± 1:30*	94.9 ± 2.1	99.9 ± 2.6	33.1 ± 5.9
	T_3	12:16 ± 1:29**	95.3 ± 2.2	99.9 ± 2.3	33.1 ± 6.1
	ES	-0.12/-0.18	0.08/0.33	0.40/0.45	0.07/0.08

INT, intensity group; VOL, volume group; HRavg, average HR of the 3000-m running test in relation to the maximum HR of the incremental treadmill test; HRpeak, peak HR of the 3000-m running test in relation to the maximum HR of the incremental treadmill test; CMJ, countermovement jump test; ES, effect size as Cohen's *d* for changes from T_1 to T_2/T_3. *p < 0.05, **p < 0.01, ***p < 0.001 within-group changes compared with T_1. #p < 0.05, ##p < 0.01, ###p < 0.001 between-group changes compared with T_1. [b]Difference observed from T_1 to T_2 and T_2 to T_3.

5.3.2 Blood and urine samples

The results of blood and urine sample analyses from studies II and III are presented in TABLE 10. In study II, no main effects or interactions were observed in any of the variables. In study III, a main effect of time was observed in norepinephrine ($p < 0.001$) (TABLE 10). Norepinephrine increased in the INT from T_1 to T_2 ($p = 0.01$) and remained elevated in T_3 ($p = 0.018$). In addition, a significant increase was observed in CK activity of VOL from T_1 to T_2 ($p = 0.036$).

TABLE 10 Mean ± SD average blood and urine sample results before the training period (T_1) and immediately after the training period (T_2). In study III, measurements were performed also after a recovery week (T_3).

		Ftesto (pmol·l⁻¹)	Cor (nmol·l⁻¹)	Ftesto/Cor	CK (µmol·l⁻¹)	NE (µmol)
Study II						
INT	T_1	40 ± 25	343 ± 97	0.11 ± 0.06	-	-
	T_2	36 ± 22	356 ± 90	0.10 ± 0.05	-	-
	ES	-0.16	0.13	-0.23		
VOL	T_1	30 ± 21	363 ± 85	0.10 ± 0.05	-	-
	T_2	28 ± 22	346 ± 110	0.09 ± 0.08	-	-
	ES	-0.07	-0.17	0.06		
Study III						
INT	T_1	40 ± 27	422 ± 88	0.09 ± 0.06	103 ± 64	0.11 ± 0.04
	T_2	41 ± 26	419 ± 80	0.10 ± 0.06	124 ± 53	0.15 ± 0.04*
	T_3	43 ± 28	442 ± 115	0.10 ± 0.06	122 ± 130	0.15 ± 0.04*
	ES	0.00/0.02	-0.03/0.20	0.07/0.10	0.09/0.08	0.91/1.03
VOL	T_1	36 ± 23	410 ± 106	0.09 ± 0.06	107 ± 35	0.12 ± 0.05
	T_2	36 ± 26	459 ± 88	0.08 ± 0.06	178 ± 102*	0.13 ± 0.05
	T_3	40 ± 26	465 ± 111	0.09 ± 0.06	126 ± 78	0.15 ± 0.06
	ES	0.00/0.04	0.51/0.51	-0.17/-0.08	0.52/0.13	0.19/0.53

INT, intensity group; VOL, volume group; Cor, serum cortisol concentration; Ftesto, serum free testosterone concentration; CK, serum creatine kinase activity; NE, urine norepinephrine concentration ES, effect size as Cohen's *d* for changes from T_1 to T_2/T_3. *$p < 0.05$ compared with T_1.

5.4 Recovery and performance during training periods

5.4.1 Effects of progressively increased intensity or volume

In study II, changes in monitoring variables across mesocycles are presented in FIGURE 12. When control and training periods were compared as a whole, differences between the periods were observed in the session RPE of INT (p = 0.001, ES = 0.58), perceived recovery of VOL (-6.3 ± 10.1%, p = 0.021) and nocturnal HR of INT (p = 0.016). The relative change of nocturnal HR was also significantly different between the groups (INT -2.1 ± 2.6% vs. VOL 0.4 ± 2.5%, p = 0.013). In addition, the perceived recovery tended to decrease in the INT (-6.1 ± 11.4%), p = 0.056). All other markers stayed unchanged during the training period and across the mesocycles.

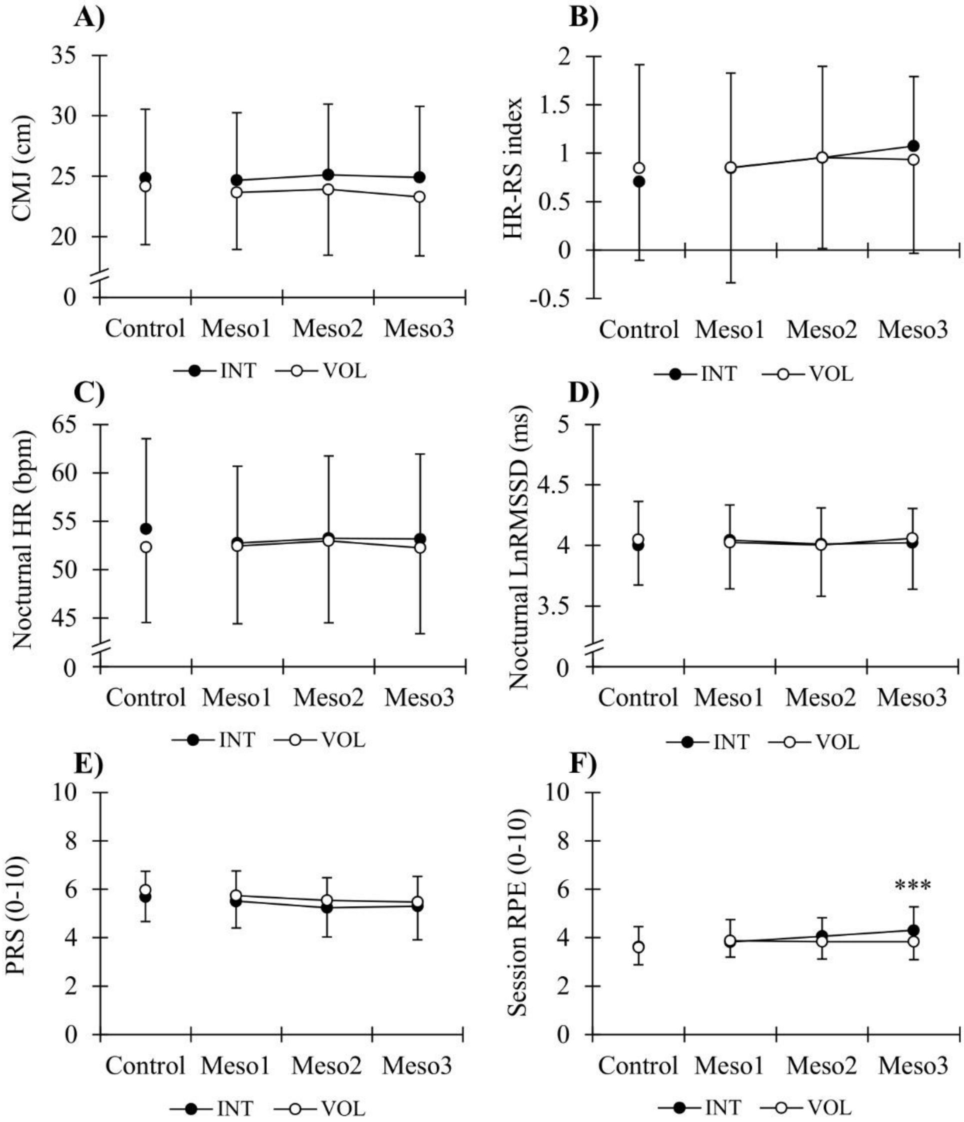

FIGURE 12 Mean ± SD values during the 10-week control period and across three mesocycles during training period (Meso1 = weeks 2-4, Meso2 = weeks 5-7, Meso3 = weeks 8-10) in the nocturnal heart rate (HR) and heart rate variability (LnRMSSD), countermovement jump (CMJ), heart rate-running speed index (HR-RS index), session RPE and perceived recovery (PRS). ***$p < 0.001$ in within-group comparison to control.

5.4.2 Effects of intensity or volume block

In study III, the INT increased their running speed in the interval session and the VOL increased the HR-RS index (FIGURE 13). In the INT group, the average HR during the intervals decreased ($p < 0.05$) from the first session (90.7% ± 1.8% of HRmax) to the 6th, 7th, 9th, and 10th sessions (88.1%–88.6% of HRmax). In the VOL group, the average HR remained similar within-session type and was on average 72.6% ± 4.9% of HRmax during the basic sessions and 69.0% ± 4.5% during the long-distance sessions.

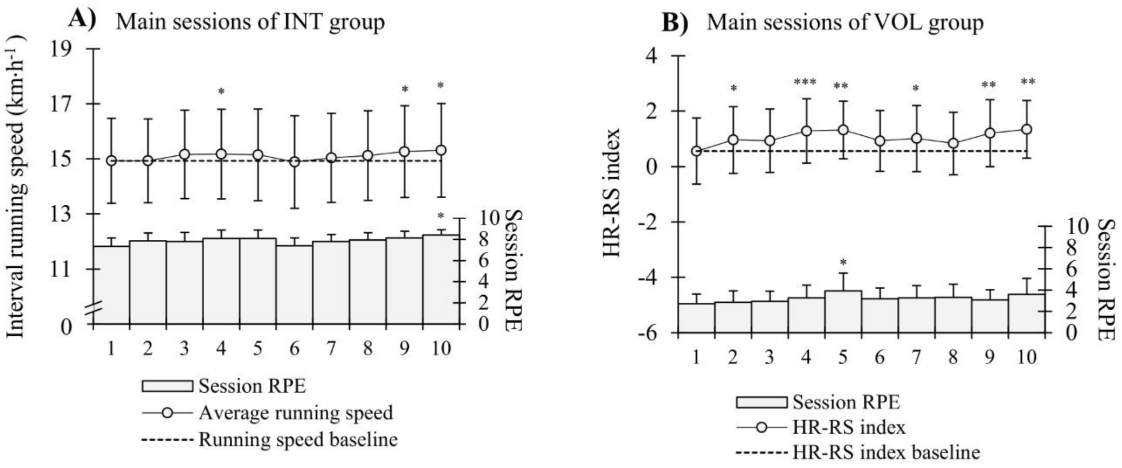

FIGURE 13 Mean ± SD average running speed during the 6 × 3-min intervals performed at maximal sustainable effort, and session RPE of each interval session prescribed (A). Mean ± SD HR-RS index and session RPE of basic (1–4, 6–9) and long-distance (5, 10) LIT sessions prescribed (B). *p < 0.05, **p < 0.01, ***p < 0.001 compared with the first session.

A main effect of time ($p = 0.001$) was found in nocturnal HR, and time × group interaction was found in nocturnal HR ($p = 0.001$), nocturnal LnHF ($p = 0.036$), and nocturnal LnRMSSD ($p = 0.027$) (FIGURE 14). The nocturnal HR decreased in the INT from Pre to Week3 ($p = 0.002$) and from Week2 to Week3 ($p < 0.001$). Changes in the nocturnal HR from Pre to Week1 (INT 1.9 ± 4.0% vs. VOL -1.6 ± 5.1%, $p = 0.045$) and from Week2 to Week3 (INT -3.8 ± 3.2% vs. VOL 0.1 ± 2.9%, $p = 0.003$) were different between the groups. In the nocturnal LnHF, no significant within-group changes were found, but the change from Pre to Week1 was different between the groups (INT -1.0% ± 2.0% vs. VOL 1.8% ± 3.2%, $p = 0.008$). The same pattern was observed in the nocturnal LnRMSSD where the change from Pre to Week1 differed between the groups ($p = 0.014$).

Among perceptual markers, a main effect of time was found in muscle soreness ($p < 0.001$), and time × group interaction was found in the readiness to train ($p = 0.008$) and muscle soreness ($p = 0.001$) (FIGURE 14). Readiness to train decreased in INT from Pre to Week3 ($P = 0.045$) and tended to decrease from Pre to Week2 ($p = 0.057$). In addition, the change in readiness to train from Pre to Week3 was different between the groups ($p = 0.002$). Muscle soreness increased in INT ($p < 0.001$) from Pre to Week1 and Week2, and the change was different between the groups from Pre to Week1 ($p < 0.001$), Week2 ($p = 0.012$), and Week3 ($p = 0.001$).

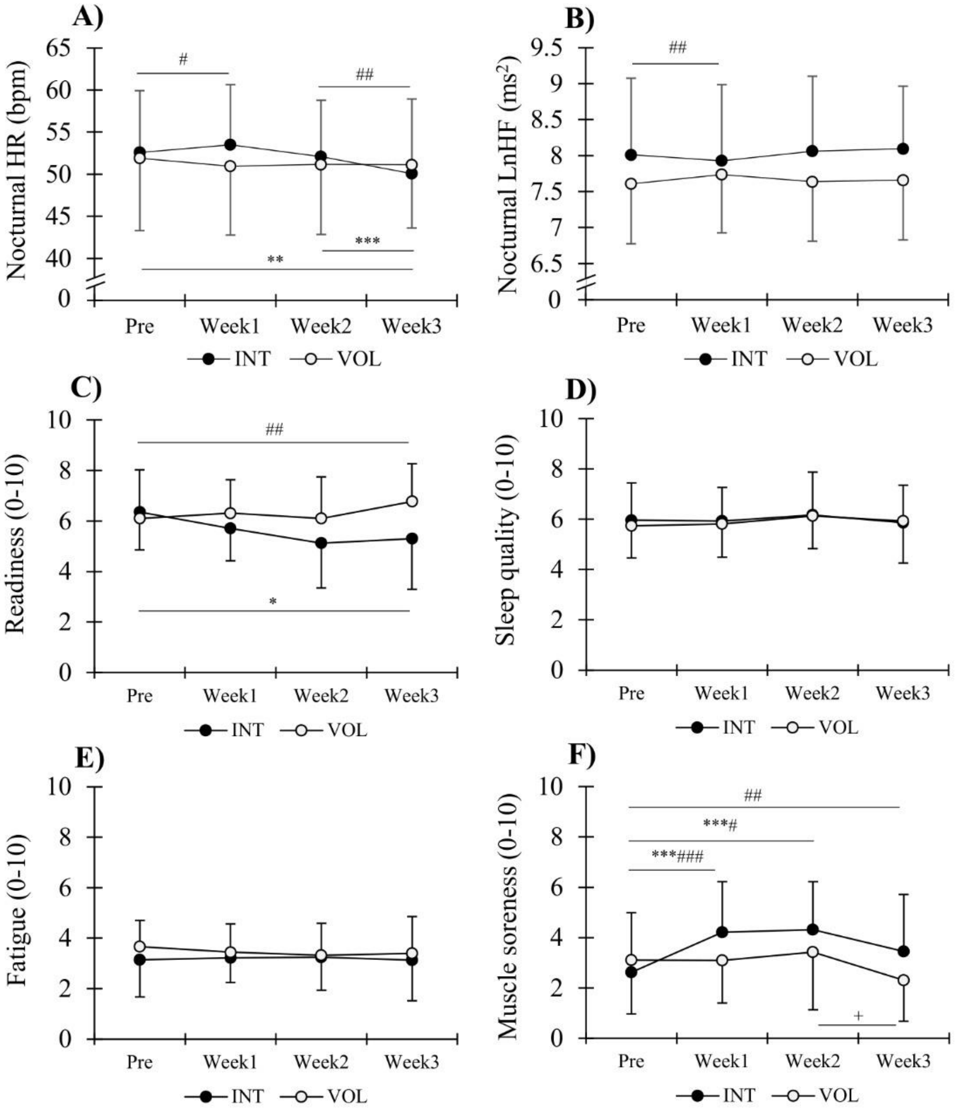

FIGURE 14 Mean ± SD average weekly values of nocturnal HR, nocturnal LnHF, and perceptual recovery at first recovery week (Pre), during the training period (Week1 and Week2), and second recovery week (Week3). INT, interval group; VOL, volume group. *$p < 0.05$, **$p < 0.01$, ***$p < 0.001$ compared with Pre in INT. #$p < 0.05$, ##$p < 0.01$, ###$p < 0.001$ between-group changes compared with Pre. +Compared with the previous week in VOL.

5.4.3 Agreement between changes in HRV and other monitoring variables

Agreement between responses from baseline to the end of training period in nocturnal HRV and other monitoring variables was analyzed separately for studies II and III. In both studies, the highest agreement with the response was found for nocturnal HR (study II, 67% agreed; study III, 69% agreed) while the lowest agreement was found for CMJ (23% and 24% agreed). TABLE 11 demonstrates individual responses within each monitoring variable.

TABLE 11 Agreement between responses of nocturnal HRV (LnRMSSD) and other monitoring variables. In study II, the change from the control period to the last mesocycle was compared and in study III, the change from Pre to Week2. The numbers indicate participants within each response (- = greater decrease than SWC, ± = change is within SWC, + = greater increase than SWC). Green indicates a similar response, grey indicates a different response, while red indicates an opposing response between variables. In these analyses it was assumed that an increase in HRV would be a positive change and a decrease in HRV a negative change. In study II there were 30 participants in the analyses and in study III 29 participants (in HR-RSi 14).

		Study II Nocturnal HRV					Study III Nocturnal HRV		
		-	±	+			-	±	+
	HR	4	21	5		HR	7	9	13
-	6	0	4	2	-	12	0	2	10
±	21	2	16	3	±	10	2	5	3
+	3	2	1	0	+	7	5	2	0
	CMJ					CMJ			
-	14	1	10	3	-	10	1	3	6
±	10	2	6	2	±	7	2	2	3
+	6	1	5	0	+	12	4	4	4
	PRS					Readiness			
-	8	2	5	1	-	11	2	3	6
±	20	2	15	3	±	15	4	5	6
+	2	0	1	1	+	3	1	1	1
	HR-RSi					HR-RSi			
-	1	0	1	0	-	3	0	1	2
±	19	3	12	4	±	0	0	0	0
+	10	1	8	1	+	11	4	1	6

HR, nocturnal heart rate; CMJ, countermovement jump; PRS, perceived recovery scale; HR-RSi, heart rate-running speed index.

5.4.4 Factors related to interindividual differences in training adaptation

Potential factors contributing to interindividual differences in the training adaptations were examined with correlation analyses in studies II and III (TABLE 12). From the pretraining determinants, nocturnal LnHF ($p = 0.004$) and nocturnal LnRMSSD ($p = 0.036$) in the INT group (study II) were the only markers that correlated with the change in performance. Regarding the changes in the monitoring variables, a decrease in nocturnal LnHF ($p = 0.044$, INT; 0.033, All) and an increase in HR-RS index ($p = 0.040$, All) were associated with the training adaptation in study II, while in study III no such correlations were found.

TABLE 12 Associations between the relative change of vMax (study II) or 3000-m time (study III) and baseline determinants or changes in monitoring variables. The changes were calculated from the control period to the last mesocycle (study II) or from Pre to Week2 during the block period (study III). In study III, the change in performance was calculated from T_1 to peak time of T_2 or T_3.

	Study II			Study III		
	INT (n = 13)	VOL (n = 17)	ALL (n = 30)	INT (n = 15)	VOL (n = 15)	ALL (n = 30)
Baseline determinants						
Age (y)	-0.178	0.177	0.062	-0.023	-0.026	0.016
Training (h·week^{-1})	0.050	0.269	0.127	0.189	0.325	0.246
VO_{2max} (ml·kg^{-1}·min^{-1})	0.260	0.280	0.248	-0.151	0.054	-0.052
LnHF (ms^2)	0.741**	0.051	0.349	0.062	0.147	0.069
LnRMSSD (ms)	0.584*	0.089	0.322	0.193	0.069	0.108
Stress (0-10)	0.156	-0.358	0.021	0.483	0.125	0.289
Change in monitoring variable						
HR (Δ%)	0.515	-0.442	0.034	0.343	-0.452	-0.155
LnRMSSD (Δ%)	-0.507	0.209	-0.225	-0.136	0.120	0.013
LnHF (Δ%)	-0.566*	-0.155	-0.390*	-0.180	0.018	-0.072
PRS (Δ)	0.254	-0.059	0.099	-	-	-
Readiness (Δ)	-	-	-	-0.271	-0.095	-0.109
Fatigue (Δ)	-	-	-	-0.014	0.227	0.108
Soreness (Δ)	-	-	-	-0.004	0.047	-0.056
CMJ (Δ%)	-0.032	0.339	0.189	0.327	0.076	0.165
HR-RSi (Δ)	0.366	0.363	0.377*	-	0.487	-
RSint (Δ%)	-	-	-	-0.271	-	-

INT, intensity group; VOL, volume group; HR, nocturnal heart rate; LnHF, nocturnal natural logarithm of the high-frequency power; LnRMSSD, nocturnal natural logarithm of the root mean square of successive differences; PRS, perceived recovery scale; CMJ, countermovement jump; HR-RS, heart rate-running speed index; RSint, average running speed during interval session. *$p < 0.05$, **$p < 0.01$

The same parameters that were used in the correlation analyses were further examined by comparing individuals with high (study II, n = 7, 6.0 ± 2.5% change in vMax; study III, n = 13, -4.1 ± 0.9% change in 3000 m time) and low training response (study II, -0.3 ± 0.7% change in vMax; study III, n = 4, 0.1 ± 0.7% change in 3000 m time). In study II, none of the pretraining determinants differed between subgroups, but in the monitoring variables changes differed in the HR-RS index (high 0.8 ± 0.5 vs. low -0.1 ± 0.2, p = 0.002) and LnHF (high -1.6 ± 1.1% vs. low 1.8 ± 3.7%, p = 0.035). There was also a tendency for a difference in CMJ (high

0.6 ± 7.1% vs. low -6.6 ± 5.1%, $p = 0.064$), and CMJ was impaired in all individuals in the low subgroup. In study III, no differences were found between subgroups in any of the pretraining determinants or changes in monitoring variables.

5.5 Individualized endurance training

5.5.1 Training periodization

The weekly training volume and intensity distribution in PD and IND are illustrated in FIGURE 15. The total accumulated training volume during the VOL-P and the INT-P was 56.9 ± 13.0 h (range 43.7-83.9 h) in PD and 54.7 ± 9.0 h (range 40.3-69.1 h) in IND. The volume was distributed into 52 ± 11 sessions (range 42-80 sessions) in PD and 53 ± 7 sessions (range 46-71 sessions) in IND. Regarding the training adjustments of IND during the intervention, 55 ± 12% maintained the training load, 35 ± 10% increased the training load and 10 ± 8% decreased the training load.

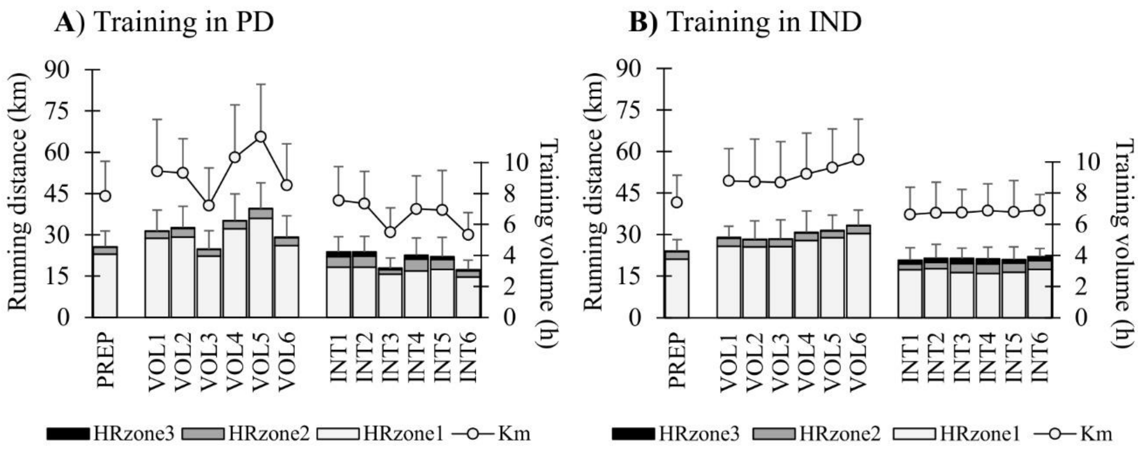

FIGURE 15 Training volume, running distance, and training intensity distribution (time in HRzone1, HRzone2, and HRzone3) at baseline (PREP) and across the volume (VOL1-VOL6) and interval (INT1-INT6) training periods in the predefined (A) and individualized (B) training groups.

5.5.2 Performance and laboratory tests

A main effect of time was observed in vLT2, vMax, and VO_{2max} ($p < 0.001$) (TABLE 13). Both groups improved ($p < 0.001$) their maximal treadmill performance from T_1 to T_3 (PD 3.0 ± 2.4%; IND 4.0 ± 1.9%, between-group ES = 0.46), and T_2 to T_3 (PD 1.8 ± 2.5%, $p = 0.022$; IND 2.7 ± 2.8%, $p = 0.001$, between-group ES = 0.34).

TABLE 13 Mean ± SD performance and laboratory test results before the VOL-P (T_1) between the VOL-P and INT-P (T_2) and after the INT-P (T_3).

	vLT1 (km ·h^{-1})	vLT2 (km ·h^{-1})	vMax (km ·h^{-1})	VO_{2max} (ml ·kg^{-1} ·min^{-1})
PD				
T_1	10.7 ± 0.9	13.3 ± 1.4	16.1 ± 1.8	46.7 ± 3.9
T_2	10.8 ± 1.1	13.5 ± 1.5	16.3 ± 2.0	47.8 ± 5.2
T_3	11.1 ± 1.2	13.6 ± 1.6*	16.6 ± 2.1***+	50.7 ± 6.1***+++
ES	0.10/0.33	0.15/0.18	0.11/0.26	0.26/0.80
IND				
T_1	10.6 ± 1.1	13.1 ±1.6	16.0 ± 2.0	47.3 ± 7.2
T_2	10.8 ± 1.0	13.3 ±1.4	16.2 ± 2.0	47.0 ± 7.2
T_3	10.8 ± 1.3	13.5 ±1.6**	16.6 ± 1.9***++	50.3 ± 7.6**+++
ES	0.23/0.14	0.16/0.23	0.10/0.32	-0.03/0.40

PD, Predefined training group; IND, Individualized training group; vLT1, the speed at the first lactate threshold; vLT2, the speed at the second lactate threshold; vMax, maximal speed of the incremental treadmill test; VO_{2max}, maximal oxygen uptake; ES, effect size as Cohen's *d* for the changes compared to T_1. *$p < 0.05$, **$p < 0.01$, ***$p < 0.001$ within-group compared to T_1, + $p<0.05$, ++$p<0.01$, +++$p<0.001$ within-group compared to T_2.

No main effects or interactions were observed in CMJ performance, which was tested before the treadmill test (PD, 28.0 ± 5.2, 28.8 ± 4.7, and 28.6 ± 4.4 cm; IND, 30.3 ± 6.3, 30.6 ± 6.8, and 30.0 ± 6.2 cm). Also, serum CK (PD, 115 ± 54, 148 ± 90, and 115 ± 54 µmol·l^{-1}; IND, 118 ± 55, 130 ± 65, and 129 ± 79 µmol·l^{-1}), free testosterone (PD, 27.0 ± 26.6, 26.9 ± 25.5, and 27.3 ± 23.3 pmol·l^{-1}; IND, 18.6 ±17.5, 18.2 ±16.8, and 18.6 ± 16.4 pmol·l^{-1}), and cortisol (PD, 382 ± 102, 439 ± 107, and 411 ± 96 nmol·l^{-1}; IND, 464 ± 145, 468 ± 145, and 456 ± 125 nmol·l^{-1}) concentrations remained unchanged at T_1, T_2 and T_3, respectively.

A main effect of time ($p < 0.001$) and time × group interaction ($p = 0.006$) was observed in 10-km running time (FIGURE 16). PD (-2.9 ± 2.4%, $p = 0.004$, ES = 0.20) and the IND (-6.2 ± 2.8%, $p < 0.001$, ES = 0.46) improved the 10-km running time from T_1 to T_3, and the respective change differed between the groups ($p = 0.002$, ES = 1.23). The running time was improved from T_1 to T_2 only in the IND (-2.6 ± 3.1%, $p = 0.001$, ES = 0.19) while in the PD it remained unchanged (-0.8 ± 2.1%, $p = 0.534$, ES = 0.08). However, the change was not different between the groups ($p = 0.125$, ES = 0.64). The improvement was also significant between T_2 and T_3 in IND (-3.7 ± 2.2, $p < 0.001$, ES = 0.27) and tended to be significant in PD (-2.0 ± 3.3%, $p = 0.051$, ES = 0.14) with no between-group differences ($p = 0.087$, ES = 0.61). Main effects of time were also observed in average HR ($p = 0.035$) and peak HR ($p = 0.002$) during the running test (FIGURE 16).

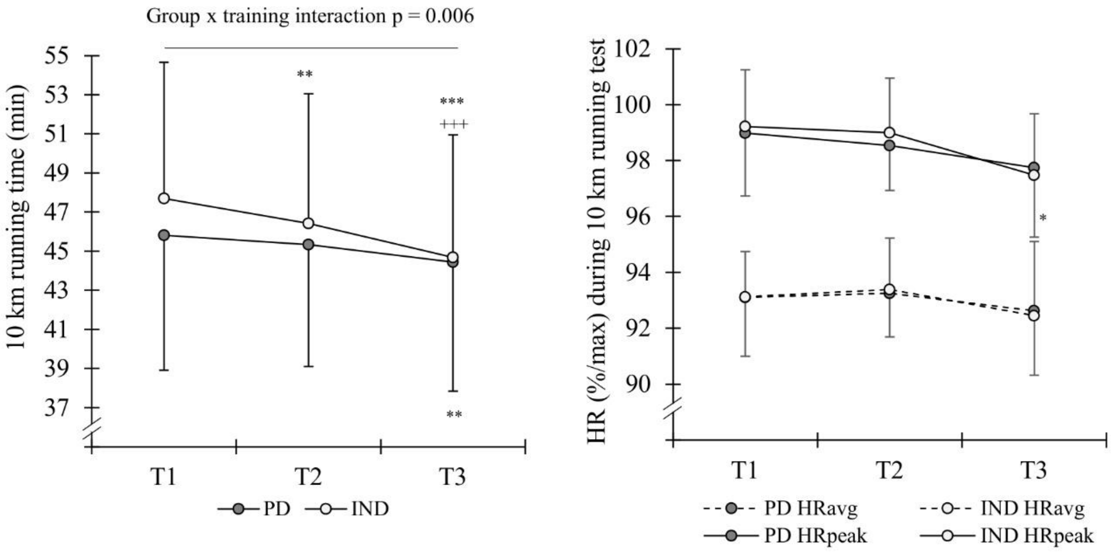

FIGURE 16 Running time and HR in the 10-km test before the VOL-P (T_1), between the VOL-P and INT-P (T_2), and after the INT-P (T_3) in the predefined (PD) and individualized (IND) training groups. *$p < 0.05$, **$p < 0.01$, ***$p < 0.001$ within-group compared to T1, +++$p < 0.001$ within-group compared to T_2.

In addition to the statistical analyses, the individual response magnitudes in the maximal treadmill performance and the 10-km running performance from T_1 to T_3 were examined (FIGURE 17). In the vMax, the percentage distribution for high, moderate, and trivial responders were 29/50/21% for PD and 50/50/0% for IND, respectively. Meanwhile, in the 10-km running test, the percentage distributions for high, moderate, trivial, and moderate negative responders were 23/54/15/8% for PD and 81/6/13/0% for IND, respectively.

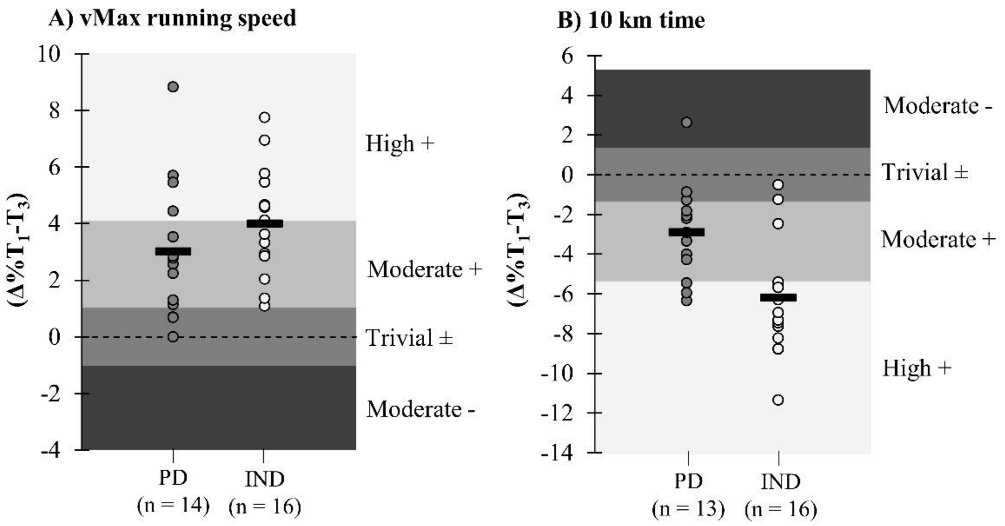

FIGURE 17 The magnitude of individual responses in maximal treadmill speed (A) and 10-km running time (B). Magnitudes were set based on the CV of the parameter between T_0 and T_1. High + and Moderate + indicate improved performance, Trivial ± unchanged performance, and Moderate - impaired performance.

5.5.3 Monitoring variables

Main effects for time were observed in the HR-RS index (FIGURE 18) and the average running speed of interval sessions ($p < 0.001$). The running speed in the intervals increased in the IND from week 1 (14.4 ± 1.6 km·h^{-1}) to week 3 (14.8 ± 1.8 km·h^{-1}, $p = 0.023$), week 4 (14.8 ± 1.8 km·h^{-1}, $p = 0.005$), and week 6 (14.9 ± 1.8 km·h^{-1}, $p = 0.023$), while no change was observed in the PD (14.6 ± 2.0 km·h^{-1} vs. 14.7-14.9 km·h^{-1}). In addition, some significant within-group differences were found in the staleness score and nocturnal HR (FIGURE 18) which were analyzed with nonparametric tests. The IND had significantly higher proportion defined as normal in HR-RS index ($82 \pm 6\%$ vs. $75 \pm 7\%$, $p = 0.015$) and LnRMSSD (52 ± 5 vs. $45 \pm 5\%$, $p = 0.046$) when the percentage of data points being within individual SWC was analyzed, whereas in fatigue ($68 \pm 11\%$ vs. $75 \pm 14\%$) and muscle soreness ($69 \pm 17\%$ vs. $69 \pm 24\%$) no differences were observed.

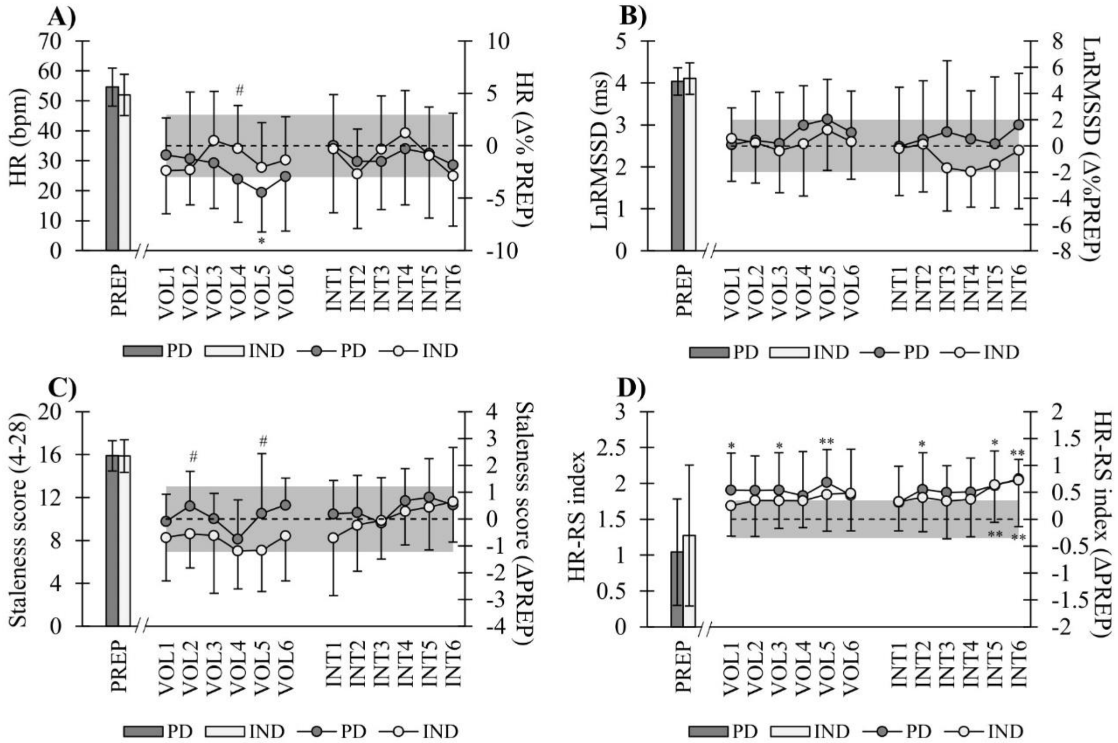

FIGURE 18 Mean (± SD) baseline values (PREP) and weekly changes (VOL1-6, INT1-6) in nocturnal HR (A), nocturnal LnRMSSD (B), staleness score (C), and HR-RS index (D). Grey area represents the smallest worthwhile change of the parameter based on individual average values during PREP. In A and B = 0.5 x CV, in C and D = 0.5 x SD. *p < 0.05, **p < 0.01, ***p < 0.001 within-group compared to PREP. #p < 0.05 between-group at respective time point.

6 DISCUSSION

The present study aimed to examine physiological, perceptual, and performance responses to endurance exercises differing in intensity as well as responses and adaptations to training periods increasing either training volume or intensity. Lastly, this study compared individually adjusted endurance training prescription based on recovery and training status to predefined endurance training. Comparisons between single training sessions and longer training periods demonstrated some differences in the demands of high-volume vs. high-intensity training. Furthermore, responses to the training seemed quite individual and dependent on the viewpoint being taken (e.g., neuromuscular performance vs. ANS recovery). Individualizing training load by considering multiple aspects seems to be a potential method to augment endurance training adaptations.

6.1 Acute responses to different types of endurance exercises

In the present thesis, comparisons were performed between LIT, MIT, and HIIT, regarded as the foundational session types of endurance training. In addition, SMIT sessions were performed, since this type of training has also induced positive endurance adaptations (Cicioni-Kolsky et al., 2013; Gibala & McGee, 2008). One of the main findings was that single sessions rarely impaired recovery significantly, but the interpretation also depends largely on the viewpoint that was chosen. It was also confirmed that different recovery markers do not necessarily agree with each other in short-term recovery kinetics.

Characteristics of training sessions
Study I, aimed to examine representative examples of LIT, MIT, HIIT, and SMIT sessions. While RPE, blood lactate and HR responses could mostly be regarded as desirable compared to those suggested for each intensity zone (Seiler & Kjerland, 2006; Seiler & Tønnessen, 2009), the only unexpected response was the increased blood lactate value after LIT. The increment occurred despite the low

relative intensity compared to the maximal treadmill test or lactate threshold performance (52%/vMax, 80%/vLT1), low HR (avg: 70%/HR_{max}, peak: 76%/HR_{max}), and RPE (12 on a 6−20 scale). Previously, Seiler et al. (2007) found no changes in blood lactate after 1- or 2-h LIT performed below the ventilatory threshold in trained or well-trained runners. On the other hand, Kaikkonen et al. (2010) found that after a 14-km run on the treadmill at 60% vVO_{2max}, blood lactate was elevated significantly compared to the control session performed at the same intensity but 3 km in distance (1.4 vs. 2.6 $mmol \cdot l^{-1}$) in recreational runners. The higher fitness level and better "durability" of well-trained athletes could, therefore, be a major factor in the observed response.

Acute responses to training sessions

Acute responses following the exercises were analyzed from multiple perspectives. ANS responses were examined via supine HRV immediately (3 min) after each session. In line with previous studies (Kaikkonen et al., 2007; Seiler et al., 2007) the largest changes in HRV were observed after the MIT and HIIT sessions. Seiler et al. (2007) have previously suggested that the first ventilatory threshold would act as a barrier to delayed parasympathetic reactivation, and it seems the sessions with high cardiovascular load induce the highest amount of stress in the ANS function. On the other hand, Buchheit et al. (2007) have suggested that parasympathetic reactivation mainly relates to the contribution of anaerobic processes during preceding activity. Therefore, it was rather surprising to observe that there was hardly any difference between LIT and SMIT despite distinct blood lactate and RPE values. Compared to previous studies that have found great HRV decreases after SMIT sessions (Buchheit et al., 2007; Niewiadomski et al., 2007), the current HR and blood lactate values were lower, which is the most likely explanation for the somewhat mild HRV responses followed by the present SMIT. In addition to intensity, also work:relief-ratio should be considered when planning interval exercise, as they both affect the cardiovascular strain and anaerobic glycolytic energy contribution significantly (Buchheit & Laursen, 2013b).

Neuromuscular responses were assessed one minute after each session with CMJ. Interestingly, the changes in CMJ performance seemed contradictory to the HRV: while the CMJ remained unchanged after MIT and HIIT, decreases were observed after LIT and SMIT. The finding is not that astonishing in view of previous studies that have reported improved CMJ performance after intensive running sessions (Boullosa & Tuimil, 2009; Vuorimaa et al., 2006). Moreover, Wiewelhove et al. (2016) have observed decreased CMJ performance after sprint interval training, while aerobic intervals did not have such an effect. Therefore, it seems that intervals with high neuromuscular demands have a different effect on CMJ than intervals that are more aerobic by nature. Although a similar pattern was observed after LIT and SMIT, it is plausible that they were caused by different mechanisms (e.g., peripheral vs. central fatigue). For example, fatigue induced by SMIT could potentially relate to peripheral contractile mechanism disturbances (Carroll et al., 2017; Škof & Strojnik, 2005). Some other possible mechanisms behind neuromuscular fatigue are decreased voluntary activation (Carroll et al., 2017) and decreased stretch-reflex sensitivity (Avela & Komi, 1998). It is important to note that CMJ as a marker of neuromuscular fatigue has its' limitations (García-Pinillos et al., 2021), and acute changes may not fully reflect the neuromuscular demands of the preceding activity.

Cardiorespiratory, metabolic, and perceptual responses to submaximal running were assessed 10 minutes after each exercise. Unlike in HRV or CMJ, no significant differences were found between sessions in any of the markers that were measured during SRT. However, responses were mainly in line with previously reported results after similar types of running sessions (James & Doust, 1998; Xu & Montgomery, 1995; Zavorsky et al., 1998). As expected, HR and RPE during SRT increased after all sessions, while RER decreased, indicating higher reliance on fat despite the intensity of preceding exercise. The potential reasons behind cardiovascular responses (e.g., cardiac drift) relate to the increases in body core temperature, sympathetic nervous system activity, dehydration, and decreases in blood volume (Coyle & Gonzalez-Alonso, 2001). Probably the most unexpected finding was that the VO_2 during SRT increased only after continuous sessions. These results are in contrast with previous studies that have reported impaired running economy levels after HIIT (James & Doust, 1998; Zavorsky et al., 1998). The lack of major changes in economy or differences between the sessions in any markers could relate to the timing of the measurement, as some session-related effects may have already disappeared at the time point used in the current study (post 18−20 min). Also, some compensatory mechanisms in the neuromuscular system (PAP), may have contributed to the lack of changes in the running economy.

Recovery from sessions

In addition to acute responses, the current study assessed recovery 24 hours after each session. Regarding HRV, Stanley et al. (2013) have previously suggested that cardiac autonomic recovery may take up to 24 hours after LIT and at least 48 hours after HIT. On the other hand, Holt et al. (2019) and Niewiadomski et al. (2007) found no significant differences compared to baseline in HRV 24 h after any type of MIT or HIIT session. In the current study, HRV also returned to baseline in 24 h after all sessions at the group level. However, there was some variation between individuals, and not all participants were fully recovered. The current results suggest that although the ANS recovery may take 24-48 hours, such a long period is not required for all (most) individuals. It is important to acknowledge that HRV could be affected by multiple external factors, especially in the daytime recordings (Buchheit, 2014), which makes it challenging to find significant changes caused by a single exercise.

While the ANS recovery seemed to occur quite rapidly after all sessions, the neuromuscular recovery did not seem to follow exactly the same pattern. CMJ performance remained decreased after SMIT, and muscle soreness increased 24 hours after LIT and SMIT. In line with the current findings, Wiewelhove et al. (2016) observed significantly decreased CMJ 24 hours after the supramaximal sprint interval session. The present results are also in line with previous studies on strength training that have reported distinct recovery kinetics for the ANS and the neuromuscular system (Flatt et al., 2019; Thamm et al., 2019). Increased muscle soreness most likely relates to the mechanical load caused by the distance (LIT) or the high intensity of the effort (SMIT). Decreased CMJ emphasizes the high neuromuscular demands of SMIT, especially in recreational runners who may be unaccustomed to this type of training.

All physiological variables (HR, VO_2, RER) that were measured during SRT returned to baseline in 24 hours, and there was even a kind of super-compensation in HR, which decreased 3-4 bpm after all sessions. Previous studies have reported slight decrements in submaximal HR 2 days after an ultramarathon event (Siegl et al., 2017), but also a lack of change 1-4 days after 30-min HIT (Morgan et al., 1990) or 26-km MIT (Quinn & Manley, 2012). One possible explanation for the acute decrement in submaximal HR could relate to increased plasma volume (Buchheit, 2014b), but it cannot be confirmed by the current study. Interestingly, despite decreased HR, the RPE remained elevated after both interval sessions. The finding demonstrates the challenging interpretation of submaximal tests. Although there exists a certain relationship between submaximal and maximal performance (Vesterinen et al., 2014, 2017), similar changes in submaximal HR (decrease) could indicate positive and negative changes in the training state (Le Meur et al., 2013a). Therefore, it has been suggested that perceptual markers should always be used besides the HR-based markers (Bellenger et al., 2016).

6.2 Training adaptations and responses to increased intensity or volume

Effects of increased intensity or volume of endurance training were compared via two separate interventions: 1) a 10-week training period, during which training volume or proportion of MIT-HIIT training was progressively increased 2) a 2-week HIIT or high-volume LIT block. Conclusively, the improvement in the endurance performance was quite similar between the groups in both training interventions, but some differences were observed in the recovery markers, especially during the 2-week block.

6.2.1 Training adaptations

The training protocols for studies II and III were planned so that the training load in both groups would be challenging but tolerable for recreational runners. In study II (10-week period), the progression was designed to be progressive and to lead at the end to similar increments in intensity or volume that have been used either in HIIT (Dolci et al., 2020) or volume overload periods (Le Meur et al., 2013b). Previously, a similar type of weekly progression (10-50%) during volume periods has been used in several studies (Bellinger, 2020; Düking et al., 2020; Vesterinen et al., 2016a). In HIIT protocols, it has been more typical to have quite a stable HIIT frequency (e.g., 2-3 sessions per week) for a certain period of time (Cicioni-Kolsky et al., 2013; Helgerud et al., 2007; Seiler et al., 2013), but also protocols progressing in intensity have been used (Vesterinen et al., 2013). In study

III (2-week block), the increase in training load was sudden, and the same load was maintained for two weeks. Previously, block periods have varied between alternating HIIT and LIT weeks (Mølmen et al., 2019) and short HIIT microcycles of >4 HIIT sessions per week (Dolci et al., 2020). Volume blocks have mostly been 2-6-week overload periods that have increased the volume of endurance training (Bellenger et al., 2016; Le Meur et al., 2013b; Lehmann et al., 1992; Uusitalo et al., 1998).

The training protocols for both interventions, as well as INT- and VOL-groups seemed quite appropriate, as significant improvements in the incremental treadmill test performance (study II) and 3000-m running performance (study III) were found. Interestingly, no differences were observed between the groups in the change of main performance parameters. The magnitude of changes in maximal treadmill performance (INT 3.4 ± 3.2; VOL 2.1 ± 1.8%) are in line with those reported previously after similar types of training interventions (Stöggl & Sperlich, 2014; Talsnes et al., 2022; Vesterinen et al., 2016a). Meanwhile, the changes in 3000-m performance could be regarded as quite high (INT 2.5 ± 1.6%; VOL 2.2 ± 1.9%), considering the short (2-week) training period in study III. On the other hand, similar or even greater relative improvements have been found in other performance-related markers (VO_{2max}, intermittent performance) after HIIT microcycles (Dolci et al., 2020), and therefore, it seems that these kinds of HIIT periods induce rapid improvements in maximal endurance performance. In turn, the significant (and rapid) improvement after the VOL block was slightly unexpected. Not too many previous studies exist that would have examined only LIT sessions, and the results of such studies have been quite contradictory (Düking et al., 2020; Ingham et al., 2008; Stöggl & Sperlich, 2014; Zinner et al., 2018). It is possible that the effectiveness of LIT requires quite a high volume, especially if performed without any concurrent MIT or HIIT. In most studies, LIT volume/increment in volume has been somewhat moderate, and for example, in Stöggl and Sperlich (2014) study, the absolute training volumes were similar between the polarized and high-volume groups.

After periods of extensively high training load, there is typically some delay in the training adaptation due to accumulated fatigue (Bellinger, 2020). In study II, there was a recovery week before the final measurements, which was expected to be sufficient for overcoming such issues. In study III, performance was assessed immediately after the block and after the recovery week. In previous studies, it has taken 12 days to reach peak performance after a 3-week HIIT period, and after a 3-week volume overload, peak performance was achieved in 14 days (Aubry et al., 2014). It was expected that training adaptation would also be delayed after the present 2-week INT and VOL blocks, although they were not necessarily planned to be overloading. Therefore, it was quite surprising that there was no significant difference between the last two test trials in either of the groups. In the INT group, 4/15 participants even impaired their performance after the recovery week. Since the recovery week was similar for both groups (no HIIT sessions), it is possible that some individuals of INT showed a kind of detraining effect. This was supported by the fact that participants of the INT group were able to improve their performance in the interval session through the block. In general, it is suggested that intensity should be maintained during tapering while only volume decreases (Bosquet et al., 2007), which is important to consider when implementing HIIT blocks into practice.

Previously, it has been suggested that in recreational runners LIT could lead more likely to positive (Zinner et al., 2018) or very positive (Düking et al., 2020) adaptations compared to HIT-training. The current results do not support these findings, as in study II, the VOL group had more individuals with no change or decrease in performance (INT 2/13; VOL 5/17), and in study III, in 14/15 participants of INT and 9/15 participants of VOL the improvement was at least moderate in magnitude. In conclusion, as both training methods seemed to induce relatively comparable effects on endurance performance, it seems likely that the combination of both leads to the optimal long-term outcome in performance, as has also been suggested previously (Laursen, 2010; Seiler, 2010; Stöggl & Sperlich, 2014).

6.2.2 Physiological and perceptual responses to training

HR-based markers

Resting HR and HRV measurements are widely used in endurance sports, and especially HRV has been suggested to be a useful monitoring tool as a non-invasive marker of cardiac parasympathetic activity (Martinmäki et al., 2006) and cardiovascular homeostasis (Stanley et al., 2013). Resting HRV has also been utilized in the guidance of endurance training by informing via the ANS function whether an individual would have sufficient readiness to train at high intensity (Düking et al., 2021). Although this type of approach has seemed beneficial, some contradictions make the interpretation of the results challenging. While increments in HRV relate to increased parasympathetic activity and a good state of recovery, in the case of parasympathetic hyperactivity, the same changes relate to an abnormal response due to increased training load (Bellenger et al., 2016; Le Meur et al., 2013b). Although the current studies induced increments in training load comparable to those that have found parasympathetic hyperactivity, no such findings were made (at least systematically) during progressively increased training load (study II) nor during HIIT or LIT blocks (study III). Previous studies have used morning HRV recordings, while nocturnal recordings were used in the present studies instead, which may partly explain the different responses. Furthermore, no overreaching was induced by the current protocols, and that is why the hyperactivity may relate more to the state of overreaching/fatigue itself rather than being a consequence of the increment in the training load. In the case of successful training, it has been suggested that a high volume of LIT would increase HRV, while more intensive periods would do the opposite (Plews et al., 2014a). This has also been supported by a large dataset of Altini and Plews (2021), where LIT increased (1.6%) and HIT decreased (-3.0%) resting HRV on the following day. In study III, this type of trend was observed during the first block week, but the difference disappeared thereafter, possibly due to more accumulated fatigue also in VOL. Although increased HRV and correlations in the change of HRV and endurance performance have previously been found after some endurance training periods (Buchheit et al., 2010; Nummela et al., 2010), it may not always be the case in individuals with long and consistent training backgrounds. In this type of situation, the goal could be to maintain the HRV within the normal range during training like in the approach used in HRV-guided training (Javaloyes et al., 2019; Vesterinen et al., 2016c).

Nowadays, resting HR may be slightly overlooked by resting HRV in the context of recovery monitoring. This is probably explained by the suggested greater sensitivity of HRV to respond to stressors (Altini & Plews, 2021). Interestingly, in studies II and III, a significant decrease in resting HR was found in the INT group while there was no change in HRV. Furthermore, the change in HR was different compared to the VOL in both studies. Block type of HIIT training has also previously induced significant decrements in resting HR (Nuuttila et al., 2017). Whether these changes could relate to the cardiac structural/functional changes (increased stroke volume) remains to be speculated. Previous findings (Astorino et al., 2017; Hatle et al., 2014; Helgerud et al., 2007) support the assumption that specifically HIIT could improve the cardiac stroke volume. Nocturnal HR, in comparison with HRV, has seemed more sensitive also in acute responses to intensive exercise (Myllymäki et al., 2012; Thomas et al., 2020). Therefore, it is recommendable to use both markers concurrently. This could also be helpful for individuals having a low resting HR which may induce saturation in acetylcholine-receptors and lead to decreased HRV despite decreased HR and high parasympathetic activity (Kiviniemi et al., 2004).

In addition to resting HR, submaximal tests that examine the relation between speed and exercise HR can be used as an indirect estimate of the current performance level. These types of assessments can be performed in the laboratory (Vesterinen et al., 2017) or field conditions (Vesterinen et al., 2014; Vesterinen et al., 2016b). In study II, despite significantly improved treadmill test performance, no significant changes were observed in either of the groups in HR-RS index. The lack of changes could relate to the comparatively long averaging period (mesocycle or whole training period) as well as the lack of strict standardization (terrain) of the analyzed sessions. In study III, the training sessions were always performed in the same location under similar circumstances, and a significant increase in the HR-RS index was found, supporting the latter assumption and highlighting the importance of sufficient standardization when assessing the relation between exercise HR and running speed. Although significant correlations have previously been found between changes in the submaximal test performance and changes in the treadmill test performance (Vesterinen et al., 2017; Vesterinen et al., 2016b), it is also important to acknowledge the same limitations that concern resting HRV: a similar change in submaximal HR could indicate both positive (Vesterinen et al., 2017; Vesterinen et al., 2016b) and negative (acute) adaptations to training (Le Meur et al., 2013a). As was found in study I, perceptual responses could contradict HR responses; thus, in optimal situations, objective and subjective markers should be used side by side.

Neuromuscular and hormonal responses

Neuromuscular characteristics are among important determinants of distance running performance (Nummela et al., 2006; Paavolainen et al., 2000; Paavolainen et al., 1999b). In competitive runners, it has been observed that CMJ performance seems to align with the running performance across the training season (Bachero-Mena et al., 2017; Balsalobre-Fernández et al., 2014). Continuous monitoring of neuromuscular performance could, therefore, provide relevant information also for endurance athletes. In studies II and III, neuromuscular performance was monitored using CMJ which was assessed weekly (study II) or before all main sessions (study III). Based on previous studies suggesting a negative association between training load and CMJ performance (Balsalobre-Fernández et al., 2014), it was expected that the current training protocols would also have a negative impact on neuromuscular performance. Interestingly, neither of the 2-week blocks nor the 10-week training periods had a significant effect on the CMJ. It is possible that the training of recreational runners (running speeds, absolute volumes) may not be as demanding as in well-trained athletes (Bachero-Mena et al., 2017; Balsalobre-Fernández et al., 2014), and the neuromuscular demands of training may differ. Furthermore, a slight learning effect could not be ruled out since most of the participants had not performed CMJ tests before the study. Another marker that was used to analyze neuromuscular recovery in study III was serum CK which could be regarded as an indirect marker of muscle damage. While previous studies have found increased CK concentration after HIIT blocks (Weippert et al., 2018; Wiewelhove et al., 2015) and long-distance sessions (Quinn & Manley, 2012), similar responses were anticipated after LIT and HIIT blocks. Interestingly, serum CK concentration was increased only in the VOL group, which probably relates to the structural damage in the running muscles caused by high running volumes and the last long-distance session that was performed two days before the CK assessment.

The state of recovery was also assessed via resting hormone concentrations which were expected to demonstrate possible negative adaptations to increased training load (Urhausen et al., 1995). In studies II and III, free testosterone and cortisol were analyzed. In addition, urine noradrenaline was analyzed in study III. Similar to previous studies that have led to improved endurance performance (Vesterinen et al., 2013; Vesterinen et al., 2016a), no significant changes were found in serum free testosterone or cortisol. Although hormonal balance is stated as one aspect of a general state of homeostasis, the lack of changes may relate to the fact that hormonal responses to exercise may be more sensitive to the changes in the state of recovery than those of basal levels (Cadegiani & Kater, 2017). For example, Meeusen et al. (2004) reported diminished growth hormone responses to maximal exercise in a compromised state of recovery. It is also possible that more frequent and separate analyses for both sexes would have been required to find systematic changes. However, since the performance was improved, and the participants could not be regarded as overreached, significant changes in serum hormone concentrations might not be even expected. Interestingly in study III, the resting norepinephrine concentration increased in the INT and remained elevated also after the recovery period. The finding somewhat contradicted previous studies where resting values have either remained similar (Le Meur et al., 2014; Uusitalo et al., 1998) or have decreased after intensified training (Lehmann et al., 1992). Based on the increase in resting norepinephrine and the decrease in peak HR during the 3000-m tests after the HIIT block, a longer recovery period may be advisable to restore normal ANS function at rest and during exercise. Although resting HRV and catecholamine concentration are thought to reflect the ANS function, it seems that responses to intensified training may differ between these markers.

Perceptual markers

While physiological and objective markers of recovery have their strengths, subjective/perceptual markers, can provide relevant information from a point of view that cannot be assessed otherwise. Perceptual markers have been suggested to be useful in the prediction of overreaching and staleness (Hooper et al., 1995; ten Haaf et al., 2017), and they could also help contextualize changes in physiological markers, such as exercise HR or resting HRV, which may sometimes act paradoxically (Bellenger et al., 2016; Le Meur et al., 2013b). In the current study, perceived recovery was assessed via a 0-10 PRS (Laurent et al., 2011) (study II) and via a 0-10 VAS that was modified from ten Haaf et al. (2017) and included a few separate aspects (readiness to train, sleep quality, fatigue, muscle soreness, stress). In line with the suggestion by Saw et al. (2016), perceptual markers seemed more responsive to changes in training load than objective markers. In study II, the VOL induced decrement in the PRS, and there was also a tendency for decrement in the INT. In addition, average session RPE increased in the INT, but it probably relates only to the increased proportion of MIT/HIIT sessions. However, in the case where the external training load is maintained, it has been suggested that the increased RPE could indicate accumulated fatigue (Fusco et al., 2020). This phenomenon was demonstrated also in the SRT of study I. In study III, the most significant changes were found in muscle soreness which increased in the INT during the block weeks, and the change compared to baseline differed from the VOL across the block and recovery weeks. The possible reasons behind these differences could relate to the biomechanical characteristics of HIIT vs. LIT (cadence, ground reaction forces) (Paquette et al., 2020). Furthermore, HIIT most likely strains more type II motor units compared to LIT (Seiler & Tønnessen, 2009). Similar to the SMIT session in study I, it is plausible that most participants were unfamiliar with the maximal sustainable effort intervals, and especially such a high frequency of HIIT sessions, which may have further augmented the soreness in the running muscles. Interestingly, CK increased only in the VOL; thus, muscle soreness contradicted those results. On the other hand, CK has also previously been elevated after LIT without an increase in muscle soreness (Quinn & Manley, 2012), highlighting the possibility of different patterns for these markers.

Agreement between monitoring variables

While recovery or readiness to train is sometimes assessed from a single point of view (e.g., HRV, CMJ), current results demonstrate the challenge of such a simplified evaluation. Previously, Flatt et al. (2019) and Thamm et al. (2019) have demonstrated the distinct recovery kinetics of neuromuscular and ANS recovery after strength training exercises. While similar aspects have not been assessed after endurance exercises, the current study examined the agreement between the responses of HRV and other monitoring variables. As hypothesized, a fairly low level of agreement was found between responses in HRV and other markers measured in the laboratory post 24 h in study I (33-52% of the responses fully agreed). What is critical to notice when interpreting the results is the definition of SWC. For example, in the case of HRV, ranges of 0.2 × SD (Ruiz-Alias et al., 2022) to 1.0 × SD (da Silva et al., 2019) have been used inducing quite different thresholds for meaningful changes. In the current study, 0.5 × SD of the pre-exercise results was individually used in line with the studies utilizing HRV-guided prescription (Javaloyes et al., 2019; Vesterinen et al., 2016c). However, especially slight disagreements between variables (e.g., one decreased while the other remained unchanged) could relate to methodological issues or the noise of the measurement. That is why opposing responses can be interpreted with more confidence. In the current study, depending on the variable, 9-17% of the responses were opposed with the acute HRV responses.

In addition to single exercises, agreement between changes in HRV and other monitoring variables was assessed at the end of training periods in studies II and III. The current approach was chosen, because the most meaningful differences were expected to occur at the end of the training period. In general, acute changes in study I, were better aligned than the changes within weeks or mesocycles in studies II and III. As was expected, the changes in HRV and CMJ did not agree very well (23% and 24%), and almost 1/3 of the participants had an opposing response in CMJ and muscle soreness compared to the HRV during the block period. On the other hand, the changes in submaximal HR (HR-RS index) were better aligned (43%), but at the same time, the moderate agreement demonstrates the distinctive nature of resting and exercise HR variables. Regarding the direction of the changes in the current analyses, it is important to note that an increase in HRV was interpreted as a positive change (as e.g., decrease in muscle soreness). In reality, such a change may also relate to functional overreaching (Le Meur et al., 2013b), and this phenomenon makes it challenging to analyze how well the markers agree regarding the direction of change in the long term. On the other hand, current interventions did not induce overreaching-related effects in performance, which makes current analysis logic more justified. To summarize the findings from studies I-III, acute and long-term HRV responses do not always appear to be well aligned with performance-related markers and perceptual recovery. Therefore, a multidisciplinary approach in training and recovery monitoring seems essential for a comprehensive picture of the actual state of recovery.

Factors related to interindividual differences in training adaptation

Previously, several studies have tried to examine possible factors contributing to interindividual differences in the training adaptation followed by standardized training programs. For example, mental stress (Ruuska et al., 2012), nutrition (Stellingwerff et al., 2021), and sleep (Halson, 2008) have all been suggested to possibly affect training adaptations. In addition, HRV has been related to endurance training adaptations (Hautala et al., 2003), especially in HIT (Nuuttila et al., 2017; Vesterinen et al., 2013; Vesterinen et al., 2016a). In the current study, no clear associations were found between the baseline stress levels and the training adaptations, but in study II, the baseline HRV correlated positively with the change in endurance performance. The lack of such associations with the block periods could relate to the differences in the training protocols, and longer periods may bring out these associations more clearly than short-term blocks.

In studies II and III, the associations between training adaptation, and changes in the monitoring variables, were also examined. These aspects have not been extensively analyzed previously, as it has been more typical to analyze pre-post changes instead of observing what happens during the actual training period. It was hypothesized that the maintenance of stable HRV, perceived recovery, and neuromuscular performance would be associated with positive endurance training adaptations and that different patterns would also discriminate low and high responders. Interestingly, only a few associations were found, and exclusively in study II. The clearest positive association was observed in the HR-RS index, and based on current and previous findings (Vesterinen et al., 2014), it seems desirable to aim to increase this index in the long term. On the other hand, there was a tendency for the opposite trend during the volume block, which demonstrates the challenges of HR-based variables, especially in the short term. Similarly, increments in resting HRV do not necessarily implicate positive adaptations, as was observed in the correlations and low vs. high responder comparison; therefore, changes should always be contextualized with supplementary parameters (Bellenger et al., 2016).

One simple reason for the lack of expected associations could relate to the fact that the current training protocols were not too demanding, and almost all individuals improved their performance. If there had been more variation in the training adaptation, it could have led to different observations. Although previous studies have found some associations between neuromuscular performance and endurance performance within an individual (Bachero-Mena et al., 2017; Balsalobre-Fernández et al., 2014) or change in HRV and change in endurance performance (Buchheit et al., 2010; Nummela et al., 2010), such links are not necessarily as straightforward as sometimes assumed. One challenge could be the sensitivity of certain markers (signal-to-noise-ratio) which, for example, in the case of CMJ might not be sufficient for the monitoring purposes of recreational runners.

Although the current results did not detect unequivocal connections between the state of recovery and training adaptations, it seems reasonable to assume that it would not be desirable to accumulate a high training load during a compromised state of recovery. Most likely, the current results highlight the complex nature of training adaptation. It is very challenging to predict whether the training is or would be successful based on certain baseline determinants or changes in one single parameter. Instead, a certain combination of patterns, such as an increased HR-RS index alongside with a good state of perceived recovery, would be more useful for monitoring purposes.

6.3 Individualized endurance training prescription

Individualized endurance training has previously been examined via HRV-guided prescriptions. The current protocol was probably the first one that considered multiple aspects in the training decision schema (HRV, perceived recovery, estimated performance) and also adjusted training volume. The main findings of study IV were that both predefined and individualized training improved endurance performance, but the individualized training led to greater improvement in 10-km running performance and fewer low-responders compared to the predefined training.

Training characteristics

Previously, HRV-guided training protocols have led in many studies to a lower volume of MIT or HIIT (Javaloyes et al., 2019; Kiviniemi et al., 2007; Vesterinen et al., 2016c). In one recent study, also a higher volume of MIT was found (Carrasco-Poyatos et al., 2022). In the current study, no significant differences were found between the groups, although the weekly execution was quite different as demonstrated in FIGURE 15. While the PD group had predefined recovery weeks, in the IND group, the length and timing of such periods were defined, based on recovery data. Interestingly, only 10% of the adjustments in the IND led to a recovery block, while 55% maintained the training load and 35% increased the training load. The low proportion of recovery blocks may demonstrate that in recreational runners with a fairly low training frequency (e.g., 4 × week), specific recovery periods are not particularly critical when the training load is being increased (sufficiently) moderately. However, it is also possible that the limits for the recovery block were quite strict, and at least some individuals could have benefited from looser limits. Although it is an intriguing suggestion that the HRV-guided training could induce the same adaptations with lower training demands (Javaloyes et al., 2019; Kiviniemi et al., 2007; Vesterinen et al., 2016c), one may argue that the TID should be, on average, similar between two groups to confirm proper training load, also in the predefined group.

In previous studies using the HRV-guided approach, the training characteristics in terms of volume and TID have been quite similar compared to the present study in recreationally trained participants (Nuuttila et al., 2017; Vesterinen et al., 2016c). Among well-trained athletes, in turn, a greater training volume and a much lower proportion of training at low-intensity zones (≤ 65%) have been reported (Carrasco-Poyatos et al., 2022; Javaloyes et al., 2019). In general, endurance athletes tend to perform about 80% of the endurance training as LIT, and this type of division is typically recommended as a basis for the TID (Seiler, 2010; Stöggl & Sperlich, 2015). Furthermore, training typically progresses towards lower volumes and a higher proportion of HIT when the main event is approaching (Haugen et al., 2022; Stöggl & Sperlich, 2015; Tønnessen et al., 2014). These principles were followed in the current protocol to have a realistic approach for the training periodization.

Training adaptations

Both PD and IND improved their performance in the incremental treadmill test and 10-km running test after the 12-week training period. The magnitude of improvements in the vMax (PD 3.0 ± 2.4%; IND 4.0 ± 1.9%) (Stöggl & Sperlich, 2014; Vesterinen et al., 2016a) and 10-km running tests (PD -2.9 ± 2.4%; IND -6.2 ± 2.8%) (Buchheit et al., 2010; Muñoz et al., 2014) were in line with the above-mentioned studies, and also with the results of study II; therefore, the training programs seemed on average suitable for both groups. The most significant finding among the performance tests was the difference between PD and IND in the change of 10-km running time from T_1 to T_3. There are some potential explanations for the finding that the difference between the groups was significant only in the 10-km test. Firstly, while the PD always had a recovery week before the test week, the IND had no predefined tapering. Therefore, training adaptations could have been better realized in the latter test (10 km) of the week. Secondly, although there is a strong association between maximal treadmill performance and 10-km running performance (Noakes et al., 1990), the 10-km test may require slightly different capabilities, such as "durability" (Maunder et al., 2021). Finally, the 10-km test was run on average at 82% of the peak treadmill test speed, and as a consequence, it is possible that neuromuscular factors could have limited maximal treadmill performance more (Paavolainen et al., 2000), especially in recreational runners who may be unaccustomed to such speeds.

The greater number of high responders and the lower number of trivial or negative responders in the IND group was another interesting finding regarding the training adaptations in vMax and 10 km. This is in line with the hypothesis that individualizing the training load would decrease the likelihood of negative responses. Similar observations have also been proposed by Vesterinen et al. (2016c) who suggested that HRV-guided training would reduce the variation in the training adaptation and lead to more consistent improvements in performance. It is important to acknowledge that individualized training may not only allow sufficient recovery but also sufficient load to induce desirable adaptations. This could also relate to the smaller number of low-responders. Montero and Lundby (2017) have previously discovered that individuals stated as non-responders improved their endurance performance when the training dose was increased. Gaskill et al. (1999) illustrated the same phenomenon from a different perspective, and in their study, the individuals that were stated as low-responders to previous training improved their performance once the training was significantly intensified. On the other hand, the lack of changes in the treadmill performance after the volume period (T_1-T_2) was rather an unexpected result. For optimal performance after VOL-P, the current protocol would possibly have required longer tapering or a larger decrease in volume before the tests. In the study of Bellinger et al. (2020b), using quite a similar volume progression, the running performance was significantly improved after a 1-week taper during which the training volume was exponentially decreased by 55%.

In the monitoring variables, only a few differences were observed between the groups, and none of the markers responded negatively at the group level. Furthermore, the resting concentrations of serum hormones and the CMJ performance remained unaffected. Regarding the between-group differences in the monitoring variables, the IND had a higher proportion of normal values in the HR-RS index and nocturnal HRV, which was an expected outcome of the training model. On the other hand, accumulating a higher proportion of training at a good state of recovery may have contributed to the between-group differences in the training adaptation. While both groups improved the HR-RS index, only the IND was able to increase the running speed significantly during the interval sessions. Since intervals were always performed at the maximal sustainable effort, the finding may illustrate a compromised training state in some individuals of the PD, probably due to too high interval frequency.

6.4 Methodological strengths, limitations, and considerations

6.4.1 Methodological strengths and limitations

The current study consisted of four separate data collections, each of which had its strengths and limitations. Regarding the running sessions used in study I, they were not standardized to a certain amount of total work. This can be taken as a limitation if the aim is to examine purely the effects of intensity. On the other hand, the sessions were chosen since they represent typical sessions that are performed within each intensity zone, which was considered more relevant in the current setting. In terms of the training interventions, multiple different types of periods were performed, which allowed a comprehensive comparison between increments in volume vs. intensity of endurance training. All training periods were preceded by a control or preparatory period. Therefore, it was always confirmed how participants trained prior to interventions, and this information was also used in the training program design. In studies II and IV, training sessions were not supervised, meaning that conditions during the training may have varied between individuals. Nevertheless, current settings demonstrate the natural training of recreational runners, and the results are most likely applicable to such a target group. Most importantly, the participants had training logs, and all endurance training was confirmed via HR- and GPS data. If criteria for sufficient adherence were not met, participants were excluded from the analyses.

The data collection included both laboratory assessments and field assessments of performance as well as recovery. When interpreting the results, it is critical to understand that all parameters have certain typical error/variation not related to genuine changes. All main performance outcomes (treadmill test, 3000 m and 10-km running test) could be regarded as reliable based on the CV observed in the current settings and those reported previously (Hopkins & Hewson, 2001; Hopkins et al., 2001). Although more external factors possibly influence performance during the field tests, it was important to implement competition simulations to observe the changes in the outcome of interest (competition performance). In all studies, both recovery and responses to training were analyzed from the physiological and perceptual points of view. Even though nocturnal HRV, perceived recovery, and training data were recorded/measured mainly unsupervised, current settings demonstrate the natural user environment for the collection of such parameters. The quality of the data collection was also ensured by using methods applied in previous studies and being validated for research purposes.

In all studies, the participants were classified as recreationally endurance trained. Therefore, the current results cannot be uncritically extrapolated to untrained or competitive athletes. Except for study I, both male and female participants were involved. Unfortunately, the number of participants in each study did not allow meaningful comparison between the sexes, and possible differences between males and females in responses and adaptations could not be concluded. In spite of that, it was expected that the changes in the main parameters would not differ between sexes, although certain markers differed in absolute terms (e.g., hormonal levels) due to biological differences. In all training interventions, the dropouts decreased slightly the number of participants. However, the present drop-out rates were quite comparable to what has been reported in other studies using similar training study designs (Vesterinen et al., 2016a; 2016c), and sufficient power was achieved based on the number of participants who did complete the training interventions.

When considering differences between individualized training and other alternative training methods, there is a certain methodological challenge in the current and previous studies in terms of comparisons made to solely "predefined" training. In real conditions, especially competitive athletes are more likely to adapt their training based on their own perceptions or communication with their coach. Therefore, performing a comparison against this type of "best practice" would be an interesting and relevant additional research subject in the future.

6.4.2 Considerations regarding the individualized endurance training prescription

Because the main objective of this thesis was to examine how recovery and training-related data could be utilized in individual endurance training prescription, there are some methodological considerations that are important to highlight. Basically, these relate to the choice of proper monitoring variables, the definition of individual baseline or the normal range within each variable, and finally the actual adjustment logic in the training.

In the present model, resting HRV was chosen due to the results of previous studies on HRV-guided training, suggesting its usefulness in recovery monitoring (Düking et al., 2021). In all previous studies using the HRV-guided approach, morning recordings have been applied except for da Silva et al. (2019), where day-time recordings were used instead. In the current study, nocturnal recordings were chosen due to feasibility, as they did not demand any additional measurements. In addition, the reliability of nocturnal recordings (Mishica et al., 2022; Nuuttila et al., 2022) seems superior compared to daytime recordings (Al Haddad et al., 2011; Nakamura et al., 2017). Since the recent study by Ruiz-Alias et al. (2022) showed that weekly trends of morning and nocturnal HRV do not always agree very well, the physiological significance of HRV during different times of the day and its consequences to long-term recovery and training adaptations should be examined in more detail.

Subjective/perceptual markers are suggested to be useful tools in the detection of functional overreaching or overtraining (Hooper et al., 1995; ten Haaf et al., 2017), and in general, they are considered more sensitive markers than typical objective markers (Saw et al., 2016). They are also helpful in distinguishing positive and negative responses in HR-based markers, such as resting HRV and submaximal exercise HR (Bellenger et al., 2016; Le Meur et al., 2013b). Fatigue and muscle soreness were used in the present study, since they have previously been associated with staleness (Hooper et al., 1995) and responded to a significant increment in the training load (Bellenger et al., 2016). The suitability of other markers, such as readiness to train (ten Haaf et al., 2017) or "well-being of the legs" (Rønnestad et al., 2014), should also be considered when choosing the most sensitive marker for the changes that are most relevant within an individual. In addition to the state of recovery, the estimation of current performance provides information on the training adaptation which is the ultimate goal of the whole training process. Although submaximal performance correlates with the maximal performance with reasonable accuracy (Vesterinen et al., 2014; Vesterinen et al., 2016b), HR-based tests as such have their challenges in terms of interpretation – basically, a decrease in HR at fixed external load could indicate positive training adaptation (Vesterinen et al., 2014; Vesterinen et al., 2016b) but also fatigue that is induced by functional overreaching (Bellenger et al., 2016; Le Meur et al., 2013b). On the other hand, when supported with the information such as RPE, HR-based markers could also be useful in the detection of functional overreaching (Roete et al., 2021). This type of logic was also utilized in the present study, where it was expected that if submaximal HR decreased due to overreaching, parasympathetic hyperactivity would be revealed via increased perceived fatigue and HRV (Bellenger et al., 2016; Le Meur et al., 2013b). Consequently, the current model would have led to a necessary recovery period. Another option to exclude HR-based challenges would be testing running speed in relation to a fixed RPE (Sangan et al., 2021), for example, with a similar warm-up setting compared to the present study. This type of approach would also be interesting because it combines both subjective and objective viewpoints. To overcome issues related to the standardization of terrain, using estimations of VO_{2max} (Düking et al., 2022) or running power (Cerezueal-Esperejo et al., 2020) given by a wearable, could be one potential opportunity. However, the validity of such estimations needs to be confirmed before implementing them into practice. Similar limitations concern such variables like DFA-a1 which has been suggested to have potential in fatigue monitoring (Rogers & Gronwald, 2022).

When assessing recovery, it is also important to consider the limits/normal range within each variable. As described by Vesterinen et al. (2016c), the range should allow achieving adequate disturbances in homeostasis but at the same time ensure sufficient recovery. In HRV, trends have been typically interpreted in terms of SWC which has been formed based on the fraction of within individual SD (0.5-1 × SD) during preceding weeks. On the other hand, Piacentini and Meeusen (2015) used in their case study as high as 1.5-2.0 × SD cut-off values in subjective markers. By modifying the cut-off values, it is possible to set desirable risk levels which could vary, for example, depending on the training phase or fitness level of an individual. While in subjective markers desirable values may remain quite permanent, in the HR-based and performance-related markers, there is an occasional need for re-evaluation, since these may change due to positive training adaptations (Buchheit et al., 2010). The frequency of such evaluations has varied in previous studies from constant updating (da Silva et al., 2019; Kiviniemi et al., 2007) to updating once per week (Carrasco-Poyatos et al., 2022) or once every four weeks (Javaloyes et al., 2019; Vesterinen et al., 2016c). In the current study, constantly updated limits were used, and some individuals illustrated slow downward slipping of the limits (e.g., in HR-RS index) which would not be desirable. One way to avoid such an effect would be to set a short-term limit (e.g., 2-week) and a long-term limit (e.g., 8-week), both of which should be met. In HRV, a longer baseline period (e.g., 6-8 weeks) would perhaps be a better option to avoid negative slipping of SWC while also allowing possible adaptations to occur.

In the present study, monitoring variables were interpreted separately, similar to the approach used by Capostagno et al. (2014). It remains speculative whether the overall recovery state could be compensated by high values in some markers, for example, by calculating the sum of the markers as a Z-score in relation to SD. Certain issues, like determining when the increase in HRV transforms into parasympathetic hyperactivity and shifts from positive to negative change, would be challenging to solve. However, it is clear that strict negative/positive limits, as used in the current study, are not the only method to assess the state of recovery.

The final step of the individualization consists of the actual adjustment of the training. In previous studies, individualized training prescriptions have been utilized purely via adjustment of intensity (Capostagno et al., 2014; Carrasco-Poyatos et al., 2022; da Silva et al., 2019; Javaloyes et al., 2019; Kiviniemi et al., 2007; Nuuttila et al., 2017; Vesterinen et al., 2016c). Basically, MIT or HIIT have been performed unless the hypothetical recovery state has been impaired beyond a certain limit. However, since training volume is a critical variable in the long-term development of endurance performance (Laursen, 2010; Seiler, 2010), a model that only estimates whether an individual should train at high- or low-intensity could be regarded as somewhat incomplete. Both volume and intensity progression can be performed in several ways. It is certainly not conclusive whether progression should be accomplished by extending the volume of LIT or HIIT within single sessions, or by adding more sessions to the weekly schedule, while maintaining the duration unaltered.

Regarding the training execution, previous HRV-guided studies have mainly utilized a day-by-day approach (Carrasco-Poyatos et al., 2022; Javaloyes et al., 2019; Kiviniemi et al., 2007; Vesterinen et al., 2016c). This approach has provided promising results in short-term training periods. However, it may bypass some important aspects of training that are necessary to build long-term endurance performance improvements, and it may also be challenging from a practical point of view. Based on the results of the current study, a 3–4-day evaluation period seemed a relevant option in terms of feasibility (individuals know the session of the following day) and training load that would not lead to a serious state of fatigue or overreaching. However, it should be noted that in the present study the average training frequency was only slightly above 4 sessions per week, allowing thus quite decent recovery periods between sessions in most participants.

Finally, although the idea behind individualized training is that the training is adjusted based on data collected, there probably should always be upper and lower limits for the acute and long-term progression of the training load. Some of the previous HRV-guided protocols have included predefined rest periods after x times of MIT or HIIT (da Silva et al., 2019; Javaloyes et al., 2019; Kiviniemi et al., 2007), but in the present study, no rest blocks were performed unless the recovery state got impaired. It was decided that no predefined recovery periods would be executed to ensure a truly individualized and adapting training model. In the long term, however, predefined recovery periods (e.g., every 5th week) may secure the exclusion of excessive fatigue.

7 MAIN FINDINGS AND CONCLUSIONS

This study examined responses to different types of endurance exercises and periods at mesocycle, microcycle, and single-session level. In addition, this study examined individualized endurance training prescriptions based on recovery and training status. The main findings of the thesis were:

1) Study I highlighted the demands of the different types of running sessions. Furthermore, the results demonstrated variation of recovery kinetics between individuals and aspects being analyzed. The delay of the parasympathetic reactivation seems to relate to the intensity and cardiovascular load of the preceding session, while long-duration and supramaximal intensity sessions induced the greatest decrements in neuromuscular performance. Cardiovascular and metabolic recovery occurs rapidly, and these components of physical performance are not likely to be compromised 24 h after one single endurance exercise.

2) In studies II and III, it was found that increasing the volume or the intensity of endurance training could be effective methods to improve maximal endurance performance. When the training load is being increased progressively, both methods seem to be sustainable for recreational runners. When block type of periodization is being used, HIIT blocks may induce some negative responses compared to high-volume LIT blocks, such as decreased parasympathetic nervous system activity and increased muscle soreness. Although the performance was improved immediately after the block period and no functional overreaching was observed at the group level, the results may indicate higher demands of HIIT compared with LIT when using block type of periodization.

3) Based on associations between changes in monitoring markers and endurance performance, it seems unlikely that a trend in a single parameter could explain a great portion of training adaptation. However, continuous monitoring of training-related parameters, such as the HR-RS index, may help to predict whether an individual is adapting to training. At the same time, it is important to acknowledge the limitations of HR-based markers. The sensitivity of the

recovery-related variables may vary between individuals (signal-to-noise ratio), and interpretations as well as the choice of appropriate markers may require an individualized approach.

4) Study IV demonstrated that although predefined training improves endurance performance, individualized endurance training may induce greater improvements in running performance. Combining objective and subjective data in the recovery assessments via markers such as perceptual recovery, resting HRV, and HR-RS index and utilizing the results into training adjustments seems a potential method to increase the probability of high response while decreasing the occurrence of low or negative responses to endurance training.

In conclusion, the current results suggest that a multidisciplinary approach to monitoring is recommended to ensure that an individual is responding to the training as desired and to contextualize changes in markers that may act paradoxically. While the current individualization model seemed promising in terms of endurance training adaptations, further research is needed to determine the most suitable markers to be used in monitoring, to define the individual limits within a marker, and to discover how the training load could be manipulated during different types of periods. FIGURE 19 summarizes the findings of the present and previous studies on recovery monitoring by demonstrating the training individualization process.

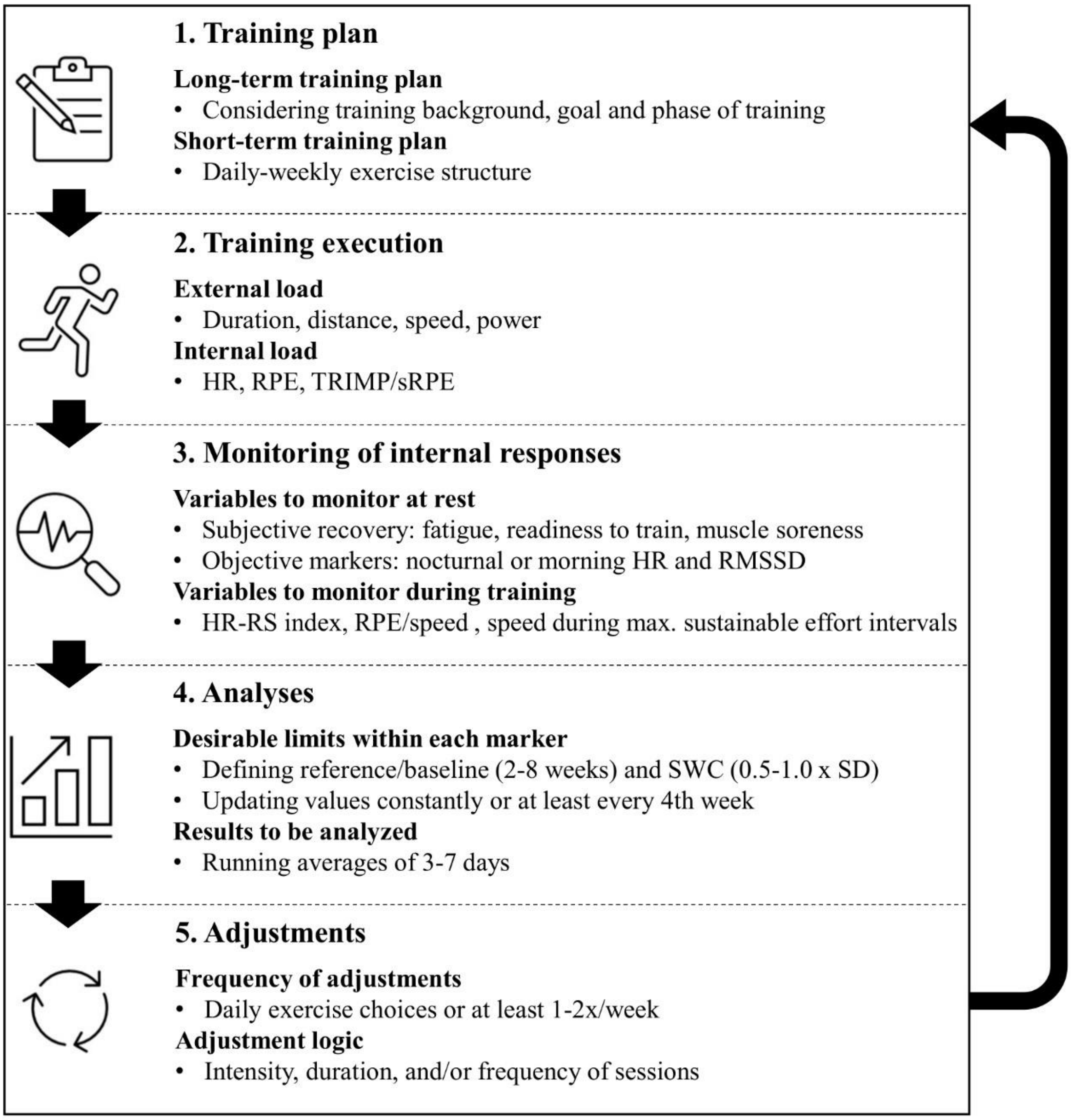

FIGURE 19 Summary of the endurance training individualization process and suggested aspects to consider during each phase based on current and previous studies on individualized endurance training.

YHTEENVETO (SUMMARY IN FINNISH)

Kestävyysharjoittelun perusperiaatteet vaikuttaisivat tutkimusten valossa varsin selviltä: tarvitaan runsas volyymi matalaintensiteettistä peruskestävyysharjoittelua (~80 %), jota täydennetään hieman pienemmällä osuudella korkeaintensiteettisempää vauhti- ja maksimikestävyysharjoittelua (~20 %). Tästä huolimatta harjoittelun intensiteetin ja määrän optimaalista jaottelua harjoituskauden eri vaiheissa voidaan pitää eräänlaisena ikuisuuskysymyksenä. Vaikka harjoitustutkimuksissa tyypillisesti havaitaan ryhmätasolla positiivisia muutoksia kestävyyssuorituskyvyssä, muutokset voivat erota yksilöiden välillä suuresti. Potentiaalisia syitä yksilöiden välisiin eroihin on lukuisia. Esimerkiksi harjoitustausta, ravitsemustila, unenlaatu ja harjoittelun ulkopuolinen stressi voivat vaikuttaa harjoittelun tuottavuuteen. Yhden ja ainoan kaikille toimivimman harjoitusmenetelmän etsimisen sijaan olisikin oleellisempaa tunnistaa, miten harjoituskuormaa voitaisiin hienosäätää yksilötasolla kuhunkin hetkeen sopivaksi, jolloin harjoittelu olisi mahdollisimman kehittävää.

Nykyteknologia mahdollistaa hyvin monipuolisen harjoittelun ja palautumisen seurannan. Harjoitusten aikaisen mittaamisen tarkoituksena on käytännössä seurata tehtyä ulkoista työmäärää (esim. minuutit, kilometrit) sekä sen aiheuttamaa sisäistä kuormitusta (esim. työn intensiteetti, syke, laktaatit, koettu rasitus). Palautumistilan mittaaminen puolestaan tarkoittaa harjoittelun ja muiden mahdollisten kuormitustekijöiden vaikutusten kontrolloitua seuraamista, esimerkiksi leposykemittauksilla. Puettava teknologia onkin tuonut uusia mahdollisuuksia erityisesti sydämen sykkeen ja sykevälivaihtelun mittaamiseen. Lepotilan sykemittausten hyödyntämistä kestävyysharjoittelun yksilöllisessä ohjelmoinnissa on myös tutkittu harjoitustutkimuksissa, joissa harjoittelun intensiteettiä on säädetty leposykevälivaihtelun perusteella.

Vaikka leposykevälivaihtelumittaukset vaikuttavat tutkimusnäytönkin perusteella potentiaaliselta menetelmältä palautumistilan arvioinnissa ja harjoitusvalintojen ohjaamisessa, sykepohjaisten muuttujien tulkinnassa on myös omat haasteensa. Melko suuren päiväkohtaisen vaihtelun lisäksi samanlaiset muutokset (sykevälivaihtelun lisääntyminen, harjoitussykkeen aleneminen) voivat olla merkki niin suorituskyvyn paranemisesta kuin harjoituskuorman aikaansaamasta väsymyksestä. Lisäksi sykevälivaihtelu ei vaikuttaisi kuvaavan kaikkia palautumistilan kannalta oleellisia tekijöitä, kuten hermo-lihasjärjestelmän palautumista, kovinkaan tarkasti. Näin ollen useamman eri seurantamuuttujan tarkastelu yhdessä loisi kokonaisvaltaisemman kuvan yksilön palautumistilasta, mikä voisi parantaa palautumistilan arvioimisen tarkkuutta ja luotettavuutta.

Tämän väitöskirjan tarkoituksena oli tutkia eri intensiteetin kestävyysharjoitusten sekä kestävyysharjoittelun määrää tai intensiteettiä kasvattaneiden harjoitusjaksojen aikaansaamia vasteita palautumisen ja suorituskyvyn näkökulmista. Lisäksi tutkimuksen tarkoituksena oli selvittää, kehittääkö palautumistilan perusteella yksilöllisesti hienosäädetty harjoittelu kestävyyssuorituskykyä enemmän kuin ennalta määrätyn ohjelman mukaan harjoittelu.

Ensimmäisessä osatutkimuksessa tutkittiin neljän erilaisen juoksuharjoituksen välittömiä vasteita sekä palautumista 24 tunnin kuluttua harjoituksista. Yhteensä 24 miespuolista kestävyyskuntoilijaa teki juoksumatolla 90 minuutin peruskestävyysharjoituksen, 30 minuutin vauhtikestävyysharjoituksen, 6 × 3 min maksimikestävyysharjoituksen sekä 10 × 30 s nopeuskestävyysharjoituksen. Jokaista harjoitusta ennen, jokaisen harjoituksen jälkeen ja 24 tunnin kuluttua harjoituksista toistettiin sykevälivaihtelumittaus, submaksimaalinen juoksutesti sekä kevennyshyppytesti. Tutkimuksen päätuloksina havaittiin, että sykevälivaihtelu pieneni eniten vauhtikestävyys- ja maksimikestävyysharjoitusten jälkeen. Vastakohtaisesti kevennyshyppy heikkeni eniten ja ainoastaan perus- ja nopeuskestävyysharjoitusten jälkeen. Vuorokauden kuluttua valtaosa muuttujista oli palautunut lähtötasolle, vaikkakin yksilöiden välillä havaittiin eroja muuttujasta riippumatta. Submaksimaalisen juoksutestin aikainen syke oli alentunut jokaisen harjoituksen jälkeen, mutta koettu rasitustaso oli yhä lähtötasoa korkeammalla molempien intervalliharjoitusten jälkeen.

Toisessa ja kolmannessa osatutkimuksessa verrattiin harjoittelun määrän ja intensiteetin kasvattamisen vaikutuksia palautumistilaan ja kestävyyssuorituskyvyn kehittymiseen. Toiseen osatutkimukseen osallistui 30 mies- (n = 16) ja naiskestävyyskuntoilijaa (n = 14). Tutkimus koostui 10 viikon kontrollijaksosta, jonka aikana tutkittavat jatkoivat omaa tavanomaista harjoitteluaan, ja 10 viikon harjoitusjaksosta, jota varten tutkittavat jaettiin kahteen ryhmään. Intensiteettiryhmä lisäsi jakson aikana vauhti- ja maksimikestävyysharjoitusten osuutta (1–3 × vko), kun taas määräryhmä kasvatti kestävyysharjoittelun kokonaismäärää (20–50 %/vko). Kestävyyssuorituskyvyssä tapahtuneita muutoksia seurattiin juoksumatolla tehdyssä maksimaalisessa testissä. Palautumistilaa seurattiin läpi tutkimuksen yösykemittauksilla, koetun palautumistilan arvioinneilla, kevennyshyppytestillä sekä harjoituksista lasketulla syke-juoksunopeusindeksillä. Tutkimuksen päätuloksina havaittiin, että molemmat harjoitusjaksot paransivat mattotestissä mitattua suorituskykyä, eikä ryhmien välillä havaittu merkitseviä eroja. Koetussa palautumistilassa puolestaan havaittiin negatiivisia trendejä molemmissa ryhmissä. Leposyke aleni intensiteettiryhmällä, mutta muut muuttujat pysyivät ryhmätasolla muuttumattomina. Seurantamuuttujista syke-juoksunopeusindeksin muutos kontrollijaksolta harjoitusjakson lopulle korreloi positiivisesti mattotestin maksiminopeuden muutoksen kanssa, minkä perusteella muuttuja vaikuttaisi hyödylliseltä harjoitusadaptaatioiden seurannassa.

Kolmenteen osatutkimukseen osallistui yhteensä 30 mies- (n = 18) ja naiskestävyyskuntoilijaa (n = 12). Tutkimusjakso koostui kahden viikon valmistavasta jaksosta, viikon palautumisjaksosta, kahden viikon blokkiharjoitusjaksosta ja toisesta viikon mittaisesta palautumisjaksosta. Harjoitusjaksoa ennen tutkittavat jaettiin kahteen ryhmään, joista intensiteettiryhmä teki jakson aikana viidesti viikossa 6 × 3 min intervalliharjoituksen, kun taas määräryhmä kasvatti peruskestävyysharjoittelun määräänsä 70 % valmistavaan jaksoon nähden. Kestävyyssuorituskyvyssä tapahtuneita muutoksia seurattiin sisäradalla tehdyssä 3000 metrin juoksutestissä. Lisäksi tutkittavien palautumistilaa seurattiin virtsa- ja verinäytteistä tehdyillä hormonianalyyseilla, koetun palautumistilan arvioinneilla, yösykemittauksilla, kevennyshyppytestillä ja harjoitusten nopeudella tai syke-juoksunopeusindeksillä. Tutkimuksen päätuloksina havaittiin molempien ryhmien parantaneen kestävyyssuorituskykyä heti harjoitusjakson jälkeen, eikä ryhmien välillä ollut merkitseviä eroja missään mittapisteessä. Valtaosa palautumistilaan liittyvistä muuttujista säilyi muuttumattomana läpi tutkimusjakson, mutta yön aikainen sykevälivaihtelu pieneni ja koettu palautumistila (lihasarkuus, harjoitusvalmius) heikkeni intensiteettiryhmässä suhteessa määräryhmään. Lisäksi stressihormoni noradrenaliinin pitoisuus virtsassa lisääntyi vain intensiteettiryhmällä ja säilyi lähtötasoa korkeammalla vielä palautusviikon jälkeenkin.

Neljännessä osatutkimuksessa verrattiin palautumistilan perusteella yksilöllisesti mukautunutta harjoitusohjelmaa ennalta määrättyyn harjoitusohjelmaan. Tutkimukseen osallistui yhteensä 30 mies- (n = 15) ja naiskestävyyskuntoilijaa (n = 15). Tutkimus koostui kolmen viikon valmistavasta jaksosta, kuuden viikon määräjaksosta ja kuuden viikon intervallijaksosta. Tutkittavat jaettiin valmistavan jakson jälkeen kahteen ryhmään, joista toinen harjoitteli ennalta määrätyn ohjelman (EM-ryhmä) mukaisesti ja toinen palautumistilan perusteella yksilöllisesti mukautuneen ohjelman (YM-ryhmä) mukaisesti. YM-ryhmän harjoituskuorma pieneni, pysyi samana tai kasvoi kahdesti viikossa riippuen yön aikaisen sykevälivaihtelun, syke-juoksunopeusindeksin ja koetun palautumistilan (väsymys ja lihasarkuus) muutoksista suhteessa yksilön omaan perustasoon. Kestävyyssuorituskyvyssä tapahtuneita muutoksia testattiin juoksumatolla tehdyssä maksimaalisessa testissä sekä 10 kilometrin maantiejuoksutestissä. Tutkimuksen päätuloksina havaittiin, että molemmat ryhmät paransivat juoksumattotestin maksiminopeuttaan sekä 10 kilometrin juoksuaikaansa 12 viikon harjoitusjakson seurauksena. Ryhmien välillä havaittiin kuitenkin merkitsevä ero 10 kilometrin juoksuajan muutoksessa, jota YM-ryhmä paransi kaksinkertaisesti EM-ryhmään verrattuna. Lisäksi YM-ryhmässä oli vähemmän matalan harjoitusvasteen yksilöitä sekä mattotestin maksiminopeuden muutoksessa että 10 kilometrin juoksuajan muutoksessa.

Tämän väitöstutkimuksen tulokset havainnollistivat erilaisten kestävyysharjoitusten ja kestävyysharjoitusjaksojen vaatimuksia eri näkökulmista. Esimerkiksi sykepohjaisten muuttujien ja koetun palautumistilan muutokset voivat olla varsin erilaisia keskenään niin lyhyen kuin pidemmän aikavälin palautumisessa. Vaikka palautumistila säilyi keskimäärin hyvänä harjoitusjaksojen aikana, erityisesti harjoitusintensiteetin äkillinen nostaminen voi aiheuttaa negatiivisia muutoksia palautumistilassa. Intensiteetti- ja määräryhmien välillä ei havaittu eroja kestävyyssuorituskyvyn kehityksessä, mikä havainnollistaa, että sekä harjoittelun intensiteetin että määrän kasvattaminen ovat toimiva keinoja.

Tutkimuksen päätuloksina voidaan pitää yksilöllisesti mukautuneen harjoittelun positiivisia vaikutuksia verrattuna ennalta määrättyyn harjoitusohjelmaan. Mukautuva harjoittelu johti vähäisempään määrään alhaisen harjoitusvasteen yksilöitä ja ryhmä paransi 10 kilometrin juoksuaikaansa ennalta määrätyn ohjelman mukaisesti harjoitellutta ryhmää enemmän. Kun harjoittelua säädetään yksilöllisesti huomioiden subjektiivinen ja objektiivinen palautuminen, harjoittelu vaikuttaisi tuottavan systemaattisemmin positiivisia harjoitusvaikutuksia.

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ORIGINAL PUBLICATIONS

I

ACUTE PHYSIOLOGICAL RESPONSES TO FOUR RUNNING SESSIONS PERFORMED AT DIFFERENT INTENSITY ZONES

by

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Acute physiological responses to four running sessions performed at different intensity zones

ABSTRACT

This study investigated acute responses and post 24-hour recovery to four running sessions performed at different intensity zones by supine heart rate variability, countermovement jump, and a submaximal running test. A total of 24 recreationally endurance-trained male subjects performed 90 min low-intensity (LIT), 30 min moderate-intensity (MOD), 6x3 min high-intensity interval (HIIT) and 10x30 s supramaximal-intensity interval (SMIT) exercises on a treadmill. Heart rate variability decreased after all sessions, and the decrease was greater after MOD compared to LIT and SMIT ($p<0.001$; $p<0.01$) and HIIT compared to LIT ($p<0.01$). Countermovement jump decreased only after LIT ($p<0.01$) and SMIT ($p<0.001$), and the relative changes were different compared to MOD ($p<0.01$) and HIIT ($p<0.001$). Countermovement jump remained decreased at 24 hours after SMIT ($p<0.05$). Heart rate during the submaximal running test rebounded below the baseline 24 hours after all sessions ($p<0.05$), while the rating of perceived exertion during the running test remained elevated after HIIT ($p<0.05$) and SMIT ($p<0.01$). The current results highlight differences in the physiological demands of the running sessions performed, and distinct recovery patterns of the measured aspects of performance. Based on these results, assessments of performance and recovery from multiple perspectives may provide valuable information for endurance athletes, and help to improve the quality of training monitoring.

Introduction

Endurance training typically consists of various training modes differing in duration and intensity. Traditional intensity zones can be set based on individual ventilatory or lactate thresholds into low-intensity training below the first lactate threshold, moderate-intensity training between first and second lactate thresholds and high-intensity training between second lactate threshold and maximal oxygen consumption [1]. In addition to endurance intensity zones, supramaximal intensity training above the intensity of $\dot{V}O_{2max}$ may improve maximal endurance performance [2, 3], and induce similar adaptations in the skeletal muscle oxidative capacity than traditional endurance training [3]. Training intensity has effects on the cardiovascular workload, substrate utilization in energy metabolism, as well as the number and type of motor units recruited during the exercise [1], all of which may influence the type of fatigue induced and responses observed followed by the session.

Fatigue during endurance exercise can be stated as perceived tiredness with concurrent decrements in muscular performance and function [4]. Typically, the body needs to adjust to the growing demand of the activity performed by increasing heart rate [5-7], oxygen consumption, [5-7] and perceived effort [8] at a given workload. The autonomic nervous system responds to exercise by increasing sympathetic drive and catecholamine secretion [9], while parasympathetic activity diminishes [10]. The origin of the fatigue and time frame to restore the normal function in the neuromuscular system seems to depend on the duration and the intensity of the preceding exercise [11].

In addition to appropriate training load, sufficient recovery is required to induce training adaptations. Resting heart rate variability (HRV) is a noninvasive measurement of the autonomic nervous system function and is suggested to provide comprehensive information about the recovery status [12]. Previous research has shown that the reactivation of the parasympathetic nervous system measured as HRV after training appears to be affected most by the intensity of the session [10, 13, 14]. Full restoration after exercise at or above the first ventilatory threshold intensity can take up to 24-48 hours [15]. Furthermore, individually adjusted endurance training based on the fluctuations of resting HRV has provided superior results compared to predefined training [16, 17]. A similar approach has also been examined with a heart rate-based submaximal cycling test [18]. The general assumption in submaximal tests is that increase in the power or speed at the same relative heart rate and perceived effort reflects positive training adaptation [19] and readiness to train [18].

Despite the potential of the resting HRV and heart rate based submaximal tests, it is unclear how well these tests reflect all aspects of recovery such as the subjective recovery or readiness of the neuromuscular system. Recently, it has been observed that the recovery timeframe of neuromuscular performance and exercise-induced muscle damage may differ from that of HRV after strength training exercise [20]. Acute responses following endurance exercise also seem to differ as countermovement jump (CMJ) performance may even improve in endurance-trained athletes after high-intensity sessions [21, 22]. Additional monitoring variables may also help to contextualize whether changes in resting HRV or submaximal heart rate are due to fatigue or positive training adaptation, as similar responses may be observed in both situations [12, 23].

Responses to training are likely related to the intensity and duration of the preceding session and subsequently, the timeframe to recover may vary depending on the viewpoint taken. In endurance sports, heart rate assessments during rest and exercise have been studied and also utilized in training monitoring widely, while less is known about the other aspects of recovery and resemblance of different markers. The purpose of this study was to compare acute responses and post 24-hour recovery in the function of the autonomic nervous system, neuromuscular performance and submaximal running test. It was hypothesized that the acute HRV decrease is related to the intensity of the training, while CMJ performance would improve after moderate and high-intensity training sessions. In addition, it was anticipated that CMJ, metabolic and cardiorespiratory recovery would occur in the 24 hours after all sessions, but parasympathetic nervous system activity would only be fully recovered after LIT.

Materials and methods

Subjects

Twenty-five recreationally endurance-trained men, aged 20-45 years, were recruited for the study. Basic characteristics of the subjects are presented in Table 1. After being informed about the study design and possible risks and benefits of participation, subjects with an appropriate training background and health status signed a written informed consent form. One subject could not finish all the training sessions due to an injury, and, therefore, the total number of subjects was 24. After low-intensity session and high-intensity interval session, one subject did not perform the post-24-hour measurements. The study was approved by the Ethical Committee of the University [redacted], and it was conducted according to the provisions of the Declaration of Helsinki and recommendations of Harriss et al. [24].

TABLE 1 ABOUT HERE

Study design

The study compared acute responses to and post 24-hour recovery following four different training sessions performed on a treadmill. The order of the training session was randomized by drawing the sequence for each subject. After a preliminary performance testing week, training sessions were performed during the one-month study period. Before (pre), immediately after (post) and 24 hours after (post24) each session, supine heart rate variability, countermovement jumps, and a submaximal running test were performed. Additionally, perceived recovery and muscle soreness was measured at pre and post24. Subjects could continue their regular training during the study period. However, on the day before each training session, no exercise was performed and on the day before only light exercise was permitted. During the recovery phase before post24 measurements, exercising was not allowed. Subjects were advised to avoid heavy meals and caffeine 3-4 hours preceding each measurement to avoid any gastrointestinal symptoms or any other possible effects on measured variables. The structure of one training session and the measurements performed are presented in Figure 1.

FIGURE 1 ABOUT HERE

<u>Preliminary examinations</u>

Incremental treadmill test: The incremental treadmill test was performed on a treadmill (Telineyhtymä Oy, Kotka, Finland). Starting speed (8.2 ± 1.1 km/h^{-1}) was individually set based on obtained information of the previous performance and training background of the subjects to have at least two stages before the velocity of the first lactate threshold, and thus allow a reliable estimation of lactate thresholds. Three-minute stages were used, and speed increased by 1 km·h^{-1} after every stage. Between the stages, the treadmill was stopped (15-20 s) for the fingertip blood lactate samples to be taken. Inclination was kept constant at 0.5 degrees through the whole test. Oxygen consumption was measured breath by breath (OxygonPro, Jaeger, Hoechberg, Germany) and heart rate was monitored with a Garmin Forerunner 920XT (Garmin Ltd, Schaffhausen, Switzerland). $\dot{V}O_{2max}$ was defined as the highest 60 s average of oxygen consumption. Maximal treadmill running speed (vMax) of the test was defined as the highest completed stage speed, or if the stage was not finished, as a speed of the last completed stage (km·h^{-1}) + (running time (s) of the unfinished stage – 30 seconds) / (180 – 30 seconds) · 1 km·h^{-1}. Running speed at the first lactate threshold (vLT1) and running speed at the second lactate threshold (vLT2) were determined based on the change in the inclination of the blood lactate curve during the test [19]. The first lactate threshold was set at 0.3 mmol·l^{-1} above the lowest lactate value and the second lactate threshold at the intersection point between 1) a linear model between first lactate threshold and the next lactate point and 2) a linear model for the lactate points with the La increase of at least 0.8 mmol·l^{-1} similar to Vesterinen et al. [19]

20 m flying sprint test: 20 m flying sprint test was performed in the indoor track. Warm-up before the test included a 10-minute low-intensity run, dynamic stretching for the lower limbs and three submaximal 50 m accelerations. Maximal running speed (v20m) was measured with two photocell gates after 30 m acceleration. Three attempts were performed with three-minutes recovery, if no more than 5 % improvement were found between the last two attempts. The best result was used in further analysis.

Anthropometrics: Fat percentage was analyzed as a sum of four skinfolds [25]. Subjects were weighed before each measurement session and the current body mass was used in $\dot{V}O_2$ ($ml \cdot kg^{-1} \cdot min^{-1}$) calculations.

Training sessions

The duration and intensity of the training sessions were pre-determined in order that they represented typical training of each intensity zone (low, moderate, high and supramaximal intensity) and to ensure it would be possible for each subject to perform the sessions. Previous studies [2, 14, 26] have also utilized similar types of training. Running speeds of the sessions were set individually based on their lactate thresholds and maximal running speed during the incremental treadmill test and the 20 m flying sprint test. A low-intensity (LIT) session was a 90-min run performed at 80 % of the speed of the first lactate threshold (vLT1). A moderate-intensity (MOD) session was a 30-min run performed at the average speed of the first and second lactate thresholds ((vLT1+vLT2)/2). A high-intensity interval (HIIT) session was 6x3 min with 2 min recovery performed between the second lactate threshold and maximal incremental treadmill test speed (vLT2+(vMax-vLT2)/3). A supramaximal intensity interval (SMIIT) session was 10x30 s with 2.5 min recovery performed at 75 % of the speed from the 20 m flying sprint (v20m · 0.75). During the recovery, treadmill speed was set at 5 km/h in both interval sessions. The submaximal running test acted as a warm-up and cool-down for the sessions. Before SMIT, one short acceleration (15 s) to the speed of the upcoming session was performed to familiarize subjects with the treadmill velocity, and the actual session started after 2.5 min recovery.

All training sessions were performed within-subject at the same time of the day (± 1 h) on the treadmill (Telineyhtymä Oy, Kotka, Finland). Heart rate was measured throughout the sessions with a Garmin Forerunner 920 XT -monitor (Garmin Ltd, Schaffhausen, Switzerland). Average and peak heart rates as well as training impulse (TRIMP), based on the Edwards [27] model, were analyzed from the training sessions. In addition, at the end of each session rating of perceived exertion (RPE) were asked with the 6-20 Borg scale [28], and blood samples were drawn from the fingertip. Blood lactate was analyzed with Biosen S_line Lab+ lactate analyzer (EKF Diagnostic, Magdeburg, Germany). After each training session, subjects were given the same recovery drink (Fast Reco2) including 41 g of carbohydrates and 20 g of proteins mixed in a 500 ml of water. The recovery drink was served to ensure similar immediate nutrition for all subjects.

Recovery measurements

Heart rate variability: Heart rate variability (HRV) was measured in a supine position with a Garmin Forerunner 920XT -monitor. Before starting three-minute data collection [29], a one-minute stabilization period was performed [30]. Subjects were able to breathe at their natural rhythm. The average natural logarithm of the square root of the mean sum of the squared differences (lnRMSSD) was calculated from the three-minute measurement period. Because the measurements were performed in the lab and not right after awakening, baseline values in each athlete were derived from pooled pre-exercise data for the four test sessions comparable to Seiler et al. [14].

Countermovement jump: Countermovement jumps were performed on a contact mat. Jump height (h) was calculated with a formula: $h = g \cdot t^2 \cdot 8^{-1}$, where t is the recorded flight time in seconds and g is the acceleration due to gravity ($9.81\ m \cdot s^{-2}$) [31]. Subjects were advised to keep their hands on their hips and jump as high as possible. The lowest knee angle for the jump was about 90 degrees. Three attempts with 30 s recovery were performed unless an improvement of 5 % or more was found between two last jumps. The best jump of three was used in further analysis. Subjects were familiarized with the jumping technique during the preliminary tests.

Submaximal running test: The submaximal running test (SRT) was modified from the Vesterinen et al. [19] submaximal running test, and it acted as a warm-up and cool down for each training session. SRT in the current study consisted of two 5-min stages which were performed at the speeds corresponding individually to 70 % (1. stage) and 80 % (2. stage) of HR_{max} during the incremental treadmill test. The same individually set speeds, which were calculated from the incremental treadmill test, were used in all measurements, despite possible changes in heart rate, to allow fair comparison between sessions and conditions. During SRT, heart rate (HR) was recorded (Garmin Forerunner 920 XT) and oxygen consumption ($\dot{V}O_2$) and respiratory exchange ratio (RER) were measured (OxygonPro, Jaeger, Hoechberg, Germany). Average of the last two minutes during the 80 % running speed was used in further analysis, as higher intensities reflect better changes in maximal performance [19]. After SRT, RPE was asked using the 6-20 Borg scale [28] and blood lactate values were analyzed from the fingertip sample.

Subjective markers: Perceived recovery was estimated on the 0-10 scale [32]. Perceived muscle soreness of the lower limbs was estimated on the 10 cm visual analogy scale where 0 represented no soreness at all and 10 represented the highest possible soreness [33].

Statistical analyses

All values are expressed as mean and standard deviation (SD). Normal distribution of the data was checked with the Shapiro-Wilk test and homogeneity of the variances by Levene`s test. A one-way repeated measures ANOVA was used to compare training load variables measured during training sessions. A two-way repeated measures ANOVA was performed to examine main effects (training mode, time) and interaction (training mode x time) across measured variables. When appropriate, a Bonferroni post hoc test was used. Furthermore, in case of significant training mode x time interaction, relative changes from pre-values to post and post24 were compared between training modes using paired samples t-test with Bonferroni correction. Muscle soreness was not normally distributed even after log-transformation, so Wilcoxon signed-rank test was used for within-group comparisons and Mann-Whitney U-test for between-group comparisons. To further analyze the magnitude of observed changes, the effect size was assessed by Cohen`s D (difference of the means divided by the pooled standard deviation) [34], and after nonparametric tests by a formula: $ES = Z/\sqrt{n}$, where Z is the z-score, and n are the number of observations on which Z is based. An effect size of <0.20 was considered trivial, ≥0.20 small, ≥0.50 medium, and ≥0.80 large [34]. Statistical significance level was set to $p<0.05$. Analysis were performed with IBM SPSS Statistics v.26 -programs (SPSS Inc, Chicago, IL, USA) and Microsoft Excel 2010 (Microsoft Corporation, WA, USA).

Results

Training sessions

Results of the training sessions performed are presented in Table 2.

TABLE 2 ABOUT HERE

Supine heart rate variability

A significant main effect for the training mode ($p<0.001$), time ($p<0.001$) and training mode x time interaction ($p<0.001$) were found in lnRMSSD. lnRMSSD decreased ($p<0.001$) after LIT (3.8 ± 0.5 ms vs. 2.9 ± 0.7 ms, ES=-1.83), MOD (4.0 ± 0.5 ms vs. 1.9 ± 0.8 ms, ES=-3.13), HIIT (3.9 ± 0.4 ms vs. 2.1 ± 0.7 ms, ES=-3.12) and SMIT (3.9 ± 0.5 ms vs. 2.5 ± 0.6 ms, ES=-2.55). The relative decrease was smaller after LIT when compared to MOD ($p<0.001$, ES=1.35) or HIIT ($p=0.001$, ES=1.09)

(Figure 2). A smaller decrease was also observed after SMIT than MOD (p=0.009, ES=0.90) (Figure 2). lnRMSSD returned to baseline after all sessions at 24 hours with no differences compared to baseline within (LIT ES=0.15, MOD ES=-0.17, HIIT ES=0.00, SMIT ES=0.08) or between sessions. Relative mean and individual changes from the baseline in the lnRMSSD are presented in Figure 2.

FIGURE 2 ABOUT HERE

Countermovement Jump (CMJ)

A significant training mode x time interaction (p<0.001) was observed in CMJ. CMJ height decreased after LIT (35.8 ± 4.7 cm vs. 34.2 ± 4.9 cm, p=0.001, ES=-0.34) and SMIT (36.1 ± 4.7 cm vs. 34.4 ± 4.1 cm, p<0.001, ES=-0.37), while no difference compared to baseline was observed after MOD (35.3 ± 5.8 cm vs. 35.8 ± 5.3 cm, ES=0.09) or HIIT (35.7 ± 5.5 cm vs. 36.4 ± 5.0 cm, ES=0.13). The relative changes after LIT and SMIT were also different compared to MOD (LIT, p<0.001, ES=-1.06; SMIT, p=0.002, ES=-1.08) and HIIT (LIT, p<0.001, ES=-1.33; SMIT, p<0.001, ES=-1.43) (Figure 3). CMJ remained decreased after SMIT 24 hours after the session (p=0.018, ES=-0.19), while no difference was observed after other sessions (LIT, ES=-0.06; MOD, ES=0.02; HIIT, ES=-0.04). Relative mean and individual changes from the baseline in the CMJ height are presented in Figure 3.

FIGURE 3 ABOUT HERE

Submaximal running test

A significant main effect for time (p<0.01) were observed in all variables measured during the submaximal running test. In addition, significant main effect for training mode as well as training mode x time interaction was found in blood lactate (p<0.001). Heart rate during submaximal running test increased after all sessions (p<0.001) followed by a decrease below the baseline at 24 hours after LIT (p=0.001), MOD (p=0.023), HIIT (p=0.016) and SMIT (p=0.011). RPE during submaximal running test increased after LIT (p<0.001), MOD (p=0.004), HIIT (p=0.001) and SMIT (p=0.002), and it returned to baseline at 24 hours after LIT and MOD but remained increased after HIIT (p=0.048) and SMIT (p=0.007). Oxygen consumption during submaximal running test increased after LIT (p=0.017) and MOD (p=0.002), while no significant difference was observed after SMIT or HIIT. Oxygen consumption returned to baseline after all sessions at post24 measurements. The only between-group difference observed during the submaximal running test was in blood lactate which was higher after SMIT than any other session (p<0.001) The absolute values and effect sizes measured during the submaximal running test are presented in Table 3.

TABLE 3 ABOUT HERE

Subjective markers

No significant main effects or interaction were observed in perceived recovery (LIT 7.4 ± 1.5 vs. 6.7 ± 1.7, p=0.054, ES=-0.42; MOD 7.0 ± 1.5 vs. 7.0 ± 1.4, ES=-0.03; HIIT 7.3 ± 1.5 vs. ± 7.1 ± 1.7, ES=-0.13; SMIT 7.4 ± 1.4 vs. 6.9 ± 1.6, ES=-0.33). Perceived muscle soreness increased after LIT (1.5 ± 1.3 vs. 2.4 ± 1.7, p=0.003, ES=0.41) and SMIT (1.7 ± 1.9 vs. 2.4 ± 1.5, p=0.042, ES=0.25), while no change was observed after MOD (1.7 ± 1.5 vs. 2.1 ± 1.2, ES=0.20) or HIIT (1.6 ± 1.6 vs. 1.9 ± 1.7, ES=0.19). No significant differences between sessions were observed in relative changes of subjective markers.

Discussion

The aim of this study was to compare acute responses and post 24-hour recovery after training sessions performed at different intensity zones. The main findings of the study were that parasympathetic reactivation measured as HRV was diminished the most after MOD and HIIT compared to LIT and SMIT. Contradictory, CMJ performance did not decrease after MOD or HIIT but acutely decreased combined with increased muscle soreness at post24 after LIT and SMIT. The main result of the submaximal running test was that all measured metabolic parameters recovered and heart rate decreased significantly at 24 hours after all sessions, despite perceived exertion being elevated after HIIT and SMIT at the respective time points. The current results highlight how physiological demands differ between training modes. Different measures of performance and recovery may induce even contradictory results illustrating the usefulness of a broad approach to endurance training monitoring.

Training sessions

Blood lactate, heart rate, and RPE responses to running sessions confirmed that they could be regarded as representative measures of each intensity zone. Peak and average heart rate values observed during MOD and HIIT indicated a high cardiovascular demand during these sessions. Perceived effort during SMIT was estimated by the subjects similarly as after MOD and HIIT, and despite lower heart rate values, blood lactate increased the most suggesting higher anaerobic contribution during the session. During LIT, more than double the distance was covered compared to MOD and HIIT while there was almost a fourfold increase in distance covered compared to SMIT. Although the duration or distance was not the same between the sessions, they were likely similar to the ones typically utilized by athletes [1].

The only unexpected response was increased blood lactate value after LIT despite the low relative intensity (52 %/vMax, 80 %/vLT1), low heart rate (avg: 70 %/HR_{max}, peak: 76 %/HR_{max}) and RPE

(12 on a 6-20 scale). In the study of Seiler et al. [14], no changes in blood lactate were observed after 1- or 2-hour exercises performed below the ventilatory threshold. Differences compared to the present protocol were that Seiler et al. [14] had higher caliber athletes, the 1-hour session was performed on the 2-5 % incline and the longer 2-hour session was performed outside. All of these methodological differences may at least slightly influence the physiological responses compared to the present protocol. In line with the present results, Kaikkonen et al. [26] found that after a 14 km run on a treadmill at 60 % $v\dot{V}O_{2max}$ blood lactate elevated significantly compared to the control session performed at the same intensity but 3 km in distance (1.4 vs. 2.6 mmol/l) in recreational athletes. The athlete level could, therefore, be a major factor in the observed response. Because RPE and heart rate remained in target values despite elevated blood lactate levels during LIT, the training session of the present study likely illustrates a typical LIT session of a recreational endurance athlete.

Acute responses

Acute responses in supine HRV differed significantly between the sessions. HRV decreased less after LIT compared to MOD and HIIT despite higher TRIMP and more than the double distance covered during the session. The results are in line with previous studies [10, 14] indicating that intensity of the sessions, when performed below $v\dot{V}O_{2max}$ seems to influence the parasympathetic reactivation more than the duration of the session. Furthermore, MOD and HIIT produced quite similar acute responses in HRV supporting the theory that lactate or the ventilatory threshold may act as a lower bound for the intensity related delay in parasympathetic reactivation [14]. An unexpected finding was that a smaller decrease in HRV was also observed after SMIT than MOD, and no difference was observed in the HRV responses between LIT and SMIT despite significantly higher lactate values and RPE measured in SMIT. This is also contradictory to the results of Niewiadomski et al. [13] who found a greater decrease in HRV one hour after a supramaximal session (2 x 30 s Wingate) compared to a moderate intensity session (30 min 85 %/HRmax). In addition, Buchheit et al. [35] have suggested that the delay in parasympathetic reactivation is mainly related to the contribution of anaerobic processes. However, maximum heart rate [13], as well as mean heart rate and blood lactate levels [35] during supramaximal exercises were substantially higher compared to the present study, which may relate to a lower cardiovascular load and the sympathetic nervous system activity during the session. It should be also acknowledged that there is a wide range of anaerobic interval sessions differing in the intensity, work:relief-ratio and anaerobic glycolytic energy contribution [36]. Further studies are needed to understand how manipulation of these variables would affect the parasympathetic reactivation following anaerobic exercise.

Acute changes in CMJ occurred oppositely when compared to HRV responses. While no change was observed after HIIT or MOD, jump height decreased after LIT and SMIT. Previously, Boullosa et al. [21] have found improved CMJ performance after intensive running sessions in endurance-trained athletes. Because both the intensity and the work:relief-ratio of the interval exercise significantly affect neuromuscular demands of the session [36], it is somewhat expected that supramaximal intervals may induce different types of response compared to the intervals of lower intensity. Wiewelhove et al. [37] reported decreased CMJ performance after sprint interval training, while aerobic high-intensity training did not induce such an effect. Blood lactate is probably not the main contributor behind this difference as improved CMJ performance has been observed in the absence of higher blood lactate values [21] compared to the present study. In general, it is thought that neuromuscular fatigue after high-intensity exercise is mainly peripheral and caused by contractile mechanisms disturbances [11, 38], while fatigue induced by longer duration activities are mainly of central origin observed as decreased voluntary activation [11] or changes in stretch-reflex sensitivity and muscle stiffness [39]. It is plausible that different mechanisms are behind the CMJ decrease observed after LIT and SMIT, and the time needed to recover is longer after SMIT, at least in recreationally trained athletes.

All cardiorespiratory, metabolic and perceptual measures during the submaximal running test were quite similar between the sessions, and the responses were mainly in line with previous studies using similar types of running protocols [5, 6, 7]. Heart rate and RPE during submaximal running test increased after all sessions, with a concurrent decrease in RER indicating higher reliance on fat as a substrate despite the nature of the preceding exercise. Oxygen consumption during submaximal running test increased slightly, but still significantly only after continuous sessions. This was somewhat surprising and in contrast to the results reported by previous studies [5, 7]. However, effect sizes in acute responses remained trivial after all sessions, so any major difference between session types cannot be stated. Blood lactate during the submaximal running test remained elevated after SMIT, which was probably mainly the outcome of a higher absolute value after the exercise itself. A longer recovery period seems to be necessary for lactate clearance after such a session. Increases in body core temperature and sympathetic nervous system activity along with dehydration and a decrease in blood volume are likely the main contributors to the cardiovascular responses observed in the present study [40]. Increased heart rate may also contribute to the impaired running economy [41]. Muscle glycogen content has been shown to decrease after prolonged as well as high-intensity exercises [42], and its depletion further influences substrate utilization [43] and oxygen cost during running [44]. It is plausible that running sessions of the present study did not induce significant differences in the aforementioned factors. The lack of major differences between the sessions in the submaximal running test could also be related to the time frame of the measurement, as some session-related effects may have already disappeared at the time point used in the current study (post 18-20 min).

24-hour recovery

Supine HRV returned to baseline in 24 hours after all sessions. Stanley et al. [15] concluded in their review, that cardiac autonomic recovery after strenuous exercise may take up to 24-48 hours. The lack of any differences within or between the sessions at post24 could possibly be related to methodological differences between nocturnal and daytime recordings. It is well known that HRV is affected by many external factors especially during the daytime [12], which makes it challenging to find significant changes in the autonomic modulation caused by a single training session. While nocturnal HRV has remained suppressed after a moderate and heavy endurance exercise [45], Niewiadomski et al. [13] measured HRV in the laboratory conditions, and found no change compared to baseline 24 hours after moderate or high-intensity training sessions.

Recently, it has been observed that the recovery of the neuromuscular performance and markers of muscle damage follow different patterns than HRV after strength training exercise [20]. Similar observations were found in the present study, as HRV was fully recovered at 24 hours after all sessions, but CMJ performance after SMIT remained decreased and muscle soreness was apparent after LIT and SMIT. Although it should be acknowledged that effect size of the pre-post24 change in CMJ was trivial after all sessions, it is likely that cardiac parasympathetic reactivation after exercise does not reflect all aspects crucial to recovery in endurance training, such as repletion of the energy stores and neuromuscular performance [12, 15].

All physiological variables measured during the submaximal running test recovered at least to baseline levels at 24 hours after all exercises with no significant differences between the sessions. However, increased perceived exertion during the submaximal running test was still apparent after both interval exercises and muscle soreness were increased after LIT and SMIT. All these changes took place despite the significantly decreased heart rate in the submaximal running test. In addition to increased muscle soreness and perceived exertion during the submaximal running test, also CMJ remained decreased at 24 hours after SMIT, which emphasizes the high neuromuscular demand of these types of sessions, which is also supported by Wiewelhove et al. [37]. It is possible that in addition to peripheral factors [11], high mechanical load of the running speed that recreational endurance athletes may be unaccustomed to further amplified the neuromuscular fatigue and time needed to recover after SMIT.

Like resting HRV, heart rate recordings during exercise could also be affected by multiple external factors, and a natural day to day variation during submaximal exercise can be up to 3-8 bpm [46]. Taking this into account, it was interesting that the heart rate during submaximal running test decreased significantly at 24 hours after all sessions by 3-4 bpm. Previously, submaximal running tests have mainly been studied after intensive training or the competition period, while effects of a single session have been less examined. Siegl et al. [47] found heart rate decrements of 3 bpm (70 %/v$\dot{V}O_{2max}$) and 2 bpm (85 %/v$\dot{V}O_{2max}$) with a concurrent increase of RPE two days after an ultramarathon event. Other studies have failed to show any differences in submaximal heart rate 1-4 days after a 30 min high-intensity run [48] or 1-3 days after a 26 km run at an intensity of 80 %/HR_{max} [49]. One possible reason for heart rate decrease during submaximal exercise could relate to an increase in plasma volume [12], but this variable was not measured in the present study and the actual reason remains inconclusive.

Running economy is an important determinant of endurance performance [41], and a recovery pattern of the economy would therefore be an important aspect to examine. In the present study, oxygen consumption as well as RER during the submaximal running test returned to the baseline level at 24 hours after all sessions. This was not surprising though already acute responses in the oxygen consumption could be stated as trivial after all sessions. In previous studies, running economy has recovered 24 hours after a 30 min high-intensity run [48], 26 km run at the intensity of 80 %/HR_{max} [49] as well as 48 hours after a marathon [50]. Despite exercise-induced fatigue potentially declining running economy via multiple mechanisms [41], it seems that metabolic recovery occurs quite rapidly, and running economy will not likely be impaired in the following day of a single intensive or prolonged low-intensity training session.

Despite clear relationships between maximal and submaximal endurance performance [19] results of the submaximal tests are sometimes complicated to interpret. Similar changes in submaximal heart rate can be a sign of a positive training adaptation [19] or negative adaptation indicating fatigue/overreaching [51]. Similarly, it may be difficult to make assertions relating blood lactate values during submaximal exercise [51]. In the present study, RPE during the submaximal running test remained elevated after both interval sessions despite the decreased heart rate and the baseline level blood lactate values. Because maximal performance was not measured in the present study, it is difficult to ascertain whether the changes in perceptual markers would be a sign of decreased maximal performance. However, Marcora and Bosio [52] found that exercise-induced muscle damage and muscle soreness may impair 30 min maximal time-trial running performance. The authors suggested that the performance impairing effect might be mediated by the increased sense of effort during the time trial caused by muscle soreness [52]. Therefore, it seems reasonable to assume that higher perceptual effort at the submaximal level and increased muscle soreness may also have influenced maximal performance.

Study limitations

The study population consisted of recreationally endurance-trained men and the results cannot be straightforwardly transferred to well-trained or elite-athletes. Although the physiological characteristics of each intensity zone are likely quite universal, more studies are needed to confirm the findings among high-level athlete populations and in both sexes. Because the follow-up measurements were not performed later than 24 hours after each session, all variables did not reach the baseline in all subjects. It could not, therefore, be concluded, what would have been the time frame to recover for each of the variables. Training sessions of the present study were not matched for training load but were instead chosen as one representative session type of each intensity zone. Changing session intensity or duration would possibly influence the results, so further studies are needed to grow the understanding of how manipulation of these variables would affect responses and recovery. Lastly, although trying to standardize the testing protocol and days surrounding it, there remain some aspects that may potentially influence recovery within and between individuals such as nutrition, sleep, or leisure-time activity.

Conclusions

In conclusion, the results of the present study highlight differences in the physiological demands of the running sessions performed and distinct recovery patterns following these sessions in the measured variables of performance and training state. The delay of the parasympathetic reactivation after endurance exercise seems to relate to the intensity and cardiovascular load of the preceding session. Running sessions of a long-duration or a supramaximal intensity have high neuromuscular demands, observed as acute decreases in neuromuscular performance, and increased muscle soreness 24 hours afterwards. Cardiovascular and metabolic recovery occurs rapidly, and these components of physical performance are not likely compromised 24 hours after a single intensive or a low-intensity prolonged session. Because subjective markers may give even contradictory results when compared to the objective measurements, it would be recommended to combine information from different sources, when estimating the actual recovery state and readiness to train.

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Figure legends

Figure 1. Pre, Post and Post24 measurements around each training session. Supine HRV, supine heart rate variability; SRT, submaximal running test; CMJ, countermovement jump; LIT, low-intensity session; MOD, moderate-intensity session; HIIT, high-intensity interval session; SMIT, supramaximal intensity interval session.

Figure 2. Mean (black line) and individual values (dots) in the relative changes compared to baseline in supine lnRMMSD. ***p<0.001, **p<0.01, *p<0.05 significant difference compared to the baseline within session. ###p<0.001, ##p<0.01, #p<0.05 significant difference in the relative change from the baseline between sessions**.** lnRMSSD, natural logarithm of the square root of the mean sum of the squared differences. LIT, low-intensity session; MOD, moderate-intensity session; HIIT, high-intensity interval session; SMIT, supramaximal intensity interval session.

Figure 3. Mean (black line) and individual values (dots) in the relative changes compared to baseline in countermovement jumps.***p<0.001, **p<0.01, *p<0.05 significant difference compared to the baseline within session. ###p<0.001, ##p<0.01, #p<0.05 significant difference in the relative change from the baseline between sessions**.** CMJ, countermovement jump; LIT, low-intensity session; MOD, moderate-intensity session; HIIT, high-intensity interval session; SMIT, supramaximal intensity interval session.

Table legends

Table 1. Basic characteristics of the subjects (n=24)

Table 2. Results of four running sessions performed.

Table 3. Baseline values (Pre), acute responses (Post), post 24-hour recovery (Post24) and effect size of the changes (ES) in submaximal running test.

II

MONITORING TRAINING AND RECOVERY DURING A PERIOD OF INCREASED INTENSITY OR VOLUME IN RECREATIONAL ENDURANCE ATHLETES

by

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Article

Monitoring Training and Recovery during a Period of Increased Intensity or Volume in Recreational Endurance Athletes

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Abstract: The purpose of the study was to examine the effects of progressively increased training intensity or volume on the nocturnal heart rate (HR) and heart rate variability (HRV), countermovement jump, perceived recovery, and heart rate-running speed index (HR-RS index). Another aim was to analyze how observed patterns during the training period in these monitoring variables were associated with the changes in endurance performance. Thirty recreationally trained participants performed a 10-week control period of regular training and a 10-week training period of either increased training intensity (INT, n = 13) or volume (VOL, n = 17). Changes in endurance performance were assessed by an incremental treadmill test. Both groups improved their maximal speed on the treadmill (INT 3.4 ± 3.2%, $p < 0.001$; VOL 2.1 ± 1.8%, $p = 0.006$). In the monitoring variables, only between-group difference ($p = 0.013$) was found in nocturnal HR, which decreased in INT ($p = 0.016$). In addition, perceived recovery decreased in VOL ($p = 0.021$) and tended to decrease in INT ($p = 0.056$). When all participants were divided into low-responders and responders in maximal running performance, the increase in the HR-RS index at the end of the training period was greater in responders ($p = 0.005$). In conclusion, current training periods of increased intensity or volume improved endurance performance to a similar extent. Countermovement jump and HRV remained unaffected, despite a slight decrease in perceived recovery. Long-term monitoring of the HR-RS index may help to predict positive adaptations, while interpretation of other recovery-related markers may need a more individualized approach.

Keywords: endurance performance; running; training load; heart rate variability

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1. Introduction

The rapid development of wearable technology has allowed for frequent monitoring of training and recovery. For example, heart rate measures during endurance training and rest are widely used, not only among elite and competitive athletes, but also in recreational athletes. While more measurement devices are available, it would be important to understand the practical relevance of the results, and how to interpret obtained results in the right context [1].

The main purpose of the monitoring process is to ensure that the body is adapting to the training stimulus and the training load is appropriate for the individual [2]. Another role of monitoring is to ensure sufficient recovery between training sessions and periods. Recovery and the training state can be analyzed from many perspectives, including assessments of performance [3], physiological markers such as hormone concentrations [4] or heart rate variability [5], and perceived estimations of the recovery [6]. Recovery-based training has been studied recently among multiple populations. Individually adjusted training-based on resting heart rate variability (HRV) has induced superior improvements in maximal endurance performance [7] and VO_{2max} [8] compared to pre-planned training in recreationally trained participants.

Responses to short-term [9] and long-term training periods [10] may vary quite a lot between individuals. Individual changes in endurance performance after a standardized endurance training program can range from slightly negative up to even a 20–30% improvement [9,11]. Multiple factors can explain the differences in the adaptation including, for example, genetics, training status, sleep, nutrition, and the recovery state [12]. It has been suggested that individualized training prescriptions may diminish variation in the adaptation [13].

It seems reasonable to assume that monitoring training and recovery could help athletes and coaches to react if an undesirable response would be detected. To the best of our knowledge, no studies have previously examined the recovery and training state in recreational athletes during an endurance training period of increased intensity or volume from a multidisciplinary point of view. Therefore, the purpose of the present study was first to examine the effects of increasing either intensity or volume on nocturnal heart rate and HRV, endurance and neuromuscular performance, and perceived recovery. Another aim was to analyze whether observed performance and recovery patterns during the training period could differentiate the low-responders from the responders. It was hypothesized that an increased volume of low-intensity training would impair neuromuscular performance assessed by countermovement jump [14] but increase the activity of the cardiac parasympathetic nervous system measured as HRV [15], unlike high-intensity training. It was also hypothesized that maintenance of stable recovery during the long-term training period as well as an improvement in the submaximal estimation of endurance performance may differentiate responders from low-responders.

2. Materials and Methods

2.1. Participants

A total of 42 recreationally endurance-trained 20–45 years old men (n = 21) and women (n = 21) were recruited for the study. There were five dropouts during the control period due to injuries (n = 3), illness (n = 1), and personal reasons (n = 1). During the training period, three dropouts occurred due to illness (n = 1) and personal reasons (n = 2). Four participants were excluded from the final analysis due to improper training adherence (<90% of the main sessions), leaving 30 participants in total for the final analysis. Participants were divided into the intensity-group (INT: 8 men, 5 women) and volume-group (VOL: 8 men, 9 women) at the end of the control period. The baseline characteristics of both groups are presented in Table 1. The study protocol was approved by the Ethical Committee of the University of Jyväskylä.

Table 1. Baseline characteristics of the participants at the beginning of the control period.

	INT (n = 13)	VOL (n = 17)
Age (yrs.)	38 ± 4	36 ± 6
Height (cm)	173 ± 11	172 ± 11
Body mass (kg)	72.0 ± 11.9	69.5 ± 11.8
Body fat (%)	17.4 ± 6.9	19.4 ± 7.7
VO_{2max} (mL/kg/min)	47.1 ± 5.6	47.2 ± 5.4
Training history (yrs.)	11 ± 10	10 ± 7

Values are presented as means ± SD. INT, intensity-group; VOL, volume-group; VO_{2max}, maximal oxygen uptake.

2.2. Study Design

The study consisted of two separate 10-week periods. During the first period subjects continued their typical training on their own (control period), while during the second period training was modified according to the group (training period). Laboratory tests, including incremental running tests on a treadmill and serum hormone analyses, were performed at the beginning of the control period (Ctrl), between the control and training periods (Pre), and at the end of the training period (Post). During the whole study period, the participants recorded weekly nocturnal heart rate (control period: 29 ± 3 nights, training period: 29 ± 4 nights), performed countermovement jump tests (control period: 8.9 ± 1.1 times, training period: 9.3 ± 1.0 times), collected training data from all endurance exercises (heart rate and speed), and filled a training log. Individual reference values for the recovery measurements and training characteristics (intensity and volume) were analyzed as an average of the control period. Weeks including illnesses were excluded from the analysis to avoid distorting the results. At the end of the control period, the participants were divided into two groups based on their background information (treadmill test performance, age, gender) and training characteristics. The INT-group increased the proportion of training sessions above the first lactate threshold, while the VOL-group increased the endurance training volume (low-intensity) during the training period.

2.3. Laboratory Tests

Fasting measurements: Fasting measurements were performed after 12 h of fasting and individually at the same time of the day (8:00–9:15 A.M.). Body mass and body fat percentage were measured with InBody770-analyser (Biospace Co. Ltd., Seoul, Korea). Blood samples were taken in a sitting position from the antecubital vein into 7 mL serum tubes using standard laboratory procedures. Whole blood was centrifuged at 2000 G rcf (Megafuge 1.0 R, Heraeus, Hanau, Germany) for 10 min, and after that serum was removed and frozen at −20 degrees until the final analysis. Serum cortisol was analyzed with chemical luminescence technique (Immulite 2000 XPi, Siemens, New York City, NY, USA). The sensitivity of cortisol assay was 5.5 nmol/L and the intra-assay coefficients of variation 3.6%. Free testosterone was analyzed with the ELISA-method (DYNEX DS 2 ELISA processing system, DYNEX Technologies, Chantilly, VA, USA). The sensitivity of free testosterone assay was 0.06 pmol/L and the intra-assay coefficient of variation was 3.6%.

Incremental treadmill test: An incremental treadmill test was performed on a treadmill (Telineyhtymä Oy, Kotka, Finland) always at the same time of the day (±2 h) within-participant. Starting speed was set to 7 or 8 km/h for women and 8 or 9 km/h for men. The starting speed was based on the background information of the participants to allow a reliable estimation of lactate thresholds and was kept similar in all tests. Three-minute stages were used, and speed increased by 1 km/h after every stage. Between the stages, the treadmill was stopped (15–20 s) for drawing the fingertip blood lactate samples. Inclination was kept constant at 0.5 degrees through the whole test. Oxygen consumption was measured breath by breath (OxygonPro, Jaeger, Hochberg, Germany) and heart rate was monitored with Garmin Forerunner 245M (Garmin Ltd., Schaffhausen, Switzerland). Maximal oxygen uptake (VO_{2max}; mL/kg/min) was defined as the highest 60 s average of oxygen consumption. Due to technical issues regarding the gas analyser, reliable oxygen consumption values were available only from the control and pre-tests. Maximal running speed (vMax) of the test was defined as the highest completed speed, or if the stage was not finished, as a speed of the last completed stage (km/h) + (running time (s) of the unfinished stage − 30 s)/(180 − 30 s) × 1 km/h. The first lactate threshold (vLT1) and the second lactate threshold (vLT2) were determined based on blood lactate changes during the test [16]. The vLT1 was set at 0.3 mmol/L above the lowest lactate value and vLT2 at the intersection point between (1) a linear model between vLT1 and the next lactate point and (2) a linear model for the lactate points with the lactate increase of at least 0.8 mmol/L.

2.4. Training

Control period: A 10-week control period began after the control tests. During the control period, the participants were advised to continue their regular training in terms of volume and intensity. However, they were advised to be at the recovered state at the end of the control period.

Training period: During the 10-week training period, the participants of the INT- and VOL-groups utilized individually scaled training programs. The aim was to increase progressively training load by either increasing the proportion of moderate and high-intensity sessions or volume of the training. After one easier week, during which the participants were familiarized with the predefined training, it was periodized into three three-week mesocycles of two intensive weeks followed by one recovery week (70% volume of the preceding week, only one moderate-intensity-session). The goal of the INT-group was to progressively increase the proportion of training above the first lactate threshold compared to the average of the control period, while maintaining the total endurance training volume the same. Progression started from one additional session and led to three additional sessions during the intensive training weeks, accounting for 10 sessions in total. Furthermore, the intensity of these sessions progressed from moderate-intensity training towards high-intensity training. The goal of the VOL-group was to progressively increase the volume of low-intensity training compared to the control period from 20% to 50% during intensive weeks while maintaining the volume of moderate and high-intensity training the same. Volume was increased primarily by adding duration to each training session, and weekly training frequency was kept similar. The training progression during the training period is illustrated in Figure 1.

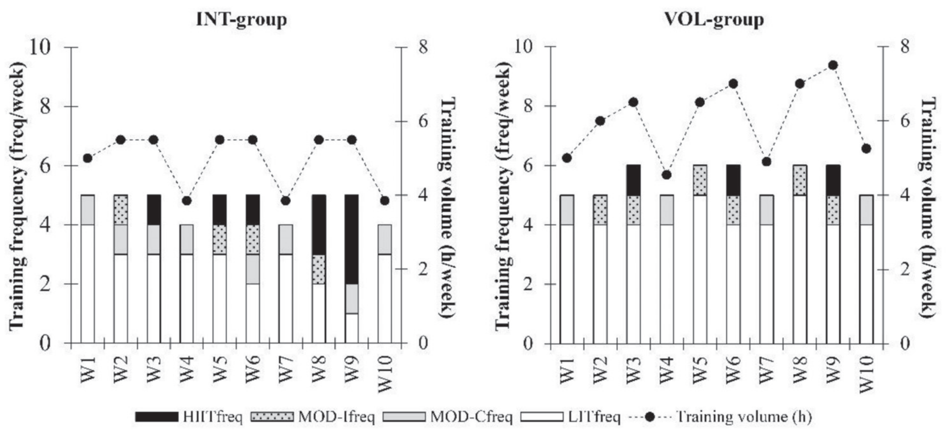

Figure 1. Training program progression of a representative participant in the INT- and VOL-groups. INT, Intensity-group; VOL, Volume-group; HIITfreq, frequency of high-intensity interval training; MOD-I, frequency of moderate-intensity interval training; MOD-Cfreq, frequency of moderate-intensity continuous training; LITfreq, frequency of low-intensity training.

The training program included low-intensity training (LIT) below the first lactate threshold, moderate-intensity training (MOD) between the first and second lactate threshold, and high-intensity training (HIT) above the second lactate threshold. Session intensity was controlled by the heart rate. The duration of the training sessions was individually determined in accordance with typical sessions performed during the control period. LIT-sessions consisted of basic sessions (30–75 min) and long sessions (>75 min). MOD-sessions consisted of long intervals (2–4 $\times$ 10–15 min) or continuous running (20–60 min). HIT-sessions consisted of 3–6 min intervals with 2:1 work: relief-ratio, and 15–30 min accumulated time in the high-intensity during the session. Interval sessions always included low-intensity warm-up and cool-down. The training was performed mainly by running. To avoid the risk of overuse injuries, alternative training modes (cycling, roller-skiing, swimming) were allowed with volumes similar to the control period. Subjects were advised not to change the amount or content of their typical strength training during the study period (control period: 0.3 $\pm$ 0.3 sessions/week, training period: 0.2 $\pm$ 0.3 sessions/week).

2.5. Training and Recovery Monitoring

Training data: The participants used the Garmin Forerunner 245M heart rate monitor (Garmin Ltd., Schaffhausen, Switzerland) during each endurance training session. Measured training data was regularly sent to the research group for further analysis. Distance covered (km) and time spent at each training intensity (LIT: HR < LT1, MOD: HR = LT1-LT2, HIT: HR > LT2) were analyzed from the sessions. Additionally, the heart rate-running speed index (HR-RS index) [17] was analyzed from all continuous-type running exercises. Sessions that were ran on trails or in the forest were excluded from the analysis. HR-RS index was calculated based on the session average running speed (S_{avg}) and heart rate (HR_{avg}) with the following equation:

$$\text{HR-RS index} = S_{avg} - (HR_{avg} - HR_{standing})/k$$

$$k = (HR_{max} - HR_{standing})/S_{peak}$$

$HR_{standing}$ was estimated by adding 26 bpm to the resting HR (average nocturnal HR during the control period) similar to Vesterinen et al. [17]. S_{peak} and HR_{max} were determined based on the first incremental treadmill test.

Training log: The participants wrote down the basic characteristics of each session, including training mode, session goal, session duration, distance covered, and optional own comments on a training log. In addition, session RPE [18] and recovery state during the training session [6] were estimated from each training day on a 0–10 scale.

Heart rate and heart rate variability: Nocturnal heart rate and HRV were measured three nights per week (2 weekdays and 1 weekend) with Firstbeat Bodyguard 2 device (Firstbeat Technologies Ltd., Jyväskylä, Finland). The participants were advised to start the measurement when going to sleep and stop the measurement right after awakening. The data was analyzed using Firstbeat Analysis Server software (version 7.5). The HRV analysis was performed by calculating the second-by-second HRV indices using the short-time Fourier transform method. Average heart rate and the natural logarithm of high-frequency power (lnHF ms^2, 0.15–0.40 Hz) were obtained from the standardized time period of 0:30–4:30 after going to bed, similar to previous studies using nocturnal heart rate recordings [16,19]. lnHF was chosen as a representative HRV parameter, because it can be used to monitor changes in cardiac vagal control [20], it has been used in endurance training guidance [21], and it has also been associated with endurance training adaptation [22].

Countermovement jump: The countermovement jump (CMJ) test was performed once per week at home conditions. In the test, the participants performed three maximal attempts with a 1-min recovery. They were advised to perform the test after a short standardized warm-up at the same time of the day (±1 h), and on the same day of the week, before any physical activity. The jumps were videotaped with the mobile phone, which should have at least 120 frames per second video feature. Participants were instructed to use a camera angle from the front (about 1.5 m from the jumper) that would allow strict estimation of the first frame in which no foot touches the ground, and first frame had at least one foot contact again. Videos were sent to the research group and jumps were analyzed by the same person with a validated MyJump2-application [22]. Average jumping height (cm) of two best jumps were used in the data analysis.

2.6. Statistical Analysis

All values are expressed as mean and standard deviation (SD). The normal distribution of the data was verified with the Shapiro-Wilk test. In the laboratory measurements, differences between time points (control, pre, post) and groups were analyzed by a repeated measures ANOVA. In the case of a significant main effect or interaction, a Bonferroni post hoc test was used. For the monitoring variables, within-group comparisons between the control and training periods were assessed by paired samples *t*-test with absolute values and between-group comparisons by independent samples t-test with relative changes. Training characteristics (absolute and relative training intensity distribution) were not normally distributed, thus the Wilcoxon signed-rank -test was used for comparisons between the control period and training period. To further analyze changes in the monitoring variables that did not differ between groups (lnHF, CMJ, HR-RSi, perceived recovery), participants were retrospectively divided into two groups based on the relative change in the maximal treadmill performance (vMax). vMax was chosen to present endurance training adaptation, as it is closely related to maximal endurance performance in a wide range, and it has also been used in a previous study [16]. The low-responder group (n = 7, range −1.8 to 0.0%) included participants with no change or decrease in performance, while the responder group (n = 7, range +4.1 to +11.3%) included participants with a greater improvement than mean response after the control period + 1 × SD (>4.0%). Group comparisons were performed with the Mann-Whitney U-test and Bonferroni adjustments. The smallest worthwhile change (SWC) was calculated by multiplying the within-participant CV of each monitoring variable during the control period by 0.5 [23], except for the HR-RS index, where between-participant SD during the control period was multiplied by 0.5. The same average values were used for all participants. To examine the magnitude of observed changes, the effect size (ES) of within-group absolute differences and between-group differences in the relative changes was calculated as Cohen's d for the main variables. The magnitude of changes was stated as <0.2 trivial, 0.2–0.5 small, 0.5–0.8 moderate, and >0.8 large. After nonparametric tests, effect size was calculated with a formula: $ES = Z/\sqrt{n}$, where Z is the z-score, and n are the number of observations. The significance level was set to $p < 0.05$. The analysis was performed with Microsoft Excel 2010 (Microsoft Corporation, WA, USA) and IBM SPSS Statistics v.26-programs (SPSS Inc, Chicago, IL, USA).

3. Results

3.1. Training

No differences were observed between the groups in the training characteristics of the control period. Average weekly training characteristics are presented in Table 2.

Table 2. Average weekly training characteristics during the control and experimental training periods.

	INT (n = 13)		VOL (n = 17)	
	Control	**Training**	**Control**	**Training**
Training volume (h)	4.9 ± 1.7	4.8 ± 1.7	4.9 ± 1.4	5.7 ± 1.8 ***
Training frequency/week	4.6 ± 1.3	5.1 ± 1.7	4.6 ± 1.1	4.8 ± 1.1
Running volume (km)	31 ± 11	38 ± 16 *	34 ± 13	44 ± 14 ***
LIT (%)	77 ± 17	71 ± 12	75 ± 15	77 ± 12
MOD (%)	21 ± 16	22 ± 9	22 ± 13	19 ± 9
HIT (%)	2 ± 3	7 ± 6 **	3 ± 3	4 ± 3

INT, intensity-group; VOL, volume-group; LIT, low-intensity training below the first lactate threshold; MOD, moderate-intensity training between the first and the second lactate thresholds; HIT, high-intensity training above the second lactate threshold. *** $p < 0.001$, ** $p < 0.01$, * $p < 0.05$ different compared to the control.

3.2. Laboratory Measurements

A significant main effect of time ($p < 0.001$) was found in vMax, vLT1, and vLT2. No differences were observed between the control and pre-tests in any of the laboratory measurements in neither of the groups. vMax improved in both groups after the training period (INT 3.4 ± 3.2%, $p < 0.001$, ES = 0.37; VOL 2.1 ± 1.8%, $p = 0.006$, ES = 0.18). In addition, running speed at the first lactate threshold (INT 4.6 ± 6.1%, $p = 0.006$, ES = 0.34; VOL 8.4 ± 5.5%, $p < 0.001$, ES = 0.62) and the second lactate threshold (INT 3.0 ± 3.1%, $p = 0.007$, ES = 0.29; VOL 3.7 ± 3.6%, $p < 0.001$, ES = 0.27) increased in both groups. In serum hormone concentrations, no significant main effect or interaction was observed. The absolute results of endurance performance and serum hormone concentrations are presented in Table 3.

Table 3. Laboratory test results at the beginning (Pre) and the end (Post) of the training period.

	INT (n = 13)		VOL (n = 17)		Effect Size
	Pre	Post	Pre	Post	INT vs. VOL (Δ% Pre-Post)
Endurance Performance					
vLT1 (km/h)	10.2 ± 1.3	10.7 ± 1.2 **	10.1 ± 1.3	10.9 ± 1.1 ***	−0.65 (moderate)
vLT2 (km/h)	12.7 ± 1.5	13.1 ± 1.4 **	12.5 ± 1.6	13.0 ± 1.5 ***	−0.19 (trivial)
vMax (km/h)	15.7 ± 1.4	16.2 ± 1.4 ***	15.5 ± 1.7	15.8 ± 1.8 **	0.50 (moderate)
Serum hormone concentrations					
Cor M (nmol/L)	343 ± 97	356 ± 90	363 ± 85	346 ± 110	0.27 (small)
fTesto M (pmol/L)	40 ± 25	36 ± 22	30 ± 21	28 ± 22	−0.03 (trivial)
fTesto:Cor	0.11 ± 0.06	0.10 ± 0.05	0.10 ± 0.05	0.09 ± 0.08	−0.39 (small)

Values are presented as means ± SD. vLT1, the speed at the first lactate threshold; vLT2, the speed at the second lactate threshold; vMax, maximal speed of the incremental treadmill test; Cor, serum cortisol; fTesto, serum free testosterone; fTesto:Cor, the ratio between serum free testosterone and cortisol; INT, Intensity-group; VOL, Volume-group. *** $p < 0.001$, ** $p < 0.01$, different compared to the pre, ES = Effect size as Cohen's D.

3.3. Training and Recovery Monitoring

Individual averaged values of the monitoring variables are presented in Figure 2. Significant differences between the control and training periods were observed in the session RPE of INT (p = 0.001, ES = 0.58), perceived recovery of VOL (−6.3 ± 10.1%, p = 0.021, ES = −0.43) and nocturnal heart rate of INT (p = 0.016, ES = −0.14). The relative change of nocturnal heart rate was significantly different between the groups (INT −2.1 ± 2.6% vs. VOL 0.4 ± 2.5%, p = 0.013, ES = −0.99). In addition, perceived recovery tended to decrease in INT (−6.1 ± 11.4%), p = 0.056, ES = −0.45). Small to moderate effect sizes were observed when relative changes were compared between the groups in CMJ (INT 0.0 ± 5.0% vs. VOL −2.3 ± 5.1%, ES = 0.46), lnHF (INT 0.7 ± 2.9% vs. −0.6 ± 1.8%, ES = 0.54), session RPE (INT 13.9 ± 12.4% vs. VOL 8.8 ± 18.4%, ES = 0.32), and in absolute changes of the HR-RS index (INT 0.2 ± 0.4 vs. 0.0 ± 0.5, ES = 0.34).

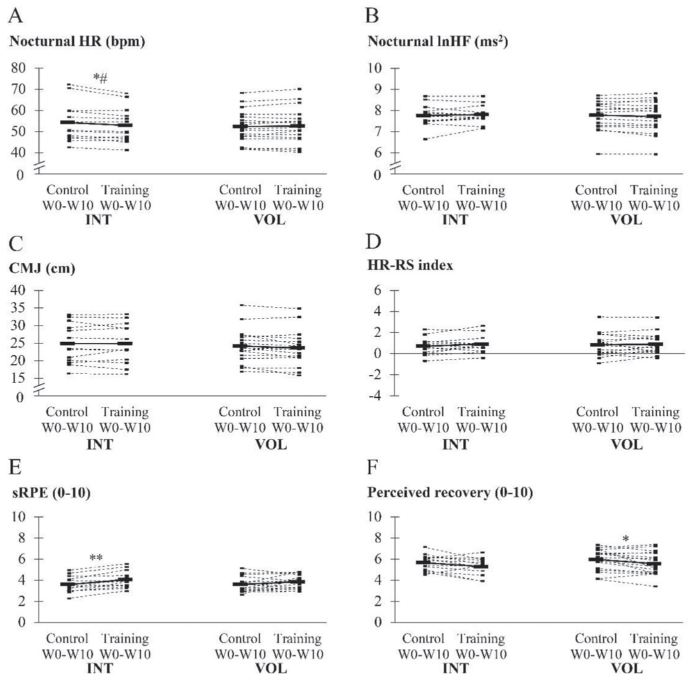

Figure 2. Individual average values during the control and training period in the nocturnal heart rate (HR) and heart rate variability (lnHF), countermovement jump (CMJ), heart rate-running speed index (HR-RS index), session RPE (sRPE) and perceived recovery. * $p < 0.05$ in within-group comparison to control, ** $p < 0.01$ in within-group comparison to control. # = $p < 0.05$ in between-group comparison with relative values.

3.4. Comparison between Responders and Low-Responders

For further analysis, the both groups were combined so that the participants were retrospectively divided into the subgroups of low-responders and responders. When the subgroups were compared across the training period, the only significant difference was observed in the HR-RS index during the last mesocycle ($p = 0.005$, ES = −0.84). In weeks 8–10, small to moderate between group effect sizes were also observed in lnHF (ES = −0.56), perceived recovery (ES = −0.32), and CMJ (ES = −0.50). Individual values in the relative changes across the training period are presented in Figure 3.

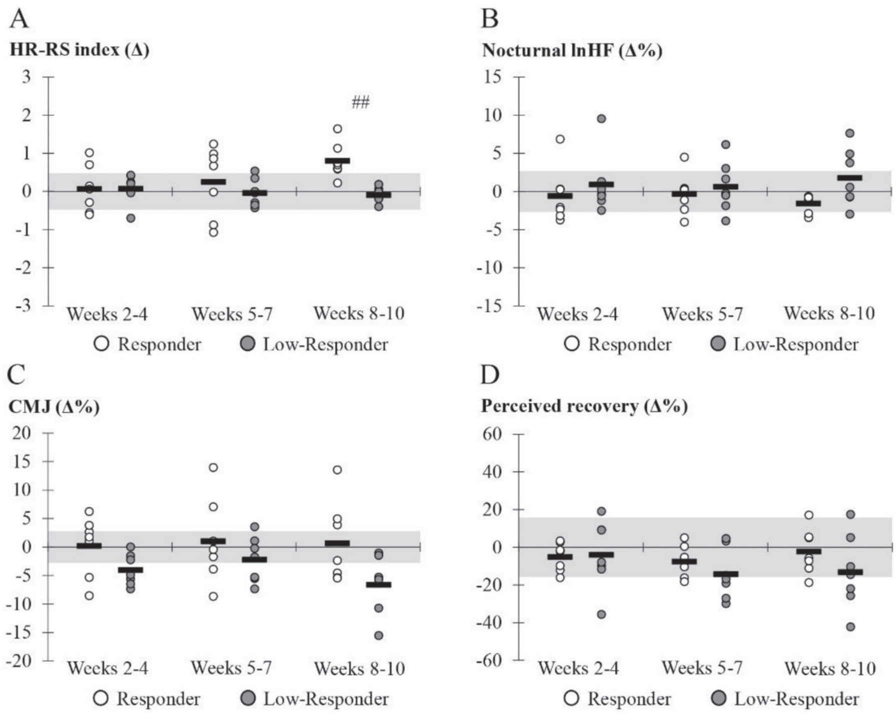

Figure 3. Mean (black line) and individual values (dots) in the relative changes compared to the control period in the nocturnal HRV (lnHF), heart rate-running speed index (HR-RS index), countermovement jump (CMJ), and perceived recovery. The gray area represents the smallest worthwhile change. ## $p < 0.01$ in between-group comparison.

4. Discussion

The main findings of the study were that the present 10-week endurance training period of either increased intensity or volume improved endurance performance quite similarly, and all participants improved lactate threshold and/or maximal running speed in the incremental treadmill test. The monitoring variables were affected rather marginally at the group level, but there was a lot of variations between individuals in the observed responses during the training period, regardless of the type of training performed. An increasing trend in the HR-RS index seems to be desirable when monitoring endurance training, while the interpretation of other recovery-related parameters, what kind of change should be regarded as worthwhile, as well as the choice of the monitoring variables may need a more individualized approach.

The training protocols were planned so that the training load would progressively increase either via intensity or volume, and training would be the most demanding at the end of the training period. The VOL-group increased their training volume approximately by 20%, while the INT-group increased the proportion of HIT-training from 2 to 7%. It is fair to assume that the training load was somewhat appropriate for the participants, as all individuals improved their maximal performance or running speed at the lactate thresholds, and none of the participants could be regarded as overreached at the time of post-tests. This was also supported by the unchanged concentrations of serum cortisol or free testosterone. Both groups improved performance almost identically, although a moderate between-group effect was observed in the improvement of the first lactate threshold in the favor of the VOL-group, and in turn, a similar between-group effect favoring the INT-group was observed in the improvement of maximal treadmill performance. The observed changes were mainly in line with previous studies using a similar type of training approach [16,24]. Regarding the training intensity distribution, typically 80% LIT and 20% MOD/HIT are stated to be a recommendable basis for endurance athletes [25]. In the present study, both group's average value was quite close to that. However, certain types of training distribution, such as high training volume in the INT-group, or high amount of moderate and high-intensity sessions in the VOL-group, may have been unfavorable during the training period, because the training was individually scaled based on control period characteristics.

Different types of heart rate measures are widely used in endurance training monitoring [26], and resting HRV is particularly suggested to be a useful marker when assessing recovery [5]. While acute responses in HRV are mostly related to training intensity, and sessions above the first lactate threshold delays parasympathetic reactivation compared to low-intensity sessions below the first lactate threshold [27,28], long-term responses to different training strategies seem to be more complicated. In the present study, no systematic changes during the training period were observed in HRV neither in INT nor in VOL. At an individual level, both decreasing and increasing responses were observed, thus illustrating the individuality of HRV. It is important to notice that both an increase and a decrease in HRV may be a sign of fatigue and overreaching [29,30], which is why values outside the SWC-range in both directions could be a negative sign when monitoring recovery [13]. Plews et al. [15] have previously suggested that high-volume low-intensity training induces increases in HRV and positive changes in the balance of the autonomic nervous system. It is possible that in the present study, such findings were not found in VOL because the amount of the MOD- and HIT-training was quite high in some individuals (2–3 weekly sessions > first lactate threshold), and the total endurance training volume was much lower than in elite rowers training almost 20 h/week during high volume periods in the study by Plews et al. [15]. It is also important to note that HRV has mainly been studied during the morning measurements [15,29,30], which may induce different results compared to the nocturnal measurements. What can be said in favor of sleep time recordings is that they are not affected by external factors to the similar extent as awake recordings, thus theoretically allowing the most standardized period for the measurement [26]. In addition, sleep itself is a very important aspect of recovery [31] and therefore, HRV monitoring during sleep may provide additional information about the recovery process itself. While nocturnal recordings may have been challenging to implement frequently [26], wearable technology will most likely keep evolving, allowing more methods for feasible and valid assessments of HRV. It is probable that recreational athletes would especially prefer monitoring tools that would not require any extra effort or time.

Besides different recording times, multiple different variables could also be obtained from the heart rate measurements. A simple nocturnal heart rate reflects somewhat similar aspects of recovery as HRV [26]. Consequently, the heart rate has been affected acutely most by the intensity of the training [27], and after high-intensity interval exercise performed in the evening, responses in nocturnal heart rate may be even more severe than in HRV [32]. On the other hand, after long-term high-intensity training, heart rate may decrease significantly [19]. In the present study, the nocturnal heart rate slightly decreased in INT, and a significant difference between groups was also observed in the relative change from the control to the training period. Based on these and previous findings, the nocturnal heart rate may react more uniformly and sensitively to high-intensity training, both acutely [32] and in the long-term [19], compared to HRV when using nocturnal recordings. Whether this is associated with physiological factors such as changes in plasma volume or cardiac morphology [26] has yet to be studied.

Submaximal exercise tests are another typical way to estimate the training state [3] and adaptations [33] to endurance training. Maximal performance is very difficult to assess regularly without disturbing the normal training process, and therefore, endurance athletes need to settle for indirect and submaximal estimations of maximal performance, typically based on the relation between heart rate and running speed [17]. In the present study, the HR-RS index that was calculated from all continuous types of training sessions was used as an indirect estimation of endurance performance. Despite the improved maximal performance, no significant difference was observed between the control and training period in either of the groups. Previously, increments in the HR-RS index [17] and running speeds of the submaximal running tests [33] have both correlated with the change in maximal running performance. The lack of significant change in the present study may relate to the long averaging period (10 weeks) of the results. Since there possibly are some fluctuations in the HR-RS index due to changes in training load, sessions that are performed at the recovered state may predict changes in performance more accurately. One clear limitation in submaximal tests relying on heart rate is that similar to resting HRV, the same type of responses (decrease in submaximal heart rate) could be found after positive training adaptation [33] and during functional overreaching [29]. Another challenge in the HR-RS index is that environmental factors such as the amount of ascent during the session or outdoor temperature may both affect the relation between the heart rate and running speed. In the current study, only continuous sessions were used in the analysis similar to Vesterinen et al. [17]. As increased intensity improves the accuracy of indirect estimations of maximal endurance performance [33], methods that would allow estimations from high-intensity interval training could also be advantageous.

Neuromuscular characteristics play an essential role in distance running performance [34,35]. Especially in running, which induces high stress in the musculoskeletal tissues of the lower limbs, mechanical fatigue caused by training may also relate to overuse injuries [36]. It would therefore seem logical that maintaining or even improving neuromuscular performance would be of importance to endurance athletes. In the present study, the CMJ performance was monitored as an indicator of neuromuscular recovery once a week, similar to Balsabore–Fernandez et al. [14], who found that increased training load and running volume were associated with impaired CMJ during a 39-week follow-up study. Furthermore, the authors found that better CMJ was accompanied by better performance in running competitions. Bachero–Mena et al. [37] also found that during the competitive season, positive trends in both CMJ and running performance were observed in middle-distance runners. In the present study, no significant differences were found between or within the groups. However, based on the effect size of the observed changes, it seems that an increase in endurance training volume may have a slightly higher risk to impair neuromuscular performance than the increase in intensity of endurance training. The training of middle-distance runners [37] and high-level athletes [14] is likely more demanding for the neuromuscular system, and responses to training could, therefore, be more distinct compared to the population of the present study. It should also be evaluated in more detail whether there are more sensitive markers to monitor neuromuscular aspects of recovery in recreational runners, such as sprint tests or variables obtained from half-squat, which have reacted to changing training load in elite runners [38].

In addition to performance and physiological markers, recovery and training state could also be assessed from a subjective perspective. In the systematic review of Saw et al. [39], subjective markers were suggested to be more sensitive than objective measures to acute and chronic changes in the training load. Haaf et al. [40] have even argued that subjective markers could predict the overreaching state after a few days of intensive cycling event. In the current study, perceived recovery was monitored with a simple 0–10 scale [6]. Perceived recovery slightly decreased during the training period in VOL and tended to decrease in the INT, suggesting that an increased training load had at least a minor effect on the subjective feeling of recovery. Also, average session RPE increased in the INT, while in the VOL, it remained the same. Although the increase in RPE may relate to exercise-induced cumulative fatigue [41], in the present study the difference was probably mainly the outcome of the increased amount of high-intensity sessions. When comparing the results to previous studies, differences in the questionnaires that have been utilized may also explain the results. Although more comprehensive surveys could provide additional and more precise information about the recovery status of an athlete, a simple 0–10 scale [6] was used to allow monitoring of perceived recovery on a daily basis and with the setting that would be practical and realistic to utilise in long-term.

When the low-responders and responders were compared, none of the used monitoring variables were able to predict positive adaptation unequivocally, and especially at the beginning of the training period, no significant differences between the subgroups were found. However, at the end of the training period, an increase in the HR-RS index seemed to differentiate positive responders and low-responders in maximal running performance. Although no other marker exclusively differentiated low-responders from responders, several trends could most likely be stated as being unfavorable. Increased nocturnal HRV compared to the smallest worthwhile change (3 vs. 0 individuals), as well as decreased perceived recovery (4 vs. 1 individuals) and neuromuscular performance (5 vs. 3 individuals) were all more frequent observations among the low-responders than responders during the last mesocycle of the training period. The results of the current study most likely illustrate how the sensitivity of different monitoring variables response to variation in training load or fatigue may vary among individuals. Furthermore, interpretation of the results—what kind of change should be regarded as worthwhile—as well as the choice of the monitoring variables that may need to be evaluated individually [42]. One unsolved and somewhat critical question regarding the interpretation is how often individual reference values should be updated. Another important aspect is to ensure the quality of the data as well as the adequate frequency of the assessments of each variable. Rather than relying on one marker only, a multifaceted approach may help to contextualize observed patterns [30] improving the quality of the monitoring process.

Study Limitations

The study population consisted of recreationally trained endurance athletes with slightly varying training background and age. Further studies are needed to study the usefulness of similar monitoring variables in more specific populations (e.g., untrained and elite-level athletes) and with larger sample sizes. In the low-responder vs. responder comparison, both groups were combined because the small sample size did not allow meaningful separate analysis. However, no significant differences were found between the groups in the changes of monitoring variables or training adaptation so the current division most likely did not affect the outcome. The study was performed under field conditions so that the participants trained and performed recovery measures by themselves, not in the laboratory. The circumstances were different compared to the strict laboratory conditions. However, the present setting most likely represents the usefulness of the chosen monitoring variables well in practice.

5. Conclusions

In conclusion, current training periods of increased intensity or volume improved endurance performance to the similar extent, and nocturnal HR and perceived recovery were the only monitoring variables that were affected by the training, while no changes at a group level were observed in HRV or CMJ performance. Based on comparison between responders and low-responders, continuous monitoring of training-related parameters, such as the HR-RS index, may help to predict whether an individual is adapting to training. The sensitivity of the recovery-related variables may vary between individuals, and interpretations, as well as choice of appropriate markers, may therefore need a more individualized approach.

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Informed Consent Statement: Informed consent was obtained from all subjects involved in the study.

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III

PHYSIOLOGICAL, PERCEPTUAL, AND PERFORMANCE RESPONSES TO THE 2-WEEK BLOCK OF HIGH- VERSUS LOW-INTENSITY ENDURANCE TRAINING

by

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Physiological, Perceptual, and Performance Responses to the 2-Week Block of High- versus Low-Intensity Endurance Training

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[1]*Faculty of Sport and Health Sciences, University of Jyväskylä, Jyväskylä, FINLAND;* [2]*KIHU – Research Institute for Olympic Sports, Jyväskylä, FINLAND;* [3]*Institute of Public Health and Clinical Nutrition, University of Eastern Finland, Kuopio, FINLAND; and* [4]*Department of Internal Medicine, Central Finland Health Care District, Jyväskylä, FINLAND*

ABSTRACT

NUUTTILA, O.-P., A. NUMMELA, H. KYRÖLÄINEN, J. LAUKKANEN, and K. HÄKKINEN. Physiological, Perceptual, and Performance Responses to the 2-Week Block of High- versus Low-Intensity Endurance Training. *Med. Sci. Sports Exerc.*, Vol. 54, No. 5, pp. 851–860, 2022. **Purpose:** This study examined the physiological, perceptual, and performance responses to a 2-wk block of increased training load and compared whether responses differ between high-intensity interval (HIIT) and low-intensity training (LIT). **Methods:** Thirty recreationally trained males and females performed a 2-wk block of 10 HIIT sessions (INT, $n = 15$) or 70% increased volume of LIT (VOL, $n = 15$). Running time in the 3000 m and basal serum and urine hormone concentrations were measured before (T_1) and after the block (T_2), and after a recovery week (T_3). In addition, weekly averages of nocturnal heart rate variability (HRV) and perceived recovery were compared with the baseline. **Results:** Both groups improved their running time in the 3000 m from T_1 to T_2 (INT = −1.8% ± 1.6%, $P = 0.003$; VOL = −1.4% ± 1.7%, $P = 0.017$) and from T_1 to T_3 (INT = −2.5% ± 1.6%, $P < 0.001$; VOL = −2.2% ± 1.9%, $P = 0.001$). Resting norepinephrine concentration increased in INT from T_1 to T_2 ($P = 0.01$) and remained elevated at T_3 ($P = 0.018$). The change in HRV from the baseline was different between the groups during the first week (INT = −1.0% ± 2.0% vs VOL = 1.8% ± 3.2%, $P = 0.008$). Muscle soreness increased only in INT ($P < 0.001$), and the change was different compared with VOL across the block and recovery weeks ($P < 0.05$). **Conclusions:** HIIT and LIT blocks increased endurance performance in a short period. Although both protocols seemed to be tolerable for recreational athletes, a HIIT block may induce some negative responses such as increased muscle soreness and decreased parasympathetic activity. **Key Words:** BLOCK PERIODIZATION, RUNNING, ENDURANCE PERFORMANCE, HEART RATE VARIABILITY, NOREPINEPHRINE, MUSCLE SORENESS

The aim of the athletic training process is to produce adequate stimuli that would lead to positive training adaptations. In endurance training, the variables that are typically modified to induce desirable responses are the intensity, duration, and frequency of training (1). In long-term periodization, it seems necessary to perform high volumes of endurance training at low intensity (1). However, in short-term periodization, block periodization—altering focus between volume and intensity (2)—or polarized periodization—mixing low- and high-intensity training (3)—have both been suggested to be the most favorable training organization methods.

Block periodization protocols have typically focused on high-intensity interval training (HIIT) consisting of 1- to 3-wk microcycles of multiple weekly or even daily high-intensity sessions (4). On the other hand, studies examining the effects of high-volume microcycles have most often included overload periods increasing both low- and high-intensity training volume (5). The length of the periods has varied predominantly between 2 and 6 wk, during which training volume has been increased by 30%–100% from the volume previously used by an individual (6–9). High-intensity and high-volume endurance training periods have mainly been studied separately, but possible differences in the physiological, perceptual and performance responses are not well established.

When there is a substantial increase in training load from the previous load, there is also an increased risk of injuries (10) and maladaptation or overreaching (5). To avoid such consequences, it would be critical to detect early signs that may predict compromised training adaptations. Monitoring of training and recovery typically consists of regular assessments of physiological,

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perceptual, or performance-related markers that are estimated to provide valuable information about the recovery and training state of an athlete (11). On one end of the monitoring tool spectrum are extensive laboratory tests, such as hormonal or biochemical examinations from blood or urine (6,12), whereas perceptual markers such as subjective surveys (13,14) or session RPE (15) represent the other end of the spectrum. In addition, noninvasive assessments of physiological markers, like heart rate variability (HRV) recordings at rest (16), heart rate (HR) during exercise (17), and performance-related markers such as various jumping tests (18), could be used in monitoring. The purpose of the monitoring process is to follow whether an athlete is adapting to the stimulus as expected and to influence decisions for the forthcoming training load (18) or session intensity (16,17).

Although monitoring has clear advantages during the training process, previous studies have disclosed several contradictions and limitations, especially regarding responses of physiological markers. In the case of submaximal HR and resting HRV, it is a well-known dilemma that a similar type of response may be observed after both a positive training adaptation and in the state of parasympathetic hyperactivity, which is associated with a decrease in maximal performance (8,19). Furthermore, plasma volume expansion may, at least acutely, affect HRV (20), regardless of the recovery state. Resting levels of catecholamines, which correlate with sympathetic nervous system activity, have previously been reported as unchanged in female endurance athletes (7) and male triathletes (21) but decreased in well-trained runners (6) after an intensified training period. In the same studies, acute responses of catecholamines to maximal exercise have also varied between unchanged (6,21) and decreased (7,21) after a period of intensified training. It has been suggested that, in general, hormonal responses to maximal exercise may be altered more than resting levels in the overtraining state (12), making regular hormonal assessments in athletes rather difficult. Acknowledging these challenges with physiological markers, subjective estimations of recovery may provide valuable "triangulating" information that improves interpretation of athlete status during training (13,14) and helps to contextualize complicated physiological changes (19).

The aim of the present study was to examine the physiological, perceptual, and performance responses to blocks of increased training load, and to compare whether these responses would differ between high-volume low-intensity training (LIT) and HIIT periods in recreationally trained male and female participants. Another aim was to explore whether training adaptation would be associated with the responses of the monitoring variables. We hypothesized that both types of training blocks would improve endurance performance after the recovery week but induce acute fatigue immediately after the training period, observed as decreased or unchanged performance and impaired perceptual recovery (8,19).

METHODS

Participants

A total of 40 recreationally endurance-trained male and female runners were recruited to participate voluntarily in the study. Participants were 20–45 yr old, healthy, and experienced in regular running training (>4 times per week). A cardiologist checked electrocardiography of all potential participants before the final acceptance to participate. One participant dropped out before any measurement because of difficulties with the timetable. In addition, six participants dropped out because of sicknesses ($n = 2$) or injuries ($n = 4$) that occurred during the preparatory period or at the beginning of the training period. From the participants that finished the whole study period, one participant was excluded from the final analysis because of insufficient training adherence (<90%/main sessions), and two participants for not following the training instructions during the preparatory or recovery periods. Baseline characteristics of the participants that were included in the final analysis ($n = 30$) are presented in Table 1. All participants gave their written consent to participate, and the study protocol was approved by the ethics committee of the University of Jyväskylä.

Study Protocol

The study consisted of four separate phases similar to the protocol used by Le Meur et al. (8): a 2-wk preparatory period (phase 1), the first recovery week (phase 2), a 2-wk training period (phase 3), and the second recovery week (phase 4). Participants were advised to continue their regular training in terms of volume during the preparatory period and to decrease training volume by 50% in the following recovery week. To ensure a similar training intensity distribution before the training intervention, participants were asked to train below the first lactate threshold, excluding one HIIT session (6 × 3 min), which was performed to familiarize participants with the interval protocol. At the end of the preparatory period, participants were matched into pairs based on sex, 3000-m performance, v_{max}, and baseline HRV, and divided into the interval group (INT) or volume group (VOL). During the 2-wk training period, the INT group performed a total of 10, 6 × 3-min HIIT sessions (5 sessions per week), whereas the VOL group increased their low-intensity running volume (h) by 70%. Proper training load for the HIIT and VOL protocols was estimated based on previous studies examining HIIT shock microcycles (4) or volume-based overload periods (6–8). After the 2-wk training period, a similar recovery week as the first was prescribed.

TABLE 1. Mean ± SD baseline characteristics of the participants.

	INT (n = 15)	VOL (n = 15)
Sex (male/female)	9/6	9/6
Age (yr)	33 ± 7	37 ± 7
Height (cm)	172 ± 10	174 ± 11
Body mass (kg)	72 ± 14	71 ± 13
v_{LT1} ($km \cdot h^{-1}$)	10.8 ± 1.2	10.7 ± 1.4
v_{LT2} ($km \cdot h^{-1}$)	13.3 ± 1.7	13.0 ± 1.6
v_{max} ($km \cdot h^{-1}$)	16.6 ± 1.8	16.4 ± 1.8
$\dot{V}O_{2max}$ ($mL \cdot kg^{-1} \cdot min^{-1}$)	50.4 ± 6.9	49.7 ± 6.4
3000 m (min:s)	12:29 ± 1:36	12:34 ± 1:35

INT, interval group; VOL, volume group; v_{LT1}, running speed at the first lactate threshold; v_{LT2}, running speed at the second lactate threshold; v_{max}, maximal speed of the incremental treadmill test; $\dot{V}O_{2max}$, maximal oxygen uptake. Baseline characteristics were measured before the preparatory period (T_0).

APPLIED SCIENCES

Performance in the 3000 m and countermovement jump (CMJ) were measured, and fasting blood and urine samples were taken and analyzed before the preparatory period (T_0), in the middle of the first recovery week (T_1), 1 d after the intensified training period (T_2), and after the second recovery week (T_3). An incremental treadmill test was performed once in the same week as the other T_0 tests to analyze lactate thresholds (LT1 and LT2) and individual training intensity zones among the participants. A day of rest was always prescribed before testing days. Training and recovery were monitored with multiple markers throughout the study.

Training Protocol

Both groups had five main sessions per week, which were supervised and performed individually at the same time of the day (±2 h) during the morning or afternoon and at the same outdoor road/track, which was tight gravel (INT) or about 50/50 combination of gravel and asphalt (VOL). The INT group performed all the sessions as 6 × 3-min intervals, whereas the VOL group performed only low-intensity sessions below the first lactate threshold. If participants performed more than five sessions during the preparatory period, these sessions were also incorporated into the training period as low-intensity training with the same duration (INT) or with increased duration (VOL) to match the requirement of the volume increment. In case participants were accustomed to alternative endurance training modes such as cycling, these modes were incorporated as part of the additional sessions with similar proportion to the preparatory period.

Interval session. HIIT session was a 6 × 3-min interval with 2-min active recovery (walking). Intervals were performed at the maximal sustainable effort (22). Before the session, a 15-min warm-up, including three 30-s accelerations to the target speed, was performed. After the session, a 10-min cooldown was prescribed. Average running speed and HR were calculated separately for each interval and for the entire session, and a session RPE score was reported after each session (15).

Low-intensity sessions. The VOL group performed four similar basic sessions (85%–95% HR of the LT1) and one long-distance session (75%–90% HR of the LT1) in a week. The aim was to increase the duration of running sessions compared with preparatory period. The duration of these sessions was individually scaled based on the training during the preparatory period. The basic session was planned to be approximately 1.50× the average session duration during the preparatory period (1:22 ± 0:10 h:min), whereas the long-distance session was 1.66× the duration of the basic session (2:16 ± 0:16 h:min). Average running speed, average HR, and HR running speed index (HR-RS index) (23) were calculated from all supervised sessions. In addition, session RPE was estimated after all sessions (15).

Performance Tests

An incremental treadmill test was performed on a treadmill (Telineyhtymä Oy, Kotka, Finland). The starting speed was set to 7 or 8 $km \cdot h^{-1}$ for women and 8 or 9 $km \cdot h^{-1}$ for men. Three-minute stages and speed increments of 1 $km \cdot h^{-1}$ were used. After each stage, the treadmill was stopped, and participants stood still for the fingertip blood lactate samples, which took approximately 15–20 s. Incline was kept constant at 0.5° throughout the test. Oxygen consumption was measured breath by breath (Jaeger VyntusTM CPX, CareFusion Germany 234 GmbH, Hoechberg, Germany), and HR was monitored with Garmin Forerunner 245 M (Garmin Ltd., Schaffhausen, Switzerland). Maximal oxygen uptake ($\dot{V}O_{2max}$, $mL \cdot kg^{-1} \cdot min^{-1}$) was defined as the highest 60 s average of oxygen consumption. Maximal running speed (v_{max}) of the test was defined as the highest completed speed, or if the stage was not finished, as a speed of the last completed stage ($km \cdot h^{-1}$) + (running time (s) of the unfinished stage – 30 s)/(180–30 s) × 1 $km \cdot h^{-1}$. The first lactate threshold (LT1) and the second lactate threshold (LT2) were determined based on lactate values during the test. The LT1 was set at 0.3 $mmol \cdot L^{-1}$ above the lowest lactate value and LT2 at the intersection point between 1) a linear model between LT1 and the next lactate point and 2) a linear model for the lactate points measured after the point when La increased at least 0.8 $mmol \cdot L^{-1}$ for the first time. The same treadmill and lactate threshold estimation protocols have been used in previous studies (16,24,25).

The 3000-m running test was performed on a 200-m indoor track. Before the test, 15-min low-intensity warm-up was performed, including 3 × 20–30 s accelerations to target pace at the latter part of the warm-up. Verbal encouragement and split times (1000 m, 2000 m) were given for all participants during the test. The test was run in small groups (maximum seven persons). All test attempts were performed individually at the same time of the day (±2 h) during the afternoon or evening.

The CMJ test was performed before supervised sessions and before the 3000-m running tests. In the test, participants performed three maximal attempts on a contact mat with a 1-min recovery. The test was performed after a standardized warm-up, including a short jog (~3 min) and two sets of different kinds of squats (half squat, lunge, and squat jump). Jump height (h) was calculated based on the measured flight time with the following formula: $h = g \times t^2 \times 8^{-1}$, where t is the recorded flight time in seconds and g is the acceleration due to gravity (9.81 $m \cdot s^{-2}$) (26). The highest jump height (cm) was used in the data analysis.

Blood and Urine Samples

Fasting blood samples were taken after 12 h of fasting and individually at the same time of the day (7:00–9:15 AM). Blood samples were taken in a seated position from the antecubital vein into 6 mL serum tubes using standard laboratory procedures. Whole blood was centrifuged at 2250g (Megafuge 1.0 R, Heraeus, Hanau, Germany) for 10 min, and the separated serum was removed and frozen at −20 C until analysis. Serum cortisol concentration was analyzed with a chemical luminescence technique (Immulite 2000 XPi, Siemens, New York City, NY). The sensitivity of the cortisol assay was 5.5 $nmol \cdot L^{-1}$, and the intra-assay coefficient of variation was 5.3%. Free testosterone concentration was analyzed with ELISA (DYNEX DS 2 ELISA processing system, DYNEX Technologies, Chantilly, VA). The sensitivity of the free testosterone assay was 0.6 pmol·L^{-1}, and the intra-assay coefficient of variation was 6.0%. Serum creatine kinase activity was analyzed with Indiko Plus Clinical Chemistry Analyzer (Thermo Fisher Scientific, Vantaa, Finland). The sensitivity of the creatine kinase assay was 2.2 U·L^{-1}, and the intra-assay coefficient of variation was 0.9%. Hemoglobin and hematocrit were analyzed with an automated hematology analyzer (Sysmex XP-300TM, Sysmex Inc., Kobe, Japan). Plasma volume was estimated from the obtained hematocrit and hemoglobin values based on the equation of Dill and Costill (27).

Urine sample collection was performed between 1900 and 0700 h during the night before fasting samples were taken. Participants were asked to document the accurate starting and ending times of the collection. After bringing the sample to the laboratory, the urine volume was determined. For the analysis of norepinephrine, a 10-mL sample was frozen at −20°C. The concentrations of hormones in the sample were assessed by the liquid chromatography (HPLC) method (Labor Dr. Kramer & Kollegen, Geesthacht, Germany). The intra-assay coefficient of variation for the norepinephrine was 2.0%. Because of slight differences in collection times, the concentration of hormones in the urine sample was multiplied by the volume of the whole urine, then divided by the collection time in hours, and multiplied by 12 to represent a similar 12-h collection time for all participants similar to Hynynen et al. (28).

Training and Recovery Monitoring

Participants wore an HR monitor (Garmin Forerunner 245 M) during all endurance training sessions. HR and GPS data (distance covered, running speed) were analyzed from all sessions. Training intensity distribution was analyzed with a time in zone model (HR_{zone1}, HR < LT1; HR_{zone2}, HR = LT1–LT2; HR_{zone3}, HR > LT2). Participants wrote in the training log basic information of each session performed and estimated session RPE on a 0–10 scale (15).

Nocturnal HR and HRV were recorded with the Firstbeat Bodyguard 2 device (Firstbeat Technologies LTD, Jyväskylä, Finland). Participants were advised to start recording when going to sleep and stop the recording right after awakening. Recordings were performed every night starting from the first recovery week. Recorded RR intervals were edited by an artifact detection filter within the Firstbeat Sports software, which excluded all falsely detected, missed, and premature heartbeats. If the error percentage representing the number of corrected interbeat intervals shown by the software was higher than 33%, recordings were excluded from the analysis, as suggested by Vesterinen et al. (24). One participant in the VOL group had a high amount of erroneous data (error percentage >33% more than 50% of the recorded nights) and was excluded from the nocturnal analysis. Average HR, natural logarithm of high-frequency power (lnHF), and natural logarithm of the root-mean-square of the successive differences (lnRMSSD) were analyzed from the sleep period of 0030–0430 h after going to bed. High intraclass correlation coefficients of 0.97 and 0.91 have been reported in HR and HF, respectively, when 4-h averages have been compared between two consecutive nights after a similar training day (29). Weekly average values were used as suggested by Le Meur et al. (8): Pre, recovery week preceding the training period; Week1, first week of the training period; Week2, second week of the training period; Week3, recovery week after the training period.

Participants filled out daily questionnaires on a 0–10 visual analog scale (VAS) regarding estimated readiness to train, sleep quality of the previous night, general fatigue, muscle soreness of lower extremities, and perceived stressfulness during the day. Questionnaires were modified from the previous studies (13,14). Results were averaged similarly to nocturnal HR and HRV results.

Statistical Analysis

Results are presented as mean ± SD. Before performing the final analysis, we determined if the magnitude of changes in the main variables differed between sexes (Kruskal–Wallis test). No significant differences were found; thus, female and male participants were analyzed in combined groups. The normality of the data was assessed with the Shapiro–Wilk test. To examine the main effects (time, group) and their interaction (time–group) in the monitoring variables (Pre, Week1, Week2, and Week3), performance or laboratory tests (T_0, T_1, T_2, T_3), and training characteristics of the main sessions (1st vs 2nd–10th sessions), repeated-measures ANOVA was applied. In the case of a significant main effect or interaction, a Bonferroni *post hoc* test was used for within-group comparisons and simple contrasts for between-group comparisons. Training characteristics (frequency, volume, running kilometers, and training intensity distribution), creatine kinase, and free testosterone results were not normally distributed; thus, the Wilcoxon signed rank test was used for comparisons between time points and the Mann–Whitney *U*-test for between-group comparisons, with Bonferroni correction (*P* values multiplied by the number of comparisons). To examine the magnitude of observed changes, the effect size (ES) of within-group absolute differences was calculated as Cohen's *d* for the main variables, and after nonparametric tests by the following formula: $ES = Z(\sqrt{n})^{-1}$, where Z is the z-score, and n is are the number of observations on which Z is based. The magnitude of changes was categorized as <0.2 trivial, 0.2–0.5 small, 0.5–0.8 moderate, and >0.8 large. In addition, the Pearson correlation coefficient was used to analyze relationships between the monitoring variables (absolute values at Week2, changes from Pre to Week2 or changes from 1st session to 10th session) and changes in the 3000-m running speed (km·h^{-1}, T_1–T_2 Δ%, T_1–T_3 Δ%). The statistical significance level was set to $P < 0.05$. Analyses were performed with

TABLE 2. Mean ± SD average weekly training characteristics during the 2-wk preparatory and the 2-wk training periods of high-intensity (HIIT block) or low-intensity training (LIT block).

	INT (n = 15)		VOL (n = 15)	
	Preparatory	HIIT Block	Preparatory	LIT Block
Training volume (h)	5.8 ± 1.7	5.2 ± 1.1	5.4 ± 2.1	9.0 ± 3.4**
Training frequency per week	5.6 ± 1.4	5.8 ± 1.3	5.3 ± 1.9	5.9 ± 1.8*
Running volume (km)	45.8 ± 12.6	49.8 ± 9.3	44.6 ± 14.7	77.0 ± 22.7**
HR_{zone1} (%)	91.5 ± 5.7	61.9 ± 7.0**	92.2 ± 3.9	99.6 ± 0.7**
HR_{zone2} (%)	6.3 ± 4.7	18.4 ± 6.0**	5.4 ± 2.9	0.4 ± 0.7**
HR_{zone3} (%)	2.2 ± 2.6	19.7 ± 5.2**	2.4 ± 1.7	0.0 ± 0.0**

*P < 0.05, **P < 0.01 compared with the preparatory period.
INT, intensity group; VOL, volume group; HR_{zone1}, HR below the first lactate threshold; HR_{zone2}, HR between the first and the second lactate threshold; HR_{zone3}, HR above the second lactate threshold.

Microsoft Excel 2010 (Microsoft Corporation, WA) and IBM SPSS Statistics version 26 programs (SPSS Inc, Chicago, IL).

RESULTS

Training. The INT group increased the weekly training volume at HR_{zone2} by 32 ± 22 min and at HR_{zone3} by 55 ± 17 min from the preparatory to the training period, whereas the VOL group increased training volume by 68% ± 5% and running distances by 76% ± 25% (Table 2). Both groups performed lower training volume (P < 0.01) compared with the preparatory period during the first (INT = 2.9 ± 1.1, VOL = 2.7 ± 1.2 h) and the second recovery weeks (INT = 2.9 ± 1.1 h, VOL = 2.9 ± 1.5 h), and only LIT, except for the 3000-m running test, was reported during the recovery weeks.

Performance and session RPE values of all main sessions are presented in Figure 1. In the VOL group, average running speed and distance covered were 9.8 ± 1.5·h^{-1} and 13.5 ± 3.0 km in the basic sessions and 9.1 ± 1.5 km·h^{-1} and 21.0 ± 4.7 km in the long-distance sessions, respectively. In the INT group, the average HR during the intervals decreased (P < 0.05) from the first session (90.7% ± 1.8% HR_{max}) to the 6th, 7th, 9th, and 10th sessions (88.1%–88.6% HR_{max}). In the VOL group, the average HR remained similar within-session type and was on average 72.6% ± 4.9% HR_{max} during the basic sessions and 69.0% ± 4.5% HR_{max} during the long-distance sessions.

Physical performance. A significant main effect of time (P < 0.001) was observed in the 3000-m running time as well as HR_{avg} (P = 0.004) and HR_{peak} (P < 0.001) measured during the test (Table 3). In addition, a significant time–group interaction (P < 0.001) was found in HR_{avg} and HR_{peak}. Both groups improved the 3000-m running time from T_1 to T_2 (INT, P = 0.003; VOL, P = 0.017) and from T_1 to T_3 (INT, P < 0.001; VOL, P = 0.001) (Fig. 2). No significant main effects nor interaction was observed in the CMJ performance, which was tested before the 3000-m tests (Table 3) or in the tests that were performed before the supervised sessions during the training period (INT, lowest mean = 31.9 ± 5.5 vs highest mean = 32.4 ± 5.1 cm; VOL, lowest mean = 31.0 ± 5.8 vs highest mean = 31.6 ± 6.0 cm).

Physiological responses. A significant main effect of time was observed in hemoglobin (P < 0.001), hematocrit (P = 0.001), and norepinephrine (P < 0.001) (Table 4). In addition, a significant increase was observed in CK activity of VOL from T_1 to T_2 (P = 0.036). Norepinephrine increased in INT from T_1 to T_2 (P = 0.01) and remained elevated in T_3 (P = 0.018). Hemoglobin concentration (P = 0.011) and hematocrit (P = 0.037) decreased from T_1 to T_2 in VOL, whereas hemoglobin tended to decrease from T_1 to T_2 (P = 0.065) and increased from T_2 to T_3 (P = 0.029) in the INT group. When plasma volume changes were estimated based on hemoglobin and hematocrit values, T_1–T_2 changes translated to 4.3% ± 5.0% and 5.1% ± 6.7% expansion in the plasma volume of INT and VOL, respectively.

A significant main effect of time (P = 0.001) was found in nocturnal HR, and a significant time–group interaction was found in nocturnal HR (P = 0.001), nocturnal lnHF (P = 0.036) (Fig. 3), and nocturnal lnRMSSD (P = 0.027). Nocturnal HR decreased in INT from Pre to Week3 (P = 0.002, ES = −0.36) and from Week2 to Week3 (P < 0.001, ES = −0.30). Changes in HR from Pre to Week1 (INT = 1.9% ± 4.0% vs VOL = −1.6% ± 5.1%, P = 0.045) and from Week2 to Week3 (INT = −3.8% ± 3.2% vs VOL = 0.1 ± 2.9, P = 0.003) were different between the groups. In lnHF, no significant within-group changes were found, but change from Pre

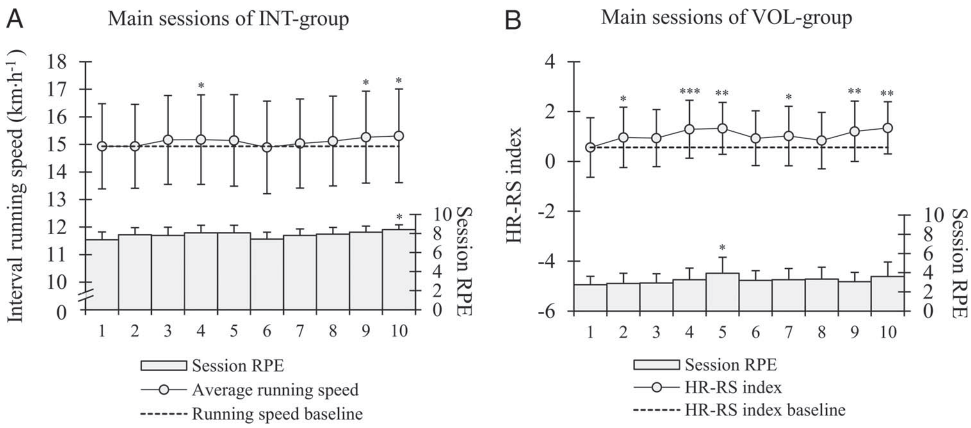

FIGURE 1—A, Mean ± SD average running speed during the 6 × 3-min intervals performed at maximal sustainable effort, and session RPE of each interval session prescribed. B, Mean ± SD HR-RS index and session RPE of basic (1–4,6–9) and long-distance (5,10) LIT sessions prescribed. *P < 0.05, **P < 0.01, ***P < 0.001 compared with the first session.

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TABLE 3. Mean ± SD average performance test results before the 2-wk training period (T_1), immediately after the training period (T_2), and after a recovery week (T_3).

	INT (n = 15)			VOL (n = 15)		
	T_1	T_2	T_3	T_1	T_2	T_3
3000 m (min:s)	12:19 ± 1:32	12:06 ± 1:32**, ES = −0.14	12:00 ± 1:27***, ES = −0.21	12:33 ± 1:33	12:22 ± 1:30*, ES = −0.12	12:16 ± 1:29**, ES = −0.18
HR_{avg} (%/max)	94.3 ± 2.4	92.2 ± 2.6***,##, ES = −0.85	93.8 ± 2.2#,a, ES = −0.24	94.7 ± 2.1	94.9 ± 2.1, ES = 0.08	95.3 ± 2.2, ES = 0.33
HR_{peak} (%/max)	99.4 ± 1.9	96.6 ± 2.4***,###, ES = −1.29	98.1 ± 1.7**,##,a, ES = −0.71	98.9 ± 2.3	99.9 ± 2.6, ES = 0.40	99.9 ± 2.3, ES = 0.45
CMJ (cm)	33.0 ± 6.2	32.6 ± 5.6, ES = −0.07	33.5 ± 5.5, ES = 0.09	32.6 ± 6.4	33.1 ± 5.9, ES = 0.07	33.1 ± 6.1, ES = 0.08

*$P < 0.05$, **$P < 0.01$, ***$P < 0.001$ within-group changes compared with T_1.
#$P < 0.05$, ##$P < 0.01$, ###$P < 0.001$ between-group changes compared with T_1.
[a]Difference observed from T_1 to T_2 and T_2 to T_3.
INT, intensity group; VOL, volume group; HR_{avg}, average HR of the 3000-m running test in relation to the maximum HR of the incremental treadmill test; HR_{peak}, peak HR of the 3000-m running test in relation to the maximum HR of the incremental treadmill test; CMJ, countermovement jump test; ES, effect size of the changes from T_1.

to Week1 was different between the groups (INT = −1.0% ± 2.0% vs VOL = 1.8% ± 3.2%, P = 0.008). The same pattern was observed in lnRMSSD, which remained unaffected through the training and recovery weeks in INT (4.18 ± 0.52 ms vs 4.14 ± 0.50, 4.21 ± 0.48 and 4.24 ± 0.42 ms) and VOL (4.03 ± 0.43 ms vs 4.10 ± 0.40, 4.06 ± 0.42 and 4.05 ± 0.41 ms), but change from Pre to Week1 differed between the groups (P = 0.014).

Perceptual responses. A significant main effect of time was found in muscle soreness (P < 0.001), and a significant time–group interaction was found in the readiness to train (P = 0.008) and muscle soreness (P = 0.001) (Fig. 4). Readiness to train decreased in INT from Pre to Week3 (P = 0.045, ES = −0.57) and tended to decrease from Pre to Week2 (P = 0.057, ES = −0.72). In addition, the change in readiness to train from Pre to Week3 was different between the groups (P = 0.002). Muscle soreness increased in INT (P < 0.001) from Pre to Week1 (ES = 0.86) and Week2 (ES = 0.94), and the change was different between the groups from Pre to Week1 (P < 0.001), Week2 (P = 0.012), and Week3 (P = 0.001).

Relationships between monitoring variables and changes in endurance performance. A significant positive correlation was found between the relative change in average running speed from 1st to 10th interval session and relative change in the 3000-m running speed from T_1 to T_2 in INT (r = 0.656, P = 0.008). In VOL, a tendency for negative correlation was found between the change in HR-RS index from 1st to 10th low-intensity session and relative change in the 3000-m running speed from T_1 to T_2 (r = −0.510, P = 0.052). In addition, the relative change in the nocturnal HR from Pre to Week2 correlated positively with the relative change in the 3000-m running speed from T_1 to T_3 in VOL (r = 0.538, P = 0.047). Among the perceptual markers and INT group, muscle soreness at Week2 correlated negatively (r = −0.564, P = 0.028), and change in the readiness to train from Pre to Week2 correlated positively (r = 0.529, P = 0.043) with the relative change in the 3000-m running speed from T_1 to T_2. The change in the stress from Pre to Week2 was the only marker that correlated significantly with the relative change in the 3000-m running speed from T_1 to T_3 in INT (r = 0.637, P = 0.011). When groups were pooled, fatigue (r = −0.449, P = 0.013) and muscle soreness (r = −0.375, P = 0.041) at Week2 both correlated negatively with the relative change in the 3000-m running speed from T_1 to T_2. Full results of all correlation analyses are presented in Supplementary Table 1 (see Table, Supplemental Digital Content 1, Pearson correlation coefficient between monitoring variables and relative change in the 3000-m running speed, http://links.lww.com/MSS/C488).

DISCUSSION

The main findings of the study were that 2-wk blocks of HIIT or LIT both improved the 3000-m running performance, and no differences were found between the groups in the training adaptations. Based on physiological and perceptual responses during the blocks, both periods could be tolerable for recreational athletes, although the HIIT block induced some negative responses compared with the LIT block, such as increased muscle soreness and decreased HRV. Running speed during the interval sessions and resting-state perceptual

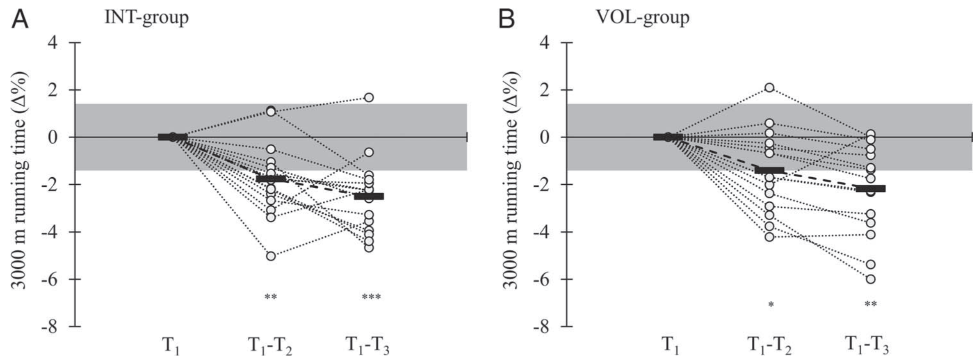

FIGURE 2—Relative individual (*white plots*) and mean changes (*black rectangle*) in the 3000-m running time immediately after the 2-wk training period (T_1–T_2) and after a recovery week (T_1–T_3). The *gray* area represents the smallest worthwhile change area (±1.41%), which was the coefficient of variation between T_0 and T_1 tests. *P < 0.05, **P < 0.01, ***P < 0.001 compared with T_1.

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TABLE 4. Mean ± SD average blood and urine sample results before the 2-wk training period (T_1), immediately after the training period (T_2), and after a recovery week (T_3).

	INT			VOL		
	T_1	T_2	T_3	T_1	T_2	T_3
Cor (nmol·L^{-1})	422 ± 88	419 ± 80, ES = −0.03	442 ± 115, ES = 0.20	410 ± 106	459 ± 88, ES = 0.51	465 ± 111, ES = 0.51
Ftesto (pmol·L^{-1})	40.4 ± 27.2	40.6 ± 26.0, ES = 0.00	42.9 ± 28.1, ES = 0.02	35.7 ± 23.3	36.0 ± 26.0, ES = 0.00	39.5 ± 26.2, ES = 0.04
CK (μmol·L^{-1})	103 ± 64	124 ± 53, ES = 0.09	122 ± 130, ES = 0.08	107 ± 35	178 ± 102*, ES = 0.52	126 ± 78, ES = 0.13
Hb (g·L^{-1})	140 ± 9	136 ± 10, ES = −0.37	140 ± 9*^{,a}, ES = 0.03	145 ± 12	141 ± 11*, ES = −0.36	143 ± 13, ES = −0.16
Hct (%)	42.3 ± 2.7	41.4 ± 3.0, ES = −0.33	42.7 ± 2.8, ES = 0.13	43.8 ± 3.1	42.8 ± 2.7*, ES = −0.35	43.3 ± 2.9, ES = −0.18
NE (μmol)	0.11 ± 0.04	0.15 ± 0.04*, ES = 0.91	0.15 ± 0.04*, ES = 1.03	0.12 ± 0.05	0.13 ± 0.05, ES = 0.19	0.15 ± 0.06, ES = 0.53

*$P < 0.05$, **$P < 0.01$ compared with T_1.
[a]Difference observed from T_2 to T_3.
INT, intensity group; VOL, volume group; Cor, serum cortisol concentration; Ftesto, serum-free testosterone concentration; CK, serum creatine kinase activity; Hb, hemoglobin concentration; Hct, hematocrit fraction; NE, urine norepinephrine concentration; ES, the effect size of the changes from T_1.

recovery seemed to be useful monitoring tools for acute responses to intensified training blocks.

Training and performance. HIIT microcycles have previously been examined mainly by 1- to 3-wk periods of >4 HIIT sessions (4), whereas typical volume periods have increased training volume by 30%–100% for 2–6 wk (6–9). The current protocols were chosen to produce a significant but tolerable increase in the training load via either training intensity or training volume, but not at the same time. The 3000-m running performance improved in both groups already at T_2, but no significant differences were found after the recovery week between T_2 and T_3. Therefore, the training load seemed to be suitable on average, and neither of the blocks induced significant acute fatigue at group level. It has been suggested that LIT training would more likely lead to positive (30) or very positive (31) training adaptations compared with HIT training. The present results did not support these findings, at least among the block periodization, as peak performance improved more than the coefficient of variation of the 3000-m test out of 14/15 participants in the INT and 9/15 in the VOL groups. Although both of the current 2-wk block protocols induced significant improvements in endurance performance, previous studies suggest that a combination of HIT and LIT may be needed for the optimal long-term development of endurance capacity (1,3).

After overload protocols, positive training adaptation is typically delayed because of acute fatigue or overreaching effect (5). Previously, after the high-volume 3-wk overload period, peak performance has been obtained after a 2-wk taper (9). After a high-frequency 3-wk HIIT period, the peak performance was achieved after 12 d (32). From this perspective, it was interesting that 4/15 participants of the INT group impaired their running performance after the recovery week, whereas there was only one clear impairment in the VOL group. This could partially relate to tapering, which included no HIIT sessions. Although the intensity is suggested to be maintained in optimal tapering (33), no HIIT sessions were prescribed to allow a similar recovery week for both groups in the present study. Therefore, it may be possible that some individuals have experienced some type of detraining effect after the low-volume and low-intensity recovery week.

Although the performance improved similarly in both groups immediately after the training period, peak and average HR during the running test decreased only in the INT group, and peak HR remained decreased at T_3. This may relate to decreased activity of the sympathetic nervous system via a reduced adrenergic response during exercise (21) or the down-regulation of β-adrenoreceptors (34) due to repetitive training at high intensity. A similar trend was observed during the intervals, where average HR decreased, especially during the second week of the training period, despite maintained or even increased running speed. It would be interesting to know whether the decrement was compensated with improved cardiac stroke volume, which has occurred after various HIIT protocols (32,35). Based on previous studies of volume overloads (6,8), it was expected that the LIT block would also decrease HR in the 3000-m tests, possibly by increased blood volume (36) and parasympathetic hyperactivity (8). Lack of changes in the VOL group could partially be related to the lower absolute training volumes of recreational athletes compared with previous studies of well-trained athletes (6,8).

Physiological and perceptual responses to training. Although studies targeting overload may provide

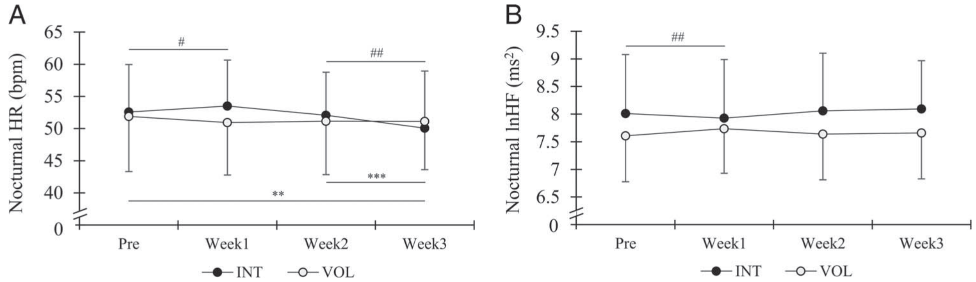

FIGURE 3—Mean ± SD average weekly nocturnal HR (A) and lnHF (B) at baseline (Pre), during the training period (Week1 and Week2), and recovery week (Week3). INT, interval group; VOL, volume group. **$P < 0.01$, ***$P < 0.001$ compared with respective time points in INT. #$P < 0.05$, ##$P < 0.01$, between-group changes compared with respective time points.

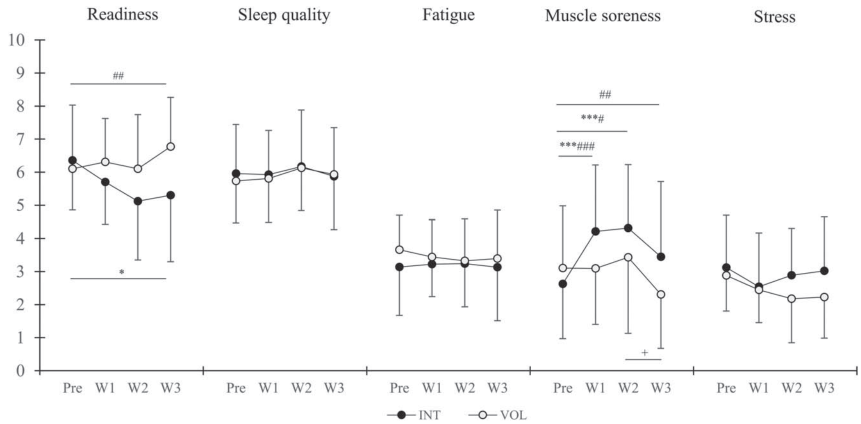

FIGURE 4—Mean ± SD average weekly values of perceptual recovery at baseline (Pre), during the training period (W1 and W2), and recovery week (W3). INT, interval group; VOL, volume group. *P < 0.05, **P < 0.01, ***P < 0.001 compared with Pre in INT. $^{\#}P$ < 0.05, $^{\#\#}P$ < 0.01, $^{\#\#\#}P$ < 0.001 between-group changes compared with Pre. $^{+}$Compared with the previous week in VOL.

information regarding the state of overreaching, the effects of the increased volume or intensity *per se* seem to remain unsolved. It is possible that physiological responses to intensified training periods have varied depending on the method of increasing training load. In the current study, the only significant change in hormonal markers was found in the resting norepinephrine concentration, which increased in INT and remained elevated also after the recovery period. The finding somewhat contradicted previous studies, which have shown that resting values either remained similar (7,21) or decreased after intensified training (6). Based on the increase in resting norepinephrine and the decrease in peak HR during the 3000-m test after a demanding block of frequent HIIT training, a longer recovery period may be advisable to restore normal autonomic nervous system function at rest and during exercise. From the other biomarkers, creatine kinase increased in VOL at T_2, whereas it was anticipated that HIIT block would also increase CK concentration (37,38). It is possible that the higher training volume of VOL, as well as a long-distance session 2 d before the CK assessment, may have induced more structural damage in the musculoskeletal tissue compared with HIIT. Previously, Quinn and Manley (39) observed elevated CK values even 72 h after a 26-km run at 60%–75% HR_{max}, which was similar to the long-distance session of the VOL group performed in the present study.

Resting HRV is a marker used to analyze the restoration of cardiovascular homeostasis and the stress/recovery state in general (40). Although increments in HRV are typically a positive sign of the increased parasympathetic activity and a good state of recovery (40), the so-called parasympathetic hyperactivity is an abnormal response to a sudden increase in training load (8,19). Previously, overload microcycles have induced significant increases in HRV with the concurrent increase of fatigue (8,19). In the current study, no significant changes in HRV were found, although the response to the first week differed between the groups (a slight decrease in INT vs an increase in VOL). It seems that the parasympathetic hyperactivity may be related to the overreaching/fatigue state itself rather than to the increased training load, as fatigue was not increased at the group level in the current study. The HRV response to the increased training load, an increase or decrease, seems to be individual, despite the type of training (25). Interestingly, nocturnal HR decreased significantly during the recovery period in the INT group, with no changes at any week in VOL. Similar findings have been observed previously (25), suggesting that high-intensity training may induce different cardiac adaptations compared with high-volume training. Although resting HR or HRV and catecholamine concentration are thought to reflect the autonomic nervous system function from another perspective, it seems that responses to intensified training may differ between these markers.

Although physiological markers provide objective information about the biological processes, perceptual markers may also provide valuable information to predict maladaptation to training (13,14) and help contextualize changes in the physiological markers (8,19). In the present study, the most significant changes were found in muscle soreness, which increased in INT and differed from changes in VOL along all the training and recovery weeks. Interestingly, the result somewhat contradicted the result of CK, which increased only in VOL. Concerning possible explanations, HIIT running differs from LIT from a biomechanical point of view (cadence, ground reaction forces) (41), and HIIT would most likely induce more strain in the type II motor units compared with LIT (1). Altogether, relative unfamiliarity combined with the abnormally high HIT frequency may have increased muscle soreness locally in the running muscles. Furthermore, CK may be elevated without an increase in muscle soreness after low-intensity running (39).

Relationships between monitoring variables and changes in running performance. Because responses to endurance training periods are quite individual, it may be challenging to find unambiguous connections between monitoring variables and changes in performance (25). In the current study, there were associations among several markers of subjective recovery (fatigue, muscle soreness, readiness to train, and stress) and changes in running performance. Previous studies have also shown that subjective markers, such as fatigue and readiness to train (14), or the sum of multiple well-being ratings (13) may be useful indicators in the prediction of overreaching or overtraining. Therefore, maintaining these parameters within the normal range seems desirable during intensified training periods. Interestingly, change in stress from Pre to Week2 was positively associated with the final training adaptation in INT. Ruuska et al. (42) have previously found that mental stress may impair training adaptation to endurance training, and it is generally suggested that intensive training may not be recommended during periods of increased stress. Because absolute stress values remained rather low through the training block, the current association was most likely coincidence, and it highlights the importance of reliable reference values when assessing individual responses in the subjective monitoring variables.

Another interesting finding was that the change in running speed from the 1st to the 10th interval session correlated with the change in the 3000-m running speed from T_1 to T_2. However, the same change did not correlate with the change from T_1 to T_3. Therefore, maximal sustainable running speed during the intervals seemed to represent the current performance level, rather than predicting the final training adaptation after a sufficient recovery period. In the VOL group, a similar but negative tendency was found between the change in the HR-RS index and the change in running speed from T_1 to T_2. Although the HR-RS index may be a useful tool in the long-term monitoring of training adaptation (23,25), in this type of short-term blocks where submaximal HR tend to drop, it or other HR-based markers should be used in accordance with perceptual markers (8,19).

Limitations. In the current study, responses to HIIT and LIT blocks were examined in males and females, but the number of participants did not, unfortunately, allow true comparisons between the sexes. Participants of the present study were recreationally trained, meaning these results should not be extrapolated uncritically to either untrained or well-trained athletes. Changes in endurance performance were assessed only with the 3000-m running test, so we cannot identify specific physiological adaptations underpinning the measured performance improvements.

CONCLUSIONS

In conclusion, both the 2-wk block of HIIT and LIT elicited statistically significant and practically meaningful short-term performance improvements. Based on the responses observed in the monitoring variables, both blocks seemed tolerable for recreational athletes. However, the HIIT block induced some negative responses not observed in response to a comparable VOL overload. This may indicate higher demands of training compared with LIT and less “margin for error” when designing this block training intervention in practice. Ensuring sufficient recovery especially after such a period would therefore be of importance. Monitoring subjective recovery alongside performance and objective markers may provide the most valid and actionable assessment of current “readiness to train.”

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INDIVIDUALIZED ENDURANCE TRAINING BASED ON RECOVERY AND TRAINING STATUS IN RECREATIONAL RUNNERS

by

Nuuttila, O.-P., Nummela, A., Korhonen, E., Häkkinen, K. & Kyröläinen, H. (2022)

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Individualized Endurance Training Based on Recovery and Training Status in Recreational Runners

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ABSTRACT

NUUTTILA, O.-P., A. NUMMELA, E. KORHONEN, K. HÄKKINEN, and H. KYRÖLÄINEN. Individualized Endurance Training Based on Recovery and Training Status in Recreational Runners. *Med. Sci. Sports Exerc.*, Vol. 54, No. 10, pp. 1690–1701, 2022. **Purpose:** Long-term development of endurance performance requires a proper balance between strain and recovery. Because responses and adaptations to training are highly individual, this study examined whether individually adjusted endurance training based on recovery and training status would lead to greater adaptations compared with a predefined program. **Methods:** Recreational runners were divided into predefined (PD; $n = 14$) or individualized (IND; $n = 16$) training groups. In IND, the training load was decreased, maintained, or increased twice a week based on nocturnal heart rate variability, perceived recovery, and heart rate–running speed index. Both groups performed 3-wk preparatory, 6-wk volume, and 6-wk interval periods. Incremental treadmill tests and 10-km running tests were performed before the preparatory period (T_0) and after the preparatory (T_1), volume (T_2), and interval (T_3) periods. The magnitude of training adaptations was defined based on the coefficient of variation between T_0 and T_1 tests (high >2×, low <0.5×). **Results:** Both groups improved ($P < 0.01$) their maximal treadmill speed and 10-km time from T_1 to T_3. The change in the 10-km time was greater in IND compared with PD (−6.2% ± 2.8% vs −2.9% ± 2.4%, $P = 0.002$). In addition, IND had more high responders (50% vs 29%) and fewer low responders (0% vs 21%) compared with PD in the change of maximal treadmill speed and 10-km performance (81% vs 23% and 13% vs 23%), respectively. **Conclusions:** PD and IND induced positive training adaptations, but the individualized training seemed more beneficial in endurance performance. Moreover, IND increased the likelihood of high response and decreased the occurrence of low response to endurance training. **Key Words:** ENDURANCE PERFORMANCE, RUNNING PERFORMANCE, HEART RATE VARIABILITY, PERCEIVED RECOVERY, PERIODIZATION

Successful endurance training requires a proper balance between training load and recovery. Although adequate training stimulus is necessary to induce favorable adaptations, inadequate recovery between training sessions and periods may lead to excessive fatigue, and if the imbalance is extended, even to nonfunctional overreaching or overtraining (1). It has been observed that acute responses and recovery kinetics to similar training sessions (2–4) as well as adaptations to training periods (5–7) vary between individuals, and processes related to adaptation could be affected by multiple factors not connected with actual training, such as nutrition (8), sleep (9), or psychological stress (10). Therefore, monitoring both training and recovery could help to take individual differences into account and in this way provide useful information for the estimation of proper training load in each case (11).

The evolution of wearable technology has produced more options for the monitoring of training and recovery, which in turn makes individual training approaches more feasible. Lately, heart rate variability (HRV)–guided training has been utilized in various populations, leading to more beneficial training effects compared with predefined training in untrained (12), recreationally trained (13–15), and well-trained (16,17) participants. The assumption in HRV is that because it reflects the cardiac parasympathetic nervous system activity, it would also relate to current readiness to adapt to training stimulus (18). The basic idea in all studies utilizing the HRV-guided approach has been similar—training intensity has been modified based on changes in daily recorded resting HRV with respect to the individually defined reference range. Furthermore, values below and above the normal range have been regarded as a sign of an abnormal state, and only low-intensity training has been prescribed until HRV has reached the individual reference value

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(14,16,17). Interestingly, none of the previous studies have tried to manipulate training volume based on HRV, although it is an important variable in the endurance training prescription (19).

Despite the fact that HRV-guided training has induced some promising results, a single marker could not establish all aspects critical to recovery. Although HRV mainly reflects cardiac autonomic nervous system activity and cardiovascular homeostasis, aspects such as muscle tissue repair or muscle glycogen repletion may not necessarily be aligned with the parasympathetic reactivation (18). Indeed, neuromuscular and perceptual recovery has differed from the pattern of HRV in several studies (3,4,18,20). It can also be argued that training adaptation and HRV (or its responses) may not be as directly associated as sometimes it has been assumed (21), especially, when taking into consideration the challenging interpretation of HRV after intensified training (22,23) and the possible influence of plasma volume expansion (18). Therefore, supplementary monitoring methods providing information on perceived fatigue and musculoskeletal strain could help to gain a more comprehensive picture of the recovery status. To the best of our knowledge, only one previous study has considered multiple variables in the training decision scheme by analyzing the rating of perceived exertion, the ability to reach target heart rate (HR), and the HR recovery from a submaximal cycling test (24). Although it seems obvious that combining both objective and subjective markers would provide the best quality for monitoring, there certainly exists a lack of research on how to implement such an approach in practice.

To investigate the effectiveness of individualized training volume and intensity, the present study compared the individually adjusted training prescription based on nocturnal HRV, perceived recovery, and estimated running performance to the predefined training program in recreationally endurance-trained males and females. We hypothesized that individualized training would induce greater training adaptations in maximal running performance compared with predefined training and decrease the likelihood of low response.

METHODS

Participants. A total of 40 recreationally endurance-trained males (20) and females (20) were recruited for the study. The minimal sample size was determined based on the data of Nuuttila et al. (15) where 5.1% ± 3.2% and 2.7% ± 1.6% changes in maximal treadmill velocity were reported in HRV-guided and predefined groups, respectively. *A priori* power analysis suggested that 15 subjects were required for both groups to achieve 80% power and a significance level of 5%. The participants were healthy and accustomed to regular running (at least 4 times a week). Before the final acceptance to participate, a cardiologist checked the electrocardiography of all participants. During the study period, seven dropouts occurred (three during volume period, four during interval period). Dropouts in the predefined (PD) and individualized (IND) groups occurred because of personal reasons (n = 1/IND), illnesses (n = 2/PD, 1/IND), or injuries of the lower extremities (n = 2/PD, 1/IND). In addition, three participants that finished the study were excluded from the final analysis because of insufficient training adherence (<90% of the main sessions, n = 1/PD), prolonged training interruption during the interval period (>2 wk, n = 1/IND), or prolonged illness between the end of the interval period and the last testing week (>2 wk, n = 1/PD). The baseline characteristics of the participants that were included in the final analysis are presented in Table 1. One participant got sick between the last incremental treadmill test and the 10-km running test, and that is why in 10-km performance, n = 13 in PD. All participants gave their written consent to participate, and the study protocol was approved by the ethics committee of the University of Jyväskylä.

Study protocol. The study period consisted of a 3-wk preparatory period (PREP), which was followed by 6-wk volume (VOL) and interval periods (INT). After PREP, the participants were matched into pairs based on sex, endurance performance (maximal treadmill speed, 10 km), and endurance training volume (h); and after that, they were randomized into a PD group and an IND group. PD trained according to the predefined program, whereas the program of IND was adapted based on measured training and recovery data. In both groups, all the programmed sessions were performed by running. The participants were allowed to continue other regular activities (e.g., cycling, muscular fitness) with a similar proportion they were accustomed to. However, only a marginal number of such sessions were reported during the study (0.2 ± 0.3 sessions per week). Laboratory measurements and endurance performance tests were performed four times during a testing week before PREP (T_0), between PREP and VOL (T_1), between VOL and INT (T_2), and after INT (T_3). In addition, all participants collected HR and Global Positioning System data from endurance exercises, recorded daily their nocturnal HR and HRV, and filled questionnaires on perceived recovery. Training was performed in field conditions and mainly

TABLE 1. Mean ± SD baseline characteristics of the participants.

	PD			IND		
	Males (n = 7)	Females (n = 7)	All (n = 14)	Males (n = 8)	Females (n = 8)	All (n = 16)
Age (yr)	33 ± 6	35 ± 8	34 ± 7	37 ± 5	38 ± 9	37 ± 7
Height (cm)	181 ± 3	168 ± 5	174 ± 8	180 ± 5	167 ± 8	174 ± 9
Body mass (kg)	82 ± 11	64 ± 8	73 ± 13	77 ± 12	59 ± 4	68 ± 13
BMI (kg·m^{-2})	25.0 ± 3.5	22.7 ± 3.3	23.9 ± 3.5	23.7 ± 3.7	21.3 ± 1.2	22.5 ± 3.0
Fat (%)	14.9 ± 5.1	21.0 ± 7.1	17.9 ± 6.7	12.0 ± 5.6	19.8 ± 4.8	15.9 ± 6.5
$\dot{V}O_{2max}$ (mL·kg^{1}·min^{-1})	47.9 ± 4.2	43.4 ± 2.5	45.7 ± 4.0	50.6 ± 6.2	42.3 ± 4.3	46.5 ± 6.7

Baseline characteristics were measured before the preparatory period (T_0).
BMI, body mass index.

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outdoors. Data collection was executed between late spring and autumn to ensure the most suitable conditions for running. The average daily peak temperature during the data collection was 17.3°C ± 7.5°C in the local weather station (FMI catalog, assessed 12.5.2022). Individuals were not given any specific guidelines regarding nutrition or fluid intake during the study period, and the aim was to maintain usual nutritional habits.

Training protocol. During the 3-wk PREP, participants were familiarized with the intensity zones and training modes of the following periods. The PREP period also facilitated the assessment of the regular training volume of the participants and the representative individual baseline for the measured recovery variables. The participants were advised to continue their regular training in terms of volume and frequency. However, they were asked to exercise only at low intensity (LIT) except for one weekly predefined moderate-intensity session (MOD). To ensure sufficient recovery before the testing week that preceded the training intervention (T_1), the participants were asked to decrease training volume by 25% during their last week of PREP. The training volume and training frequency were analyzed from this period for each individual and used as a basis in the following training programs.

After PREP, the PD and IND groups trained according to their programs. The first 6-wk VOL period focused on the progression of LIT volume, whereas the second 6-wk INT period focused on high-intensity interval training (HIT). The training program of PD was individually scaled based on the training frequency and volume during PREP. The basic structure of the program is presented in Table 2. The training modes during VOL included LIT sessions where HR was below the first lactate threshold (HRzone1) and continuous MOD sessions where HR was between the first and second lactate thresholds (HRzone2). The training was periodized in a way that 2 intensive weeks were followed by 1 recovery week. The training volume progression was similar to previous studies (7,25): during intensive weeks, it increased by 10% compared with the baseline level (2 first weeks of PREP). To ensure sufficient recovery, training volume was always decreased by 25% after 2 intensive weeks (26).

During INT, the weekly main session was 6 × 3 min performed at the maximal sustainable effort with 2-min recovery intervals in between (27). Basically, the running speed during the intervals was between the second lactate threshold and maximal treadmill test speed and at the end of intervals, HR reached values above the second lactate threshold (HRzone3). Other endurance training was executed as LIT where HR was below the first lactate threshold (HRzone1). The duration of these sessions was individually defined based on the basic sessions` average values during PREP. Similar to VOL, the training was periodized into 2 intensive weeks (three HIT sessions) followed by 1 recovery week (one HIT session and 25% decreased training volume). The weekly HIT frequency was based on previous studies using 2–3 weekly HIT sessions (28,29).

In the IND group, the training frequency and timing of different types of sessions within a week were determined according to similar principles as in the PD group. Only the duration of the sessions (VOL) or the number of HIT sessions (INT) were adjusted based on the training and recovery state. The execution of the training was individually adjusted twice a week on evaluation days (Monday and Thursday), which were always recovery days (rest or active recovery) as well. Basically, the training load of the following 3- to 4-d block was either increased, maintained, or decreased from the current level set for the individual. During VOL, the current level referred to the coefficient of the session duration compared with baseline, and similar to PD, it started from +10% (1.10 × baseline duration). During INT, the current level referred to the number of HIT sessions performed within a block and started from one HIT, like in PD. The adjustment logic for the training load is illustrated in Figure 1. The participants were not informed about the exact model behind the training modification to avoid manipulation of the results in a way that would not be related to the actual recovery and training state.

TABLE 2. The training program of the PD group during the preparatory (PREP1–3), volume (VOL1–6), and interval (INT1–6) training periods.

Week	LIT (Basic), 30–90 min	LIT (Long), >90 min	MOD, 30 min	HIT, 6 × 3 min	Tests $\dot{V}O_{2max}$, 10 km	Volume
T_0	1–3×				x	
PREP1	2–4×	1×	1×			BL
PREP2	2–4×	1×	1×			BL
PREP3	1–3×	1×	1×			0.75 × BL
T_1	1–3×				×	
VOL1	2–4×	1×	1×			1.1 × BL
VOL2	2–4×	1×	1×			1.2 × BL
VOL3	1–3×	1×	1×			0.75 × previous wk
VOL4	2–4×	1×	1×			1.3 × BL
VOL5	2–4×	1×	1×			1.4 × BL
VOL6	1–3×	1×	1×			0.75 × previous wk
T_2	1–3×				×	
INT1	1–3×			3×		BL (basic sessions)
INT2	1–3×			3×		BL (basic sessions)
INT3	2–4×			1×		0.75 × previous wk
INT4	1–3×			3×		BL (basic sessions)
INT5	1–3×			3×		BL (basic sessions)
INT6	2–4×			1×		0.75 × previous wk
T_3	1–3×				×	

All MOD and HIT sessions also included low-intensity warm-up and cool-down.
BL, baseline; LIT, low-intensity training (HRzone1); MOD, moderate-intensity training (HRzone2); HIT, high-intensity interval training (maximal sustainable effort); $\dot{V}O_{2max}$, incremental treadmill test.

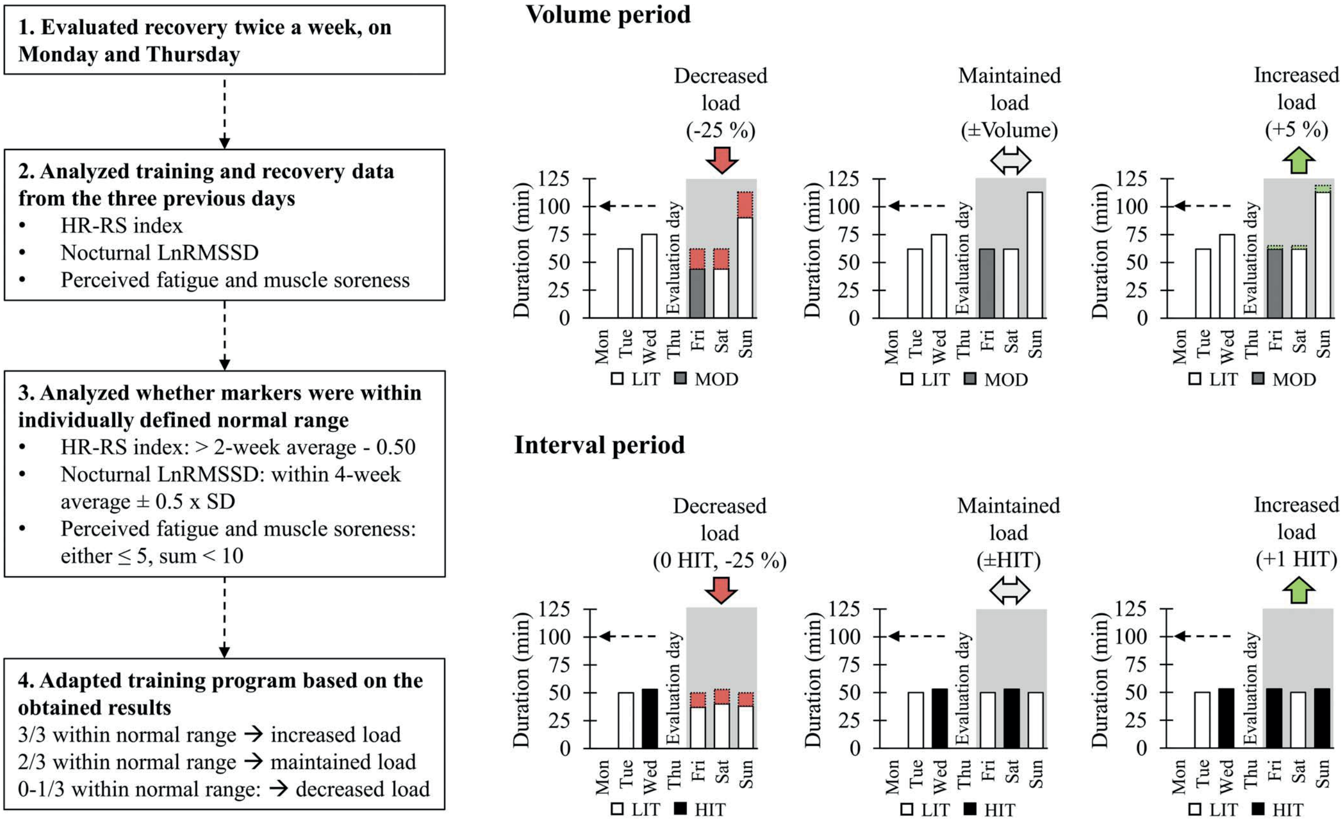

FIGURE 1—Determination logic of the training load in the IND group. Training load was adjusted twice a week on evaluation days (Monday and Thursday). If the training load was maintained, no modifications were made compared with the current level. The training load was increased via adding volume (VOL) by 5% (e.g., 1.10 × baseline level to 1.15 × baseline level) or via increasing the number of HIT sessions (INT). The training load was decreased via reducing volume by 25% compared with the current level (VOL), or via reducing volume by 25% from the current level and excluding HIT sessions (INT). After the recovery block, the training continued from the level preceding the recovery block (two-thirds of the markers within normal range) or the next level (VOL). During INT, the progression always started from one HIT. After reaching a maximum number of HIT sessions within a block (two or three sessions), no additional sessions were performed. After the last evaluation day of INT, a maximum of one HIT session was performed to ensure sufficient recovery before final tests.

The variables affecting the training load and their desirable ranges were determined in conformity with previous studies. In the nocturnal HRV, a 4-wk rolling average ±0.5 × SD was chosen, which meant that the values above or below the range were regarded as negative. Similar cutoff values have been used in studies utilizing HRV-guided training (14,16). Fatigue was expected to be sensitive for the (too high) changes in the training load (22,23) and to increase as a sign of possible overreaching (30,31). Muscle soreness has also increased after periods of intensified training (23,27,32), and high values may relate to overtraining (30). Hooper et al. (30) suggested that in a 1–7 scale, values >5 would be associated with staleness. Because the present study used a similar scale, the respective value was chosen as a cutoff for "normal" value. HR–running speed index (HR–RS index) was chosen as the third factor affecting the training load, because it is not straightforward how recovery state itself translates into training adaptation, and changes in this marker have previously correlated with the change in maximal running performance measured in the laboratory (33). Because HR–RS index was not measured in laboratory conditions and exercise HR has a certain natural day-to-day variation (34), the maximum decrement of 0.50 compared with previous 2-wk average, equivalent to 3- to 4-bpm increase in HR at the same running speed, was defined as "normal." The smallest worthwhile change (SWC) of 0.50 has also been used with the same marker previously (21).

Performance and laboratory tests. The testing week included 2 testing days, which were separated by at least 48 h. The first testing day consisted of fasting measurements (blood samples and anthropometrics) and incremental treadmill test. On the second day, a 10-km running test was executed. The tests were performed at the same time of the day (±2 h) within-participant. The last day before the test was a rest day and no HIT or long-distance sessions were performed on 2 d preceding any test.

Serum free testosterone and cortisol concentrations as well as creatine kinase activity were assessed after a 12-h fast in the morning (7:15–9:15 AM) preceding the incremental treadmill test. Samples were taken from the antecubital vein into 6-mL serum tubes, and standard laboratory procedures were followed. Whole blood was centrifuged at 2250 G (Megafuge 1.0 R; Heraeus, Hanau, Germany) for 10 min, and after that the serum was removed and frozen at −20°C until the final analysis. Serum cortisol concentration was analyzed with a

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chemical luminescence technique (Immulite 2000 XPi; Siemens, New York City, NY). The sensitivity of the cortisol assay was 5.5 $nmol \cdot L^{-1}$, and the intra-assay coefficient of variation (CV) was 5.3%. Free testosterone concentration was analyzed with enzyme-linked immunoassay method (DYNEX DS 2 ELISA processing system; DYNEX Technologies, Chantilly, VA). The sensitivity of the free testosterone assay was 0.6 $pmol \cdot L^{-1}$, and the intra-assay CV was 6.0%. Serum creatine kinase activity was analyzed with Indiko Plus Clinical Chemistry Analyzer (Thermo Fisher Scientific, Vantaa, Finland). The sensitivity of the creatine kinase assay was 2.2 $U \cdot L^{-1}$, and the intra-assay CV was 0.9%. At the same laboratory visit, body mass and body fat percentage were measured with bioimpedance device (InBody770-analyser; Biospace Co. Ltd., Seoul, Korea).

An incremental treadmill test was performed on a treadmill (Telineyhtymä Oy, Kotka, Finland). The starting speed was 7 $km \cdot h^{-1}$ for women and 8 $km \cdot h^{-1}$ for men. Three-minute stages were used, and the speed increased by 1 $km \cdot h^{-1}$ after every stage. Between the stages, the treadmill was stopped (15–20 s) for drawing blood samples from the fingertip for lactate analyses. The inclination was kept constant at 0.5° angle through the whole test. The oxygen consumption was measured breath by breath with Jaeger Vyntus CPX (CareFusion Germany 234 GmbH, Hoechberg, Germany), and HR was monitored with Polar Vantage V2 (Polar Electro Oy, Kempele, Finland). The maximal oxygen uptake ($\dot{V}O_{2max}$) was defined as the highest 60-s average of oxygen consumption. The maximal running speed (vMax) of the test was defined as the highest speed in the last completed stage, or if the stage was not finished, as the speed of the last completed stage ($km \cdot h^{-1}$) + (running time (s) of the unfinished stage − 30 s)/(180 − 30 s) × 1 $km \cdot h^{-1}$. The first lactate threshold (LT1) and the second lactate threshold (LT2) were determined based on blood lactate changes during the test. The LT1 was set at 0.3 $mmol \cdot L^{-1}$ above the lowest lactate value. For the determination of LT2, two linear models were drawn: 1) between LT1 and the next measured lactate value and 2) for the lactate points, which were preceded by a lactate increase of at least 0.8 $mmol \cdot L^{-1}$. Finally, LT2 was set at the intersection point between these two linear models. The treadmill and threshold assessment protocols were adopted from previous studies (5,14,27).

The countermovement jump (CMJ) test was performed on a contact mat before the incremental treadmill test and after a short 5-min low-intensity warm-up. The participants were advised to keep their hands on their hips and jump as high as possible. The lowest knee angle during the take-off was instructed to be about 90°. The jump height (h) was calculated based on the measured flight time with the formula: $h = g \cdot t^2 \cdot 8^{-1}$, where t is the recorded flight time in seconds and g is the acceleration due to gravity (9.81 $m \cdot s^{-2}$) (35). Three attempts were performed with a 30-s recovery, and the highest jump (in centimeters) was used in the final analysis.

The running performance was also assessed by the 10-km field test, which was run in small groups on a flat 1.6-km asphalt loop (+400-m starting line). A standardized 15-min low-intensity warm-up including 2–3 accelerations to the target speed was performed before the test. The running time, average HR, and peak HR were analyzed from the tests.

Training and recovery monitoring. The participants used an HR monitor (Polar Vantage V2, H10 sensor; Polar Electro Oy) in all endurance exercises. The training intensity distribution based on HR values (time below the LT1 = HRzone1; between LT1 and LT2 = HRzone2; above the LT2 = HRzone3), distance covered, HR–RS index (33), and average running speed from the interval sessions were analyzed from the data. To establish a fair comparison between the sessions of varying duration and terrain, the HR–RS index was primarily calculated from the beginning of running sessions (5:00–10:00). The participants were advised to run the first 10 min of each session as a warm-up on flat terrain at an intensity of LIT. The data were manually analyzed in Polar Flow software (Polar Electro Oy) to ensure sufficient data quality and flat terrain requirement (not more than 5 m ascent or descent). In cases where the criteria were not met in the original 5:00–10:00 segment, the 5-min segment was either moved until fulfilling the criteria (continuous sessions), or the longest possible segment (of at least 2 min) meeting the criteria was used (interval sessions) instead.

The HR–RS index was calculated based on the average running speed (S_{avg}) and HR (HR_{avg}) with the following equation:

$$\text{HR-RS index} = S_{avg} - \left(HR_{avg} - HR_{standing}\right)/k$$

$$k = \left(HR_{max} - HR_{standing}\right)/S_{peak}$$

$HR_{standing}$ was estimated by adding 26 bpm to the resting HR (average nocturnal HR during the PREP period) similar to Vesterinen et al. (33). S_{peak} and HR_{max} were determined based on the incremental treadmill test results at T_1.

Subjective recovery was estimated daily on a 1–7 scale, which was modified from the questionnaires of Schäfer Olstad et al. (32) and Hooper et al. (30). Muscle soreness of the lower limbs, fatigue, sleep quality, and stress were ranked from 1 (very much below/better than normal) to 7 (very much above/worse than normal), whereas 4 represented normal perception. The items were analyzed separately and as a sum index, which was defined as the "staleness score." Recovery was estimated in the morning before any exercise via Coach4Pro mobile application (Coach4Pro Oy, Espoo, Finland).

The nocturnal HR and HRV were measured via wrist-based photoplethysmography (Polar Vantage V2) every night throughout the whole study. The validity of the device has been reported previously (36). Automatically formed results from a 4-h period starting half an hour after the beginning of the detected sleep onset were used in the analysis. Values provided by the watch included the average HR and the average root mean square of successive differences, which was log-transformed (LnRMSSD) for the analysis.

Statistical analysis. The results are presented as mean ± SD. The normality of the data was assessed with the Shapiro–Wilk test. To examine the main effects (time, group) and their interaction (time–group), repeated-measures ANOVA was applied in the performance and laboratory tests (T_1, T_2, T_3), normally distributed monitoring variables (PREP vs 1–12 wk), and the running speed of the interval sessions (INT1 vs INT2–6 wk). In the case of a significant main effect or interaction, a Bonferroni *post hoc* test was used for within-group comparisons and simple contrasts for between-group comparisons. To exclude any possible effects of different baseline levels in performance parameters (treadmill test, 10-km test), a T_0 test result was used as a covariant (ANCOVA) in the between-group analysis. In parameters that were not normally distributed, the Wilcoxon signed rank test with Bonferroni correction was used for within-group comparisons and the Mann–Whitney U-test for between-group comparisons (changes from PREP). For the markers used in training adjustment (HR–RS index, 3-d HRV, muscle soreness, and fatigue), unpaired-samples t-test was used to analyze the between-group differences in the percentage of data points being within individual SWC during the training intervention. The magnitude of improvements in the main parameters (vMax, 10 km) was analyzed based on the CV between T_0 and T_1 tests, and it was stated as trivial (<0.5 × CV), moderate (0.5–2 × CV), or high (>2 × CV). Because only a relatively short period of regular training was performed between the T_0 and T_1, CV was expected to illustrate the typical error of the test caused by day-to-day variation in performance and/or environmental factors. The present division for magnitude was adapted from the study by Düking et al. (7), but as an exception, the SWC was defined as 0.5 × CV (37), similar to the cutoff value used in the recovery markers. To further investigate possible reasons behind different responses, individuals defined as high responders for both of the tests (n = 8) and individuals defined as trivial responders for either of the tests (n = 9) were compared (age, baseline fitness, training volume, perceived stress, and recovery during the intervention period) with Mann–Whitney U-test. To examine the effect size (ES) of observed changes, Cohen's d for within-group (difference of the means divided by the pooled SD), and between-group (difference of the means divided by the SD of the mean difference) comparisons and 95% confidence intervals were calculated for the laboratory and performance tests. After nonparametric tests, ES was calculated by a formula: $ES = Z \cdot (\sqrt{n})^{-1}$, where Z is the z-score, and n is the number of observations on which Z is based. The ES was categorized as <0.2 trivial, 0.2–0.5 small, 0.5–0.8 moderate, and >0.8 large. The statistical significance level was set to $P < 0.05$. Analyses were performed with Microsoft Excel 2016 (Microsoft Corporation, Redmond, WA) and IBM SPSS Statistics v.28 programs (SPSS Inc., Chicago, IL).

RESULTS

Training. No differences were observed between the groups in the mean weekly training volume during the PREP (PD, 4.6 ± 1.0 h; IND, 4.3 ± 0.8 h), VOL (PD, 5.7 ± 1.3; IND, 5.3 ± 0.9), or INT (PD, 3.8 ± 0.9; IND, 3.8 ± 0.6 h). Compared with PREP, the training volume was higher during VOL and lower during INT in both groups ($P < 0.01$). The training intensity distribution was similar in both groups across the study. In addition, the proportion of HRzone1 decreased and HRzone3 increased from PREP to INT similarly in both groups ($P < 0.01$). The weekly mean training frequency slightly increased in IND from PREP (4.2 ± 0.6) to VOL (4.4 ± 0.6, $P < 0.001$) and INT (4.3 ± 0.6, $P = 0.007$), whereas no significant differences were found in VOL (PREP, 4.2 ± 0.9; VOL, 4.5 ± 1.0; INT, 4.3 ± 0.9). The number of HIT sessions did not differ between the groups during INT (PD, 13.6 ± 0.5 sessions; IND, 15.8 ± 4.3 sessions), although the range was greater in IND (PD, 13–14 sessions; IND, 10–25 sessions). The weekly training volume and intensity are illustrated in Figure 2. The total accumulated training volume during the VOL and INT was 56.9 ± 13.0 h (range, 43.7–83.9 h) in PD and 54.7 ± 9.0 h (range, 40.3–69.1 h) in IND, and the volume was distributed into 52 ± 11 sessions (range, 42–80 sessions) in PD and 53 ± 7 sessions (range, 46–71 sessions) in IND. Regarding the training adjustments of IND during the intervention, 55% ± 12% maintained the training load, 35% ± 10% increased the training load, and 10% ± 8% decreased the training load.

Performance and laboratory tests. No between-group differences were observed in any of the performance-related variables at T_1. A significant main effect of time was observed in vLT2, vMax, and $\dot{V}O_{2max}$ ($P < 0.001$; Table 3). Both groups improved ($P < 0.001$) their maximal treadmill performance from T_1 to T_3 (PD, 3.0% ± 2.4%; IND, 4.0% ± 1.9%; between-group $P = 0.322$; ES = 0.46; −0.27 to 1.18), and T_2

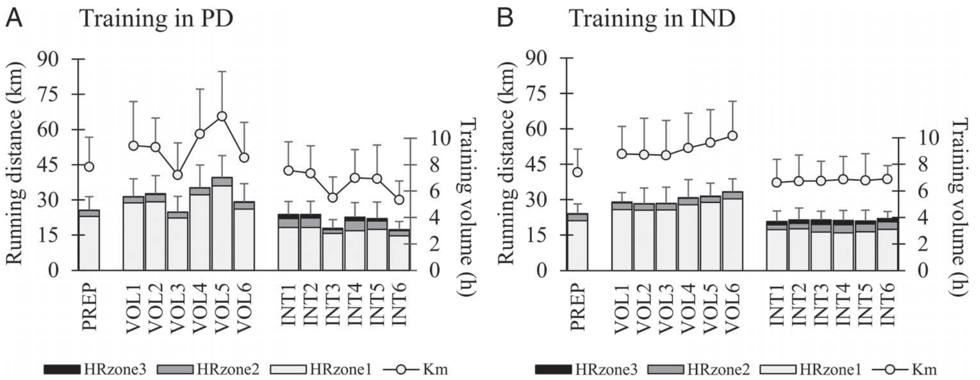

FIGURE 2—Training volume, running distance, and training intensity distribution (time in HRzone1, HRzone2, and HRzone3) at baseline (PREP) and across the volume (VOL1–VOL6) and interval (INT1–INT6) training periods in the PD (A) and IND (B) training groups.

TABLE 3. Mean ± SD performance and laboratory test results before the VOL (T_1) between the VOL and INT (T_2), and after the INT (T_3) periods.

	PD (n = 14)			IND (n = 16)		
	T_1	T_2	T_3	T_1	T_2	T_3
vLT1 (km·h^{-1})	10.7 ± 0.9	10.8 ± 1.1 (0.10; −0.43 to 0.63)	11.1 ± 1.2 (0.33; −0.21 to 0.87)	10.6 ± 1.1	10.8 ± 1.0 (0.23; −0.27 to 0.72)	10.8 ± 1.3 (0.14; −0.36 to 0.63)
vLT2 (km·h^{-1})	13.3 ± 1.4	13.5 ± 1.5 (0.15,. −38 to 0.67)	13.6 ± 1.6* (0.18; −0.35 to 0.70)	13.1 ± 1.6	13.3 ± 1.4 (0.16; −0.33 to 0.65)	13.5 ± 1.6** (0.23; −0.27 to 0.72)
vMax (km·h^{-1})	16.1 ± 1.8	16.3 ± 2.0 (0.11; −0.42 to 0.63)	16.6 ± 2.1***,† (0.26; −0.28 to 0.79)	16.0 ± 2.0	16.2 ± 2.0 (0.10; −0.39 to 0.59)	16.6 ± 1.9***,†† (0.32; −0.19 to 0.82)
$\dot{V}O_{2max}$ (mL·kg^{-1}·min^{-1})	46.7 ± 3.9	47.8 ± 5.2 (0.26; −0.28 to 0.78)	50.7 ± 6.1***,††† (0.80; −0.18;1.39)	47.3 ± 7.2	47.0 ± 7.2 (−0.03; −0.49 to 0.44)	50.3 ± 7.6**,††† (0.40; −0.12 to 0.90)
CMJ (cm)	28.0 ± 5.2	28.8 ± 4.7 (0.15; −0.38 to 0.67)	28.6 ± 4.4 (0.11; −0.41 to 0.64)	30.3 ± 6.3	30.6 ± 6.8 (0.05; −0.44 to 0.54)	30.0 ± 6.2 (−0.05; −0.54 to 0.44)
fTesto (pmol·L^{-1})	27.0 ± 26.6	26.9 ± 25.5 (0.00; −0.69 to 0.69)	27.3 ± 23.3 (0.00; −0.69 to 0.69)	18.6 ± 17.5	18.2 ± 16.8 (−0.01; −0.75 to 0.73)	18.6 ± 16.4 (0.00; −0.74 to 0.74)
Cortisol (nmol·L^{-1})	382 ± 102	439 ± 107 (0.50; −0.07;1.04)	411 ± 96 (0.24; −0.30 to 0.76)	464 ± 145	468 ± 145 (0.02; −0.47 to 0.51)	456 ± 125 (−0.06; −0.55 to 0.43)
CK (umol·L^{-1})	130 ± 63	148 ± 90 (0.06; −0.63 to 0.75)	115 ± 54 (−0.07; −0.76 to 0.62)	118 ± 55	130 ± 65 (0.05; −0.69 to 0.79)	129 ± 79 (0.05; −0.69 to 0.79)

Values in the parentheses are ES (Cohen's d) and the 95% confidence intervals for the within-group changes from T_1.
*P < 0.05 within groups compared with T_1.
**P < 0.01 within groups compared with T_1.
***P < 0.001 within groups compared with T_1.
†P < 0.05 within groups compared with T_2.
††P < 0.01 within groups compared with T_2.
†††P < 0.001 within groups compared with T_2.
CK, serum creatine kinase. fTesto, serum free testosterone; vLT1, the speed at the first lactate threshold; vLT2, the speed at the second lactate threshold; vMax, maximal speed of the incremental treadmill test.

to T_3 (PD, 1.8% ± 2.5% (P = 0.022); IND, 2.7% ± 2.8% (P = 0.001); between-group P = 0.421; ES = 0.34; −0.39 to 1.06). No significant main effects or interactions were observed in the anthropometrics or blood-derived markers (Table 3).

A significant main effect of time (P < 0.001) and group–time interaction (P = 0.006) was observed in 10-km running time (Fig. 3). PD (−2.9% ± 2.4%, P = 0.004; ES = 0.20; −0.35 to 0.75) and IND (−6.2% ± 2.8%, P < 0.001; ES = 0.46; −0.07 to 0.97) improved the 10-km running time from T_1 to T_3, and the respective change differed between the groups (P = 0.002; ES = 1.23; 0.42 to 2.02). The running time was improved from T_1 to T_2 only in IND (−2.6% ± 3.1%, P = 0.001; ES = 0.19; −0.31 to 0.68), whereas in PD, it remained unchanged (−0.8% ± 2.1%, P = 0.534; ES = 0.08; −0.47 to 0.62). However, the change was not different between groups (P = 0.125; ES = 0.64; −0.12 to 1.38). The improvement was also significant between T_2 and T_3 in IND (−3.7 ± 2.2, P < 0.001; ES = 0.27; −0.23 to 0.76) and tended to be significant in PD (−2.0% ± 3.3%, P = 0.051; ES = 0.14; −0.41 to 0.68) with no between-group differences (P = 0.087; ES = 0.61; −0.15 to 1.35).

Significant main effects of time were also observed in average HR (P = 0.035) and peak HR (P = 0.002) during the running test. The average HR values at T_1, T_2, and T_3 were 93.1 ± 2.1, 93.3 ± 1.6, and 92.6 ± 2.5%/max for PD and 93.1 ± 1.6, 93.4 ± 1.9, and 92.5 ± 2.1%/max for IND, respectively. At the same time points, peak HR values were 99.0 ± 2.3, 98.5 ± 1.6, and 97.7 ± 1.9%/max for PD and 99.2 ± 2.0, 99.0 ± 2.0, and 97.5 ± 2.2%/max for IND, respectively. In the *post hoc* analysis, the only significant difference was found in peak HR, which decreased in IND from T_1 to T_3 (P = 0.011).

In addition to statistical analysis, the individual response magnitudes in the maximal treadmill performance and 10-km running performance from T_1 to T_3 were examined (Fig. 4). In the vMax, the percentage distributions for high, moderate, and trivial responders were 29%/50%/21% for PD and 50%/50%/0% for IND, respectively. Meanwhile, in the 10-km running test, the percentage distributions for high, moderate, trivial, and moderate negative responders were 23%/54%/15%/8% for PD and 81%/6%/13%/0% for IND, respectively.

Monitoring variables. Significant main effects of time were observed in the HR–RS index (Fig. 5) and the average running speed of interval sessions (P < 0.001). The running speed in the intervals increased in IND from week 1 (14.4 ± 1.6 km·h^{-1}) to week 3 (14.8 ± 1.8 km·h^{-1}, P = 0.023), week 4 (14.8 ± 1.8 km·h^{-1}, P = 0.005), and week 6 (14.9 ± 1.8 km·h^{-1}, P = 0.023), whereas no change was observed in PD (14.6 ± 2.0 vs 14.7–14.9 km·h^{-1}). In addition, some significant within-group differences were found in the staleness score and nocturnal HR (Fig. 5), which were analyzed with nonparametric tests. IND had significantly higher proportion defined as "normal" in HR–RS index (82% ± 6% vs 75% ± 7%, P = 0.015) and LnRMSSD (52% ± 5% vs 45% ± 5%, P = 0.046) when the percentage of data points being within individual SWC was analyzed, whereas in fatigue (68% ± 11% vs

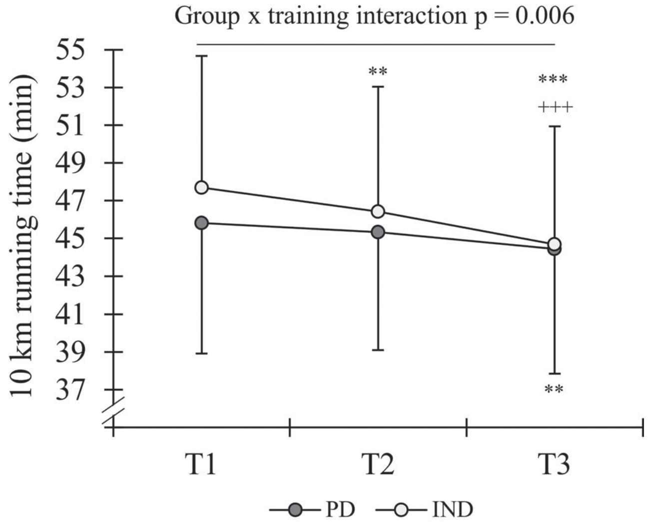

FIGURE 3—Running time in the 10-km test before the VOL (T_1), between the VOL and INT (T_2), and after the INT (T_3) periods in the PD and IND training groups. $^{**}P < 0.01$, $^{***}P < 0.001$ within groups compared with T_1 $^{+++}P < 0.001$ within groups compared with T_2.

75% ± 14%) and muscle soreness (69% ± 17% vs 69% ± 24%), no differences were observed.

Comparison between high and trivial responders. When the individuals defined as high or trivial responders were compared, no differences were observed in the age (34.3 ± 8.6 vs 36.0 ± 6.5 yr), baseline fitness (vMax, 15.5 ± 1.9 vs 15.9 ± 2.0 km·h^{-1}), training volume (56.1 ± 6.5 vs 56.6 ± 13.3 h), or perceived stress (3.5 ± 0.5 vs 3.8 ± 0.6) during the study period. Regarding the monitoring variables, high responders had a higher proportion ($P = 0.03$) of "normal" HR–RS index values compared with trivial responders (82% ± 6% vs 73% ± 8%), whereas in LnRMSSD (53% ± 7% vs 49% ± 14%), fatigue (76% ± 16% vs 72% ± 12%), or muscle soreness (76% ± 15% vs 70% ± 16%), no such differences were observed.

DISCUSSION

The main findings of the study were that the predefined and individualized training protocols improved endurance performance from the baseline in the incremental treadmill test and 10-km running test, and the most significant improvements occurred after the interval period. Although both groups had similar training characteristics on average, the change in the 10-km running performance was greater in IND. In addition, the proportion of high responders in the maximal treadmill and 10-km running performance was greater and the proportion of low responders smaller in IND compared with PD. These differences suggest that individualized training may increase the likelihood of positive endurance training adaptations.

Training characteristics. Despite different training periodization models, no significant differences were found between the groups when training periods were analyzed as a whole. However, as can be seen from Figure 2, the weekly execution of the training was quite different. In IND, similar types of recovery weeks as in PD were not observed, because the timing and length of such periods were individually defined. Interestingly, only ~10% of the training load adjustments led to a recovery block. This may illustrate that in recreational runners with quite a low training frequency, specific recovery periods may not be particularly critical when the training load is being increased (sufficiently) moderately. The findings may also relate to somewhat strict limits for the recovery block, at least in some individuals.

Previously, HRV-guided training has led not only to a lower volume of MOD or HIT (13,14,16) but also to a higher volume of MOD (17). In the present study, there was rather a slight tendency for a higher proportion of HIT during INT (IND vs PD, 15.6 vs 13.6 sessions), but the difference was not significant because there were also many individuals who performed fewer HIT sessions than PD. Although it has been previously found that the same (or superior) adaptations could be induced with lower training demands of HRV-guided training (13,14,16), one may argue that the training characteristics should be, on

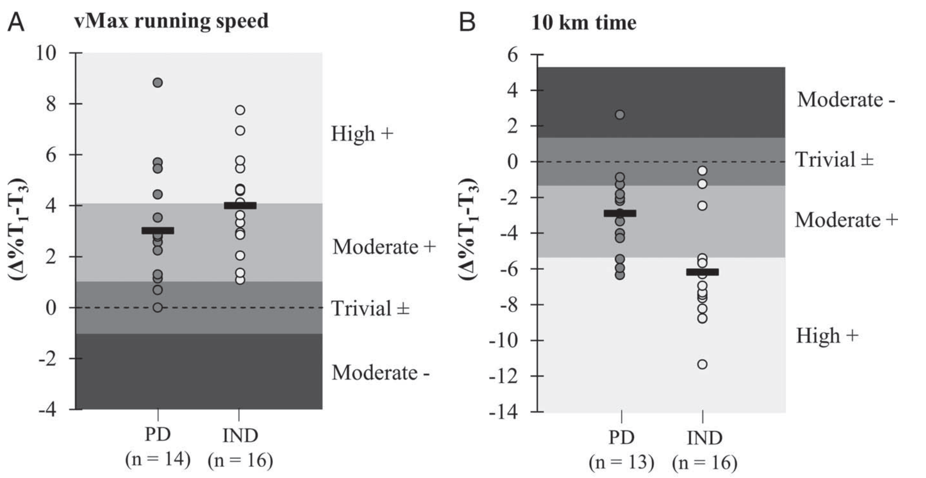

FIGURE 4—Magnitude of individual responses and mean changes (*black rectangle*) in maximal treadmill speed (A) and 10-km running time (B). Magnitudes were set based on the CV of the parameter between T_0 and T_1. High + and Moderate + indicate improved performance; Trivial ±, unchanged performance; and Moderate −, impaired performance.

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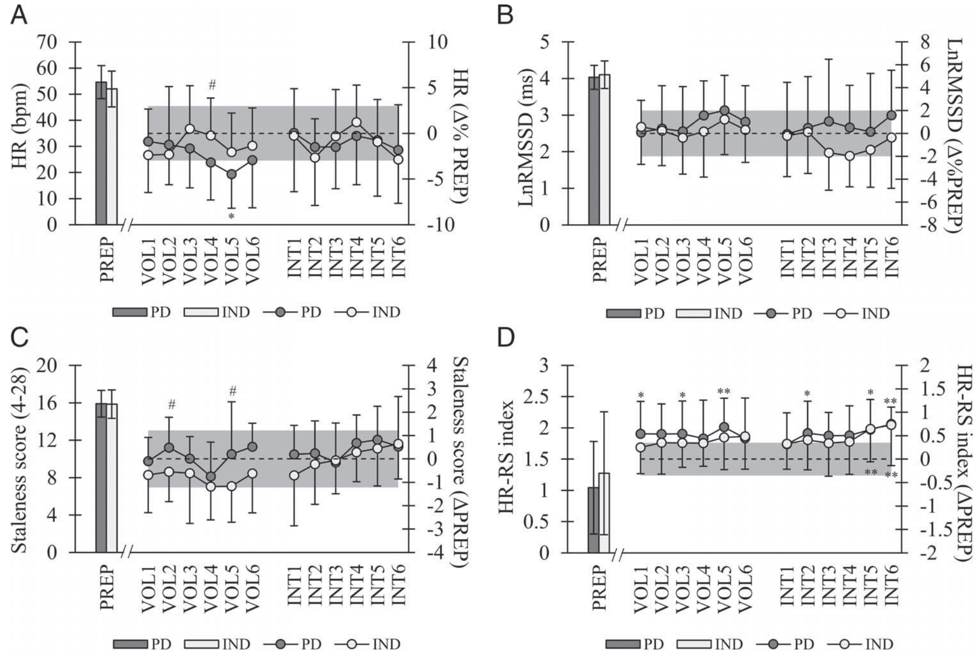

FIGURE 5—Mean ± SD baseline values (PREP) and weekly changes (VOL1–6, INT1–6) in nocturnal HR (A), nocturnal LnRMSSD (B), staleness score (C), and HR–RS index (D). *Gray area* represents the SWC of the parameter based on individual average values during PREP. In A and B = 0.5 × CV, in C and D = 0.5 × SD. *P < 0.05, **P < 0.01, ***P < 0.001 within groups compared with PREP. #P < 0.05 between groups at respective time point.

average, similar between the two groups to indicate that also the PD group has a suitable program.

Training adaptation. Both groups improved significantly their maximal performance in the incremental treadmill test and 10-km running test. The magnitudes of improvements in the vMax (PD, 3.0% ± 2.4%; IND, 4.0% ± 1.9%) (5,21) and 10-km running tests (PD, −2.9% ± 2.4%; IND, −6.2% ± 2.8%) (38,39) were in line with the aforementioned previous studies, which suggests that the training programs were appropriate for the target population of recreational runners. The most interesting finding among the performance tests was the significant difference between PD and IND in the change of 10-km running time. Regarding the greater between-group difference in 10 km compared with the treadmill test, one possible explanation could be related to the timing of the test. Because IND did not have a predefined recovery or tapering period before the test week, it is possible that, during the latter test day of the week, (10 km), the training adaptations and the actual performance were better realized. Although maximal treadmill and 10-km running performance are strongly linked (40), the 10-km test may provide information from slightly different aspects of endurance performance by requiring "durability" of high intensity for a prolonged period (41), which is quite a critical ability in most endurance events. It can also be speculated that maximal treadmill performance could be limited by neuromuscular factors (42), especially in recreational runners, since the 10-km running speed was, on average, 82% of the peak treadmill speed.

The greater number of high responders and the lower number of trivial or negative responders in the IND group were another interesting findings regarding the training adaptations in vMax and 10 km. This is in line with the hypothesis that individualizing the training load would decrease the likelihood of negative responses. Similar findings have also been proposed by Vesterinen et al. (14), who suggested that HRV-guided training would decrease the variation in the training adaptation and lead to more consistent improvements in performance. On the other hand, the lack of changes in the treadmill performance after the volume period was rather an unexpected result. For optimal performance after VOL, the current protocol would possibly have required longer tapering or a greater decrease in volume before the tests. In the study by Bellinger et al. (25), using quite a similar volume progression, the running performance was significantly improved after a 1-wk taper during which the training volume was exponentially decreased by 55%.

Monitoring variables. In the monitoring variables, only a few differences were observed between the groups, and none of the markers responded negatively at the group level. Furthermore, the resting concentrations of serum hormones and CMJ performance remained unaffected. Therefore, the training load seemed tolerable for both groups. Regarding the between-group differences in the monitoring variables, IND had a higher proportion of "normal" values in HR–RS index and nocturnal HRV, which was an expected outcome of the training model. Although both groups improved the HR–RS index, only IND was able to increase the running speed significantly during the interval sessions. Because maximal sustainable effort intervals could be regarded as a marker of the current performance level (27), the finding may illustrate a compromised training state in some individuals of PD, probably because of too high interval frequency. The importance of maintaining an

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appropriate training state was also demonstrated by a greater proportion of "normal" values in HR–RS index in high responders compared with trivial responders.

Although a positive state of recovery is in general desirable, at least a slight variation in these markers might be necessary at certain points of training periods to reflect a sufficient training load needed for long-term improvements. It is important to acknowledge that individualized training may allow not only sufficient recovery but also sufficient loading to induce desirable adaptations. This could also relate to the lesser occurrence of low responders in the current study. Montero and Lundby (43) have previously found that individuals stated as nonresponders improved their endurance performance when the training dose was increased. Gaskill et al. (44) illustrated the same phenomenon from a different perspective, and in their study, the individuals who were stated as low-responders to previous training improved their performance once the training was significantly intensified.

Methodological considerations. The current study setting was novel, and no previous recommendations exist regarding the multitargeted training model of the IND group. Therefore, several considerations based on the observations made in the present study may be beneficial for future studies or individuals implementing such an approach into practice.

First, the markers used in the recovery evaluation play a critical role, and therefore, the selection of proper markers should be considered carefully. HRV was chosen as an evaluation marker based on previous studies utilizing individualized training prescription. In all previous studies using the HRV-guided approach, morning recordings (13–17) or day-time recordings (12) have been used instead of nocturnal recordings. In the present study, nocturnal recordings were chosen because of feasibility, as they did not demand any additional measurements. Although sleep is not necessarily a stable period in terms of the autonomic nervous system function and HRV (45) when data are being averaged for a sufficient period (e.g., 4 h), a very good day-to-day reliability has been reported (46) and within-week variation could be even lower compared with morning recordings (47). Furthermore, nocturnal HRV seems to be sensitive and demonstrate internal responses to training load (46). Subjective markers are typically suggested to be useful tools in the detection of overreaching or overtraining (30,31) and helpful in distinguishing positive and negative responses in HR-based markers, such as resting HRV and submaximal exercise HR (22,23). Fatigue and muscle soreness were used in the present study, because both of these have previously been associated with staleness (30) and responded to a significant increment in the training load (23). The most useful subjective markers would probably be those that provide information from a point of view that could not be assessed via objective measures, and simple assessments consisting of only a few aspects of subjective recovery could be the most suitable and practical option (32).

In addition to the recovery state, the estimations of performance provide information on the training adaptation, which is the ultimate goal of the whole training process. In the current study, the submaximal performance was assessed at the beginning of each exercise via the HR–RS index. Previously, similar types of warm-up settings (5–10 min) have been able to capture acute (4) and chronic (38) changes in HR in the standardized conditions. Despite the fact that the current setting was not similarly standardized by treadmill or beep sounds, the use of the HR–RS index was expected to equalize slight variations in speed or HR. In addition, Vesterinen et al. (48) have found that a 15-min HR-based warm-up in field conditions was able to track training adaptation in the laboratory test. Although submaximal performance correlates with the maximal performance with a decent accuracy, especially HR-based tests have certain challenges in terms of interpretation. In the present study, it was expected that if submaximal HR decreased because of overreaching, this type of parasympathetic hyperactivity would be revealed via increased perceived fatigue and HRV (22,23). Another option to exclude HR-based challenges would be testing running speed in relation to fixed rating of perceived exertion (49), for example, with a similar warm-up setting compared with the present study.

Another important aspect to consider when assessing recovery is the limits/normal range within each variable. Although, in subjective markers, the desirable values may remain quite permanent, in the HR-based and performance-related markers, there is an occasional need for reevaluation, because these may change because of positive training adaptations (38). The frequency of such evaluations has varied in previous studies from constant updating (12,13) to updating once per week (17) or once every 4 wk (14,16). In the current study, constantly updated limits were used, and some individuals illustrated slow downward slipping of the limits (e.g., in HR–RS index), which would not be desirable. Therefore, if using constantly updating SWC in particular, one way to avoid such an effect would be to set a short-term limit (e.g., 2-wk) and a long-term limit (e.g., 8-wk), and both of them should be met. Regarding the exact cutoff values for each variable, it is possible to set a desirable "risk level," which could vary, for example, depending on the training phase or fitness level.

The final step of the individualization consists of the following question: how training should be adjusted based on the results? In previous studies, individualized training prescriptions have been utilized purely via adjustment of intensity (12–17,24). The training volume, however, is a critical variable in the long-term development of endurance performance (19,50), and consequently, a model that only estimates whether an individual should train at high- or low-intensity could be regarded as somewhat incomplete. Therefore, we argue that also the training volume should be considered in the training decision scheme. Regarding the training execution, previous HRV-guided studies have mainly utilized "day-by-day-approach" (13,14,16,17). Based on the results of the current study, a 3- to 4-day evaluation period seemed a relevant option in terms of feasibility (individuals know the session of the following day) and training load that would not lead to a serious state of fatigue or overreaching, where the recovery

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period would be extended (1). Nevertheless, it should be noted that, in the present study the average training frequency was only slightly greater than four sessions per week, thus allowing always fairly decent recovery periods between sessions in most of the participants.

Finally, although the idea behind individualized training is that the training is adjusted based on data collected, in the long term, predefined recovery periods (e.g., every fifth week) may secure exclusion of excessive fatigue. It could also be beneficial for the perceptual aspects of recovery, which are likely to get impaired during intensive training (22,23,27). Even if the training was adapted, there probably should always be upper and lower limits for the acute and long-term progression of the training load, and these should be determined based on the individual's background and target.

Limitations. In the current study, males and females were analyzed within the same group, because the number of participants did not allow meaningful separate comparisons. Further studies are needed to investigate possible sex differences and to elaborate current findings to cover untrained and competitive athletes, although it can be argued that a similar necessity for the balance between training load and recovery exists across the fitness-level spectrum. The study was performed in "field conditions"; thus, training conditions or factors such as nutrition or hydration status could not be fully controlled. In addition, the 10-km running test was performed outdoors where environmental factors could not be standardized at similar precision as in the laboratory. However, similar fluctuations in the conditions concerned both groups, and therefore, environmental factors most likely did not affect significantly within-group comparisons. It could also be argued that the current field setting reflects the conditions of the "real" training of recreational runners and thus the usefulness of both training models.

CONCLUSIONS

In conclusion, the current study provided evidence that, although predefined training improves endurance performance, individualized endurance training may induce greater improvements in running performance and increase the probability of high response while decreasing the occurrence of low or negative responses to endurance training. In the future, the most suitable markers to be used in monitoring as well as the exact method of how training load could be manipulated during different types of periods should be examined in more detail.

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The authors declare no conflicts of interest. The results of this study are presented clearly, honestly, and without fabrication, falsification, or inappropriate data manipulation. The results of the present study do not constitute endorsement by the American College of Sports Medicine.

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