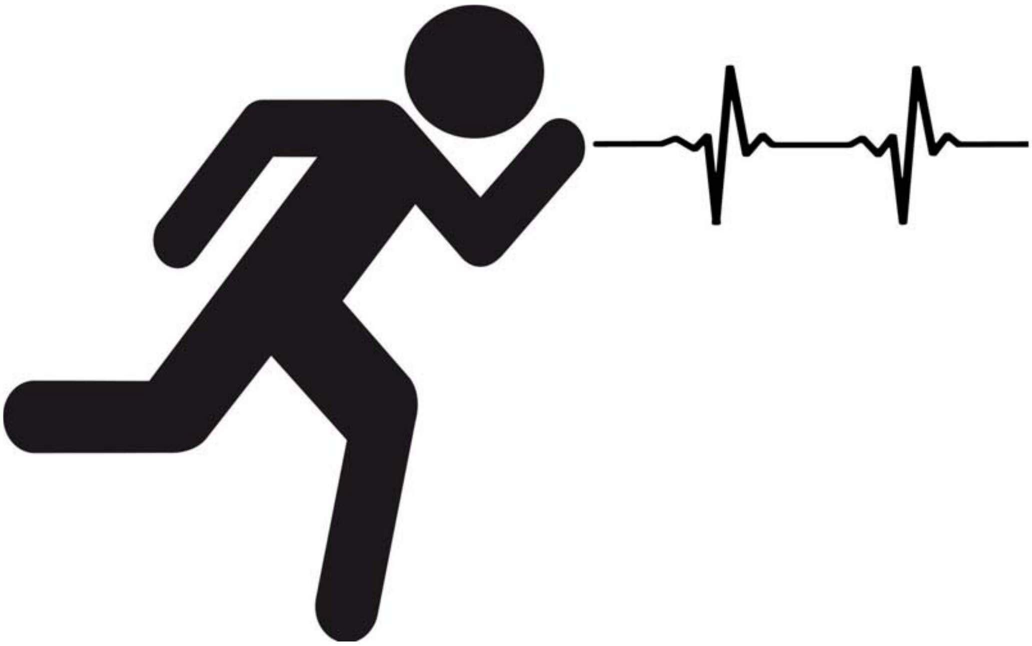
STUDIES IN SPORT, PHYSICAL EDUCATION AND HEALTH

248

Ville Vesterinen

Predicting and Monitoring Individual Endurance Training Adaptation and Individualizing Training Prescription

With Endurance Performance, Cardiac Autonomic Regulation and Neuromuscular Performance



JYVÄSKYLÄN YLIOPISTO

STUDIES IN SPORT, PHYSICAL EDUCATION AND HEALTH 248

Ville Vesterinen

Predicting and Monitoring Individual Endurance Training Adaptation and Individualizing Training Prescription

With Endurance Performance, Cardiac Autonomic Regulation and Neuromuscular Performance

Esitetään Jyväskylän yliopiston liikuntatieteellisen tiedekunnan suostumuksella
julkisesti tarkastettavaksi yliopiston vanhassa juhlasalissa S212
marraskuun 18. päivänä 2016 kello 12.

Academic dissertation to be publicly discussed, by permission of
the Faculty of Sport and Health Sciences of the University of Jyväskylä,
in building Seminarium, auditorium S212, on November 18, 2016 at 12 o'clock noon.

UNIVERSITY OF JYVÄSKYLÄ

JYVÄSKYLÄ 2016

Predicting and Monitoring Individual Endurance Training Adaptation and Individualizing Training Prescription

With Endurance Performance, Cardiac Autonomic Regulation and Neuromuscular Performance

STUDIES IN SPORT, PHYSICAL EDUCATION AND HEALTH 248

Ville Vesterinen

Predicting and Monitoring Individual Endurance Training Adaptation and Individualizing Training Prescription

With Endurance Performance, Cardiac Autonomic Regulation and Neuromuscular Performance

UNIVERSITY OF JYVÄSKYLÄ

JYVÄSKYLÄ 2016

Editors
Taija Juutinen
Faculty of Sport and Health Sciences, University of Jyväskylä
Pekka Olsbo, Timo Hautala
Publishing Unit, University Library of Jyväskylä

Cover illustration: Ville Vesterinen

URN:ISBN:978-951-39-6804-5
ISBN 978-951-39-6804-5 (PDF)

ISBN 978-951-39-6803-8 (nid.)
ISSN 0356-1070

Jyväskylä University Printing House, Jyväskylä 2016

ABSTRACT

Vesterinen, Ville
Predicting and monitoring individual endurance training adaptation and
individualizing training prescription with endurance performance, cardiac
autonomic regulation and neuromuscular performance

Jyväskylä: University of Jyväskylä, 2016, 102 p.
(Studies in Sport, Physical Education and Health,
ISSN 0356-1070; 248)
ISBN 978-951-39-6803-8 (nid.)
ISBN 978-951-39-6804-5 (PDF)

Humans adapt differently to standardized endurance training programs. While some individuals may achieve huge improvements in physical fitness, other individuals may even suffer from negative adaptations. Special attention should be paid to identification of non-responders, which would enable to modify training to be more effective. Therefore, the aim of the present study was to investigate whether running performance, cardiac autonomic regulation and neuromuscular performance can be used in 1) predicting subsequent endurance training adaptations; 2) monitoring training adaptations; and 3) individualizing training prescription in recreational endurance runners. Three longitudinal training studies were performed consisting of: 1) a 28-wk period with progressively increasing training volume and intensity (n = 28); 2) an 18-wk period including either a high volume of low-intensity (HVT) or high-intensity training (HIT) (n = 40); and 3) a 12-wk study with heart rate variability (HRV) guided training (n = 40). Nocturnal HRV was the strongest pretraining subject characteristic to predict training adaptation being negatively associated with the adaptation to HVT and positively to HIT. Thus, runners with lower HRV showed greater positive changes in endurance performance after HVT, while runners with higher HRV responded well to HIT. Running speeds of 80-90% of HR_{max} in a three-stage warm-up running protocol were the most competent variables to monitor changes in maximal endurance performance during the training period. In the final study, the HRV-guided group trained according to daily HRV measures. HIT was completed, if HRV was within a normal range. Otherwise, low-intensity training was performed. Endurance and neuromuscular performances improved in the HRV-guided group but not in the traditional predefined training group. The findings of the thesis suggest that resting HRV and the warm-up running protocol show great potential as practical tools for monitoring of adaptations and individualizing training by selecting the content of training and for prescribing the timing of HIT sessions.

Keywords: endurance training, individual training adaptation, monitoring, training prescription, cardiac autonomic regulation.

Author's address
Ville Vesterinen
KIHU – Research Institute for Olympic Sports
Rautpohjankatu 6
FI-40700 Jyväskylä
Finland
ville.vesterinen@kihu.fi

Supervisors
Professor Keijo Häkkinen, PhD
Department of Biology of Physical Activity
University of Jyväskylä, Finland

Docent Ari Nummela, PhD
KIHU – Research Institute for Olympic Sports
Jyväskylä, Finland

Reviewers
Professor Robert P. Lamberts, PhD
Division of Orthopedic Surgery
Stellenbosch University
Stellenbosch, South Africa, and
Division of Exercise Science and Sports Medicine
University of Cape Town,
Cape Town, South Africa

Professor Stephen Boutcher, PhD
School of Medical Sciences
University of New South Wales
Sydney, Australia

Opponent
Professor Stephen Seiler, PhD
Faculty of Health and Sport Sciences
University of Agder
Kristiansand, Norway

ACKNOWLEDGEMENTS

The study was conducted by KIHU – Research Institute for Olympic Sports, Jyväskylä, Finland and the Department of Biology of Physical Activity, University of Jyväskylä, Finland. There are many people who has contributed my work and I would like to express my thanks to all of them; without their effort this would not have been possible.

I have been most fortunate to have Professor Keijo Häkkinen ja Docent Ari Nummela as my supervisors. Keijo, thank you for your great guidance and introducing me to the science world. Ari, I am grateful for the opportunity to work in your research group and excellent guidance during these years.

I was honored to have Professor Robert Lamberts (Stellenbosch University, University of Cape Town, South Africa) and Professor Stephen Boutcher (University of New South Wales, Australia) as the reviewers of my thesis. I am grateful for the effort and valuable comments that have improved this thesis.

A sincere thank you to my colleagues and co-authors Dr. Esa Hynynen, Jussi Mikkola, Tanja Laine and Laura Joensuu for your valuable contribution to this study. Thank you also to Sirpa Vänttinen for your hard work in the laboratory. In addition, I would like to thank Dr. Sami Äyrämö for valuable contribution in data analysis.

I acknowledge my co-authors not mentioned above including Ida Heikura, Javier Botella and colleagues from South Africa Theresa Mann, Ben Capostagno and David Leith (University of Cape Town) and other students who have valuable contribution to this work. In addition, I would like to express my thanks to Dr. Ritva Taipale for revision of the English language of this thesis.

It has been a pleasure to work in KIHU. Thus, I would want to thank all the staff of KIHU. This work is truly a team effort.

Without all the participants who volunteered in the training projects, this study would not be possible to carry out. Thank you.

I owe my sincere thanks to my family, relatives and all my friends for an immense support during all my life. Finally, my deepest thanks go to my love Hanna and our lovely children for sharing your life with me.

This study was financially supported by TEKES – the Finnish Funding Agency for Innovation, the Finnish Ministry of Education and Culture, KIHU – Research Institute for Olympic Sports, the Department of Biology of Physical Activity, Foundation of Sports Institute, the Finnish Sports Research Foundation, Pajulahti Sports Institute, Firstbeat Technologies Ltd., Suunto Ltd.

Jyväskylä, October 2016
Ville Vesterinen

ABBREVIATIONS

AerT	aerobic threshold
AnT	anaerobic threshold
ATP	adenosine triphosphate
CMJ	counter movement jump
ECG	electrocardiography
EXP	HRV-guided experimental training group
GPS	global positioning system
HFP	high frequency power
HIT	high-intensity training
HR	heart rate
HR_{max}	maximal heart rate
HR_{rest}	resting heart rate
HRR	heart rate recovery
HRV	heart rate variability
HVT	high volume training
INT	intense training period
LFP	low frequency power
LIT	low-intensity training
LT	lactate threshold
MOD	moderate-intensity training
PREP	preparation period
RE	running economy
RJ	reactivity jump
RMSSD	square root of the mean squared differences between successive RR intervals
RPE	rate of perceived exertion
RRI	RR interval
RS	running speed
RS_{peak}	peak treadmill running speed
SCE	submaximal control exercise
SDNN	standard deviation of RR intervals
SRT	submaximal running test
SWC	the smallest worthwhile change
TP	total power
TRAD	traditional, preprogrammed training group
VLFP	very low frequency power
VO_{2max}	maximal oxygen uptake

LIST OF ORIGINAL PUBLICATIONS

This thesis is based on the following original articles, which are referred to in the text by Roman numerals:

I Vesterinen, V., Häkkinen, K., Hynynen, E., Mikkola, J., Hokka, L. & Nummela, A. (2013) Heart rate variability in prediction of individual adaptation to endurance training in recreational endurance runners. *Scandinavian Journal of Medicine and Science in Sports*, 23: 171-180.

II Vesterinen, V., Häkkinen, K., Laine, T., Hynynen, E., Mikkola, J. & Nummela, A. (2016) Predictors of individual adaptation to high-volume or -intensity endurance training. *Scandinavian Journal of Medicine and Science in Sports*, 26: 885-893.

III Vesterinen, V., Nummela, A., Laine, T., Hynynen, E., Mikkola, J. & Häkkinen, K. (2016) A submaximal running test with post-exercise cardiac autonomic and neuromuscular function in monitoring endurance training adaptation. *Journal of Strength and Conditioning Research* (In Press).

IV Vesterinen, V., Nummela, A., Äyrämö, S., Laine, T., Hynynen, E., Mikkola, J. & Häkkinen, K. (2016) Monitoring training adaptation with a submaximal running test in field conditions. *International Journal of Sports Physiology and Performance,* 11: 393-399.

V Vesterinen, V., Nummela, A., Heikura, I., Laine, T., Hynynen, E., Botella, J., & Häkkinen, K. (2016) Individual endurance training prescription with heart rate variability. *Medicine and Science in Sport and Exercise*, 48: 1347-1354.

CONTENTS

1 INTRODUCTION

Beneficial effects of regular endurance training on health and physical fitness have been widely recognized. Numerous studies have confirmed enhancements in cardiorespiratory fitness, aerobic metabolism and cardiac autonomic function after endurance training. The focus of research has mainly been on the mean effects in maximal oxygen uptake (VO_{2max}) or endurance performance, however, several studies have also expressed that individuals adapt differently to standardized endurance training programs (Bouchard & Rankinen 2001; Hautala et al. 2003; Vollaard et al. 2009; Scharhag-Rosenberger et al. 2012). While some individuals have shown over 50% improvement in VO_{2max} after endurance training, other individuals have shown negative responses to training. Therefore, results presented as means do not give adequate information about the effectiveness of endurance training. Special attention should be paid to individuals without any improvements or even negative adaptations after regular training. The questions remain, whether it is possible to identify non-responders prior to training and whether non-responders improve better to varied endurance training programs. It has been proposed that genetic variance could partly explain the inconsistency in training adaptations in sedentary people (Bouchard et al. 2011). In addition, many other factors have been shown to be related to individual training adaptation including age, sex, pretraining fitness level, and cardiac autonomic regulation (Bouchard & Rankinen 2001; Hautala et al. 2003). Nevertheless, an individual's trainability to different endurance training programs is still unclear.

One crucial factor in successful training is the optimal regulation of training load and recovery. If the training stimulus is too easy or demanding in relation to recovery, training may lead to undesirable adaptations. Daily information about the progress of training adaptations may give beneficial information for coaches and athletes for optimizing training load and recovery. Typically, athletes perform a maximal laboratory test two to three times per year in order to get objective information about the effectiveness of their training program. However, the maximal laboratory testing is not possible to repeat weekly to obtain regular information about training adaptations due to its impracticality, expensiveness, and interfering effects on normal training habits. Submaximal power, heart rate variability (HRV) and heart rate recovery (HRR) have been suggested to be important determinants of endurance training adaptation (Scharhag-Rosenberger et al. 2009; Buchheit et al. 2010; Lamberts et al. 2011; Daanen et al. 2012). In addition, neuromuscular function of the lower extremities has been observed to be related to endurance running performance (Dumke et al. 2010; Hebert-Losier, Jensen & Holmberg 2014). These measurements have been proposed to have potential for monitoring fatigue and predicting changes in endurance performance parameters. However, most of the previous studies have investigated the methods in predicting maximal endurance performance in cross-sectional setups and less is known about the usefulness of the methods in monitoring changes in endurance running performance in longitudinal training studies. In addition, most of the studies have been conducted in laboratory conditions and less is known about the applicability of the methods as training monitoring tools in real training conditions.

Endurance training programs are typically predetermined based on literature, general recommendations, experience of coaches, and presumptions about an athlete´s current training and recovery status. It is well known that adaptations to endurance training are individual. The same training program causes different responses in individuals and is not necessarily optimal for everyone despite similar training backgrounds. Individualized training prescription according to the status of cardiac vagal activity may be a beneficial method to achieve greater improvements and reduce large variation in training adaptations. In studies by Kiviniemi et al. (2007; 2010) the timing of intensive endurance training exercises was based on daily HRV measurements. However, it has been proposed that it is more valuable to use longer trends of HRV, e.g. a week rolling average compared with assessing HRV on a single day (Plews et al. 2013). The use of the long-term HRV trend in training prescription allows block periodization of high-intensity training (HIT) sessions, wherein shorter training periods (1–4 weeks) are utilized to focus on improving a few selected characteristics. Block periodized HIT has recently been suggested to provide superior training adaptations compared with traditionally organized HIT (Ronnestad, Hansen & Ellefsen 2014; Ronnestad et al. 2016). However, the timing of HIT blocks has been typically determined subjectively without objective information about athlete´s training status and may not always be optimal in terms of regulating training load and recovery.

The ultimate purpose of this thesis was to clarify possible methods to improve the effectiveness of endurance training, which would be beneficial in terms of training for physical fitness, health care and well-being in recreational and elite athletes as well as in sedentary people. Therefore, this thesis investigated individual endurance training adaptations with an emphasis on cardiorespiratory, cardiac autonomic and neuromuscular factors in predicting and monitoring individual adaptations and individualizing training programs in recreational endurance runners.

2 REVIEW OF THE LITERATURE

2.1 Determinants of endurance performance

Many physiological factors are limiting and regulating endurance performance capacity. Maximal oxygen uptake (VO_{2max}) has been proposed to be one of the most important determinants of endurance performance (Figure 1). It refers to the highest rate at which the body can consume oxygen during intense exercise. VO_{2max} integrates the ability of the lungs to transfer oxygen from the air to the blood, the ability of the blood and red blood cells to carry oxygen, the heart to pump blood, the circulatory system to distribute blood to muscles and the muscles to use oxygen. VO_{2max} sets the upper limit for aerobic energy production in endurance performance but it does not determine the final performance (Bassett & Howley 2000). VO_2 or performance at lactate threshold (LT) has been proposed to be the best physiological predictor of distance running performance by integrating VO_{2max}, fractional utilization of VO_{2max}, and running economy (RE) (Coyle 1995; Bassett & Howley 2000). However, in a homogenous group of well-trained endurance athletes, RE may be a stronger predictor of endurance performance than VO_{2max} (Coyle 1995; Paavolainen, Nummela & Rusko 1999). Furthermore, neuromuscular characteristics play an essential role in endurance running performance (Paavolainen et al. 1999; Nummela et al. 2006). In addition to aerobic power and capacity, anaerobic characteristics, such maximal anaerobic performance e.g. measured by running speed in maximal anaerobic test (V_{MART}) and anaerobic capacity, have effects on endurance running performance. During marathon running the relative amount of anaerobic metabolism is small yet in shorter distances (i.e. 5 and 10 km running), it is significant (Joyner & Coyle 2008). On the other hand, glycogen stores and fat oxidation have important roles in energy metabolism in prolonged (> 90 min) endurance performance (Yeo et al. 2011).

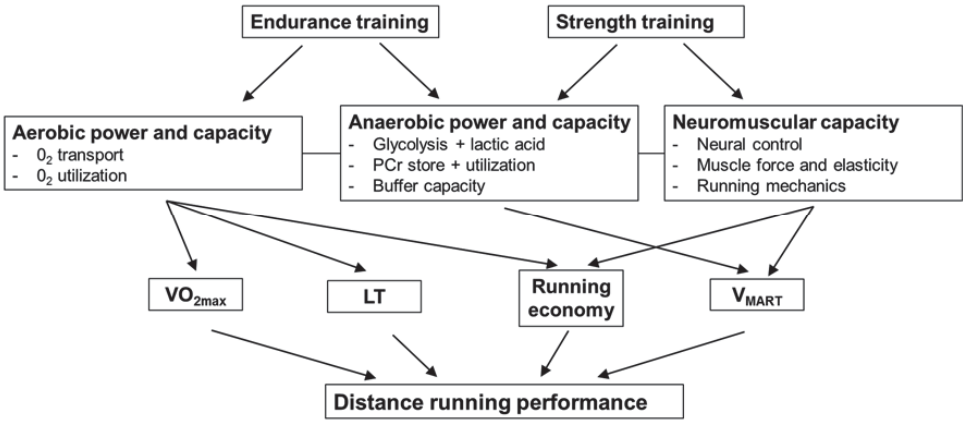


FIGURE 1 Determinants of distance running performance (from Paavolainen et al. 1999). VO_{2max}, maximal oxygen uptake; LT, lactate threshold; V_{MART}, peak velocity in maximal anaerobic test.

2.2 Adaptations to endurance training

According to the overload principle, the human body adapts positively to training if the training stimulus is adequate for disturbing homeostasis and the recovery time after the stimulus allows for a return to homeostasis and for an increase in performance up to the initial level (Figure 2). This is often referred to as the “one-factor theory” or “supercompensation theory”. This theory was first described by Jakowlew in 1976. The optimal regulation of training stimulus and recovery plays an important role in successful training. Failure in this regulation may lead to undesirable adaptations to training marked as a decreased performance, such as under- or overtrained state (Uusitalo 2001; Meeusen et al. 2013). Each bodily function adapts differently to training and needs different recovery times, which makes finding the optimal balance between training load and sufficient recovery time difficult.

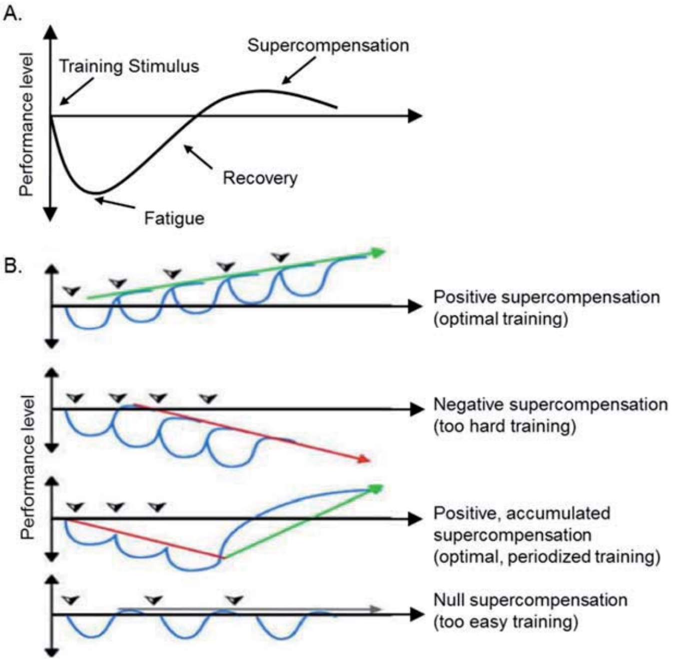


FIGURE 2 The theory of supercompensation (one-factor theory). Supercompensation models to a single training session (A) and different kind of training (B) (modified from Zatsiorsky & Kraemer 2006, 10-12).

In addition, Zatsiorsky & Kraemer (2006, 12-15) proposed the two factor theory, which is based on the idea that preparedness (characterized by the athlete´s potential sport performance) is not stable but rather varies with time (Figure 3). There are two components of the athlete´s preparedness: physical fitness (considered to be the slow-changing component) and fatigue (both mental and physical; considered to be the fast-changing component). According to the two-factor theory of training, the immediate training effect after a training session is a combination of these two processes: athlete preparedness improves due to performance gains and worsens due to fatigue.

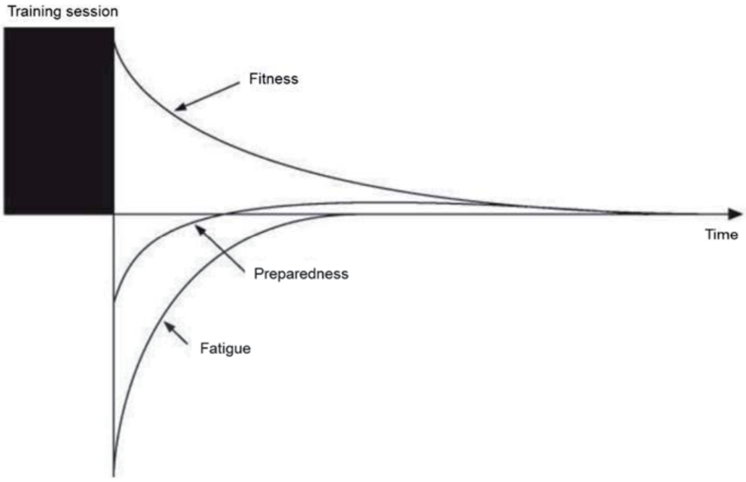


FIGURE 3 Two-factor theory of training (modified from Zatsiorsky & Kraemer 2006, 13).

2.2.1 Cardiorespiratory and metabolic adaptations

Endurance training can induce many physiological adaptations leading to improved endurance performance. The magnitude of the endurance training adaptations depends on the frequency, intensity and duration of the training sessions, and recovery periods, along with the initial training status, genetic potential, age and sex of the individual (Jones & Carter 2000). The main effects of endurance training focus on the function of the cardiorespiratory system as well as the oxidative capacity and glycogen stores of the muscles. Cardiorespiratory fitness refers to the ability of the heart, lungs and circulatory system to deliver oxygen to working muscles and is usually measured by VO_{2max}. Both central and peripheral mechanisms behind the training adaptation are described in the Fick equation: VO_2 = cardiac output * a-vO_{2diff} (where cardiac output = HR * stroke volume (SV) and a-vO_{2diff} = arteriovenous oxygen difference). Aerobic capacity is strongly related to maximal cardiac output. The heart size and SV are higher in endurance-trained compared with untrained individuals (Jones & Carter 2000; Wang et al. 2012). The increases in SV, plasma volume, and cardiac output with training are mainly responsible for improved VO_{2max} since maximal heart rates (HR) tend to be similar in elite athletes and sedentary individuals (Green, Jones & Painter 1990; Jones & Carter 2000). Higher intensities of training have been shown to be more effective for improving VO_{2max} than lower intensities (Gormley et al. 2008). High-intensity interval training (HIIT) has been reported to cause more gains in SV and cardiac output compared with continuous moderate-intensity training (MOD) (Daussin et al. 2007; Gormley et al. 2008). On the other hand, more prolonged HIIT (~ 3.5 min) at the speed of VO_{2max} may induce greater improvement in VO_{2max} compared with shorter (~ 30 s), supramaximal sprint interval training (Esfarjani & Laursen 2007). It has been suggested that 95-100% of VO_{2max} speed (Hill & Rowell 1997;

Midgley, McNaughton & Wilkinson 2006) or 90-95% of HR_{max} intensity (Helgerud et al. 2007; Seiler et al. 2013) would be optimal for improving aerobic capacity, but there have been no well controlled training studies to support this presumption (Midgley, McNaughton & Wilkinson 2006).

Aerobic energy metabolism is the main pathway for adenosine triphosphate (ATP) resynthesis for longer than two minutes of endurance performance (Gastin 2001). The process requires a sufficient delivery of oxygen to the active muscles via oxidative phosphorylation and the respiratory and cardiovascular systems. Endurance training may enhance mitochondrial density and increase the number of capillaries surrounding muscle fibers. The adaptations increase the capacity for aerobic energy production from both fatty acid and carbohydrate oxidation, which improves muscle performance (Gastin 2001). Metabolic adaptations to endurance training are influenced by the volume and intensity of training and the duration of a regular training period. While high-intensity (interval) training improves VO_{2max} mainly by improved cardiorespiratory adaptations, improvement of VO_{2max} with low-intensity training (LIT) and MOD is based mainly on peripheral mechanisms. MOD is more effective in increasing muscle oxidative capacity than HIT (Daussin et al. 2007). Prolonged, LIT sessions produce increases in mitochondrial density (Dudley, Abraham & Terjung 1982). Furthermore, increased $a\text{-}vO_{2diff}$ has been proposed to include increased capillary density and transformation of type IIX muscle fibers into fatigue resistant type IIA fibers (Spina 1999). Furthermore, it has been reported that activity of oxidative enzymes such as succinate dehydrogenase (SDH), that enable mitochondria to break down nutrients to ATP, may increase after HIT and are associated with endurance performance (Evertsen et al. 1999). In addition, endurance training may enhance aerobic metabolism by increasing muscle blood flow, the capacity of muscles to store glycogen, and the ability of muscles to use fat as an energy source (Greiwe et al. 1999; Laughlin & Roseguini 2008). It has been reported that endurance training increases rates of fat oxidation and decreases muscle glycogen utilization during submaximal exercise. The increased fat oxidation is generally related to increased mitochondrial volume along with increased mitochondrial enzymatic adaptations to use fat, coupled with decreases in the signals that activate the major enzymes that metabolize carbohydrates (Yeo et al. 2011). In addition to aerobic energy metabolism, the ability to generate ATP anaerobically is also important in shorter endurance sports and in sprint finishes between athletes whose aerobic capacities are similar (Houmard et al. 1991). Anaerobic metabolism can be improved by HIT or maximal interval/sprint and power training by increasing the rate of energy production via the ATP-creatine phosphate (CP) system and anaerobic glycolysis (lactate system).

2.2.2 Adaptations in cardiac autonomic regulation

The autonomic nervous system regulates many bodily functions such as the function of the cardiovascular system. The autonomic nervous system consists the parasympathetic (vagal) and sympathetic branches, which together regulate optimal functions, such as peripheral vascular tone, blood pressure and HR during various situations and activities. The vagus nerve is responsible for parasympathetic control of the heart. Nerve impulses are received by the cardiac sinoatrial node, atrioventricular conducting pathways, and the atrial and possibly ventricular myocardium. The sympathetic activity originates from the spinal cord and is received by all regions of the heart. Vagal stimulation decreases HR and increases HRV, which refers to the variation in consecutive R-R intervals (RRI), whereas sympathetic stimulation produces the opposite effects (Hainsworth 1998, 3-28). Therefore, HRV provides an indirect, non-invasive method to evaluate the status of the autonomic nervous system. HRV at high frequencies (HF, 0.15-0.40 Hz) and the overall variability of RRIs represented by total power (TP) are generally viewed to reflect vagal regulation (Figure 4) (Task Force 1996; Uusitalo et al. 1996; Martinmaki et al. 2006). In addition to the frequency domain measures of HRV, the time domain measures, including the square root of the mean squared differences of successive RRIs (RMSSD) and the standard deviation of the RRIs (SDNN) have been proposed to reflect the state of vagal activity (Task Force 1996; Uusitalo et al. 1996). The physiological meaning of low (LF, 0.04-0.15 Hz) and very low frequencies (VLF, 0-0.03 Hz) is more controversial. It has been proposed that LF reflects both sympathetic and vagal activity (Martinmaki et al. 2006), and only sympathetic activity of the autonomic regulation (Malliani et al. 1991).

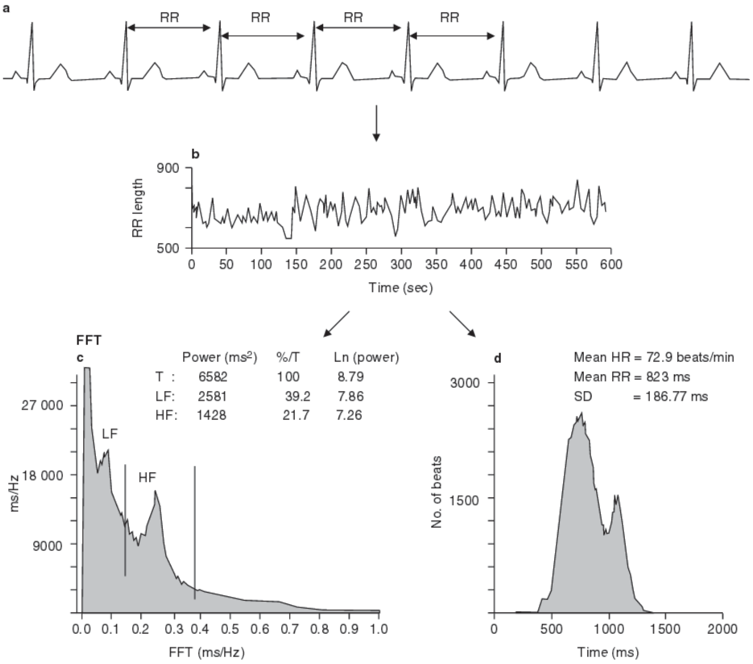


FIGURE 4 Analysis of heart rate variability. Calculation of consecutive RR intervals on ECG (a), results in the tachogram (b) that can be analysed in the frequency domain (c) and the time domain (d) (Aubert, Seps & Beckers 2003).

Age and cardiovascular fitness are related to cardiac autonomic activity (Goldsmith et al. 1992; Aubert, Seps & Beckers 2003; Zhang 2007; Sztajzel et al. 2008). Ageing tends to cause a decrease in HRV (Zhang 2007), while endurance training has the opposite effect. Many previous studies have suggested that endurance training induces a decrease in HR and an increase in HRV at rest or during exercise at a submaximal intensity (Yamamoto et al. 2001; Borresen & Lambert 2008; Scharhag-Rosenberger et al. 2009; Buchheit et al. 2010; Bellenger et al. 2016; Nummela et al. 2016). The decrease in HR and the increase in HRV may be caused by a decrease in the intrinsic rhythmicity of the heart and decreased cardiac sympathetic activity and/or increased parasympathetic activity (Smith et al. 1989). On the other hand, decreased HRV has been found after intense training periods, indicating increased sympathetic activity due to accumulated training load and physical stress, so called overreaching (Pichot et al. 2000; Pichot et al. 2002; Baumert et al. 2006; Hynynen et al. 2007). In contrast, Le Meur et al. (2013b) found a progressive decrease in HR and an increase in HRV at both rest and exercise during three weeks of intense training with decreased endurance performance, indicating increased cardiac vagal activity (parasympathetic hyperactivity) in functionally overreached athletes. After one week of tapering, HR and HRV values recovered to the baseline level simultaneously with an improvement in endurance performance (Le Meur et al. 2013b). On the other hand, unchanged HRV has also been reported in overreached athletes after an intense training period (Hedelin et al. 2000a). Training load can be increased by increasing training volume, intensity or frequency. The differences in training contents may partly explain the differences in cardiac autonomic adaptation between the studies. Plews et al. (2014) observed that increased cardiac vagal activity was related to an increased training time spent at low-intensity, while HIT suppressed cardiac vagal activity. In addition, the timing, posture and methodology of HRV data collection may explain the contradicting results. Morning and night-time HRV measurements have been used for determining resting HRV. Autonomic cardiac activity is highly sensitive to environmental factors, such as noise, light, and temperature (Achten & Jeukendrup 2003). Nocturnal HRV collection is more standardized because it is free of external disturbances (Pichot et al. 2000). On the other hand, sleep patterns may cause fluctuations in nocturnal HRV, especially over short analyzing periods (Buchheit et al. 2004). In shorter (typically 3-5 min) morning collections, it has been recommended to use the time domain analysis of HRV due to greater reliability than spectral analysis of HRV (Al Haddad et al. 2011).

2.2.3 Neuromuscular and hormonal adaptations

Neuromuscular factors have been shown to be important determinants of endurance running performance (Paavolainen et al. 1999; Nummela et al. 2006). The countermovement jump (CMJ) has been used in several sports to assess lower-body muscle power and has often been found to correlate with running performance (Dumke et al. 2010; Hebert-Losier, Jensen & Holmberg 2014). Endurance training typically has no major effect on force production ability of muscles. Combined endurance and strength training is needed for achieving improvements in force production (e.g. McCarthy, Pozniak & Agre 2002; Mikkola et al. 2007; Taipale et al. 2014). It has been observed that simultaneous explosive-strength training, with sprinting and endurance training caused improvement in 5 km running performance without changes in VO_{2max}. Improved neuromuscular characteristics were transferred into improved muscle power and running economy in well trained athletes, which is one key factor in distance running performance (Noakes, Myburgh & Schall 1990; Paavolainen, Nummela & Rusko 1999; Saunders et al. 2004). In addition, combining endurance training with maximal strength training can enhance endurance running performance by improving RE (Taipale et al. 2010). Improved endurance performance may be related to delayed activation of less efficient type II muscle fibers, improved neuromuscular efficiency, conversion of fast-twitch type IIX muscle fibers into more fatigue-resistance type IIA fibers, or improved musculo-tendinous stiffness (Ronnestad & Mujika 2014). On the other hand, Vikmoen et al. (2016a; 2016b) observed that combining endurance training with heavy strength training induced improvements in endurance performance and economy in cycling but not in running. A high volume of combined endurance and strength training can lead to what is known as the interference effect in neuromuscular adaptations, which results in a reduced capacity to develop strength (Hickson 1980). Endurance exercise may negatively affect intracellular pathways for myofibrillar protein synthesis and may thus impair the hypertrophic response to strength training (Mujika, Ronnestad & Martin 2016).

The endocrine system has profound regulatory effects within the human body and thus has the ability to maintain appropriate function within many physiological systems (Hackney & Lane 2015). Testosterone and cortisol hormones play an important role in protein and carbohydrate metabolism (Urhausen, Gabriel & Kindermann 1995). An acute increase in testosterone and cortisol is typically observed after an endurance training session (Hackney, Sinning & Bruot 1988; Kraemer & Ratamess 2005). Exercise duration, intensity and mode affect the magnitude of the acute hormonal responses (Hackney et al. 2012; Wahl et al. 2013). In addition, the subsequent recovery after exercise and training status may have an effect on both acute hormonal responses and chronic adaptations (Kraemer & Ratamess 2005). After prolonged endurance training, an increase (Grandys et al. 2009), a decrease (Wheeler et al. 1991; Hoogeveen & Zonderland 1996) or no change (Taipale et al. 2010; Schumann et al. 2015) in basal concentrations of testosterone, have been observed. Even after a similar training content, hormonal adaptations can be different. Lee et al. (2016) observed significant improvements in endurance performance, without any changes in testosterone, while Zinner et al. (2014) found improvements in endurance performance and an increase in basal testosterone concentrations after 2 weeks of HIT in triathletes. It has been suggested that the increase in serum testosterone may represent a positive adaptation to the training load (Purge, Jurimae & Jurimae 2006; Grandys et al. 2009). Furthermore, a negative adaptation to endurance training has been associated with a decrease in basal levels of serum testosterone (Wheeler et al. 1991; Urhausen, Gabriel & Kindermann 1995; Hoogeveen & Zonderland 1996; Uusitalo et al. 1998). On the other hand, well-trained endurance athletes tend to have lower levels of testosterone compared with untrained individuals (Hackney, Sinning & Bruot 1988). The lowered testosterone levels of the endurance-trained male could disrupt some of their anabolic or androgenic processes (Hackney, Moore & Brownlee 2005). In addition, nutrition, circadian rhythms, maturation level, and menstrual cycles in women may have effects on hormonal adaptations to training and diversities in the observations (Hackney & Viru 2008). The possible association between hormone concentrations and endurance training adaptation is still unclear.

2.3 Pretraining determinants of individual variation in adaptation to endurance training

The beneficial effects of regular aerobic endurance training on cardiovascular fitness, endurance performance, and health are well known. Typically training interventions have been focused on the mean effects in endurance performance or VO_{2max}. However, several studies have shown that individuals adapt differently to standardized endurance training programs. Although mean improvements in VO_{2max} following standardized training often fall within 5-15% of baseline values, individual responses have been shown to range from negative values to over 50% improvement (Bouchard & Rankinen 2001; Hautala et al. 2003; Vollaard et al. 2009; Scharhag-Rosenberger et al. 2012). Genetic variance may partly explain the difference in training adaptations in sedentary people (Bouchard et al. 2011). Nevertheless, an individual's trainability to different endurance training programs among different populations is not well-known.

2.3.1 Effects of age, sex, training background, and fitness level on training adaptation

A possible method to reduce large variation in training adaptations may be individualized training. The challenge is to identify individuals who will not respond adequately to traditional training as early as possible. Many factors can lead to great variation in the adaptation to endurance training including: genetics, age, sex, nutrition, prior training, fitness level, sleep, rest, and stress. However, Bouchard & Rankinen (2001) summarized that age, sex, race, and baseline fitness level together accounted only for 11% of the variance in the response to 20 weeks of standardized endurance training in 720 healthy sedentary subjects. In recreational endurance runners, age, sex, compliance with the training program, and baseline VO_{2max} explained 16% of the variance in training adaptation (Scharhag-Rosenberger et al. 2012). In addition, Hautala et al. (2003) found that age accounted for 16% of the variation in adaptation to 8 weeks of training, in sedentary males but did not observe a relationship between training adaptation and pretraining fitness level. It seems that the pretraining characteristics of subjects explain only a relatively small amount of the subsequent training adaptations.

2.3.2 Cardiac autonomic regulation as a predictor of endurance training adaptation

During recent years, more studies are supporting the idea that HRV, reflecting cardiac autonomic activity, at baseline could predict subsequent training adaptations (Hedelin, Bjerle & Henriksson-Larsen 2001; Hautala et al. 2003; Buchheit et al. 2010; Boutcher et al. 2013). The positive relationship between vagal mediated resting HFP at baseline and increase in VO_{2max} has been observed after eight weeks of MOD in sedentary men (Hautala et al. 2003) and after twelve weeks of HIT in sedentary women (Boutcher et al. 2013). In addition, Hedelin et al. (2001) observed the positive relationship between pretraining HFP and the change in VO_{2max} after 7 months of a training and competition season in national level endurance athletes proposing that the higher pretraining vagal activity was related to greater improvement in aerobic capacity. Interestingly, individuals with lower HRV were identified as non-responders for the regular endurance training (Hedelin, Bjerle & Henriksson-Larsen 2001). In contrast, Buchheit et al. (2010) reported the negative relationship between pretraining RMSSD and the change in 10 km running performance after an 8-week endurance training period in moderately trained runners. In the previous studies, endurance training has mostly been a mixture of LIT, MOD, and HIT, which may partly explain contradictory results. Previous studies have not focused on the effects of training intensity and volume in the relationship between cardiovascular autonomic regulation and training adaptations. However, specific physiological adaptations in cardiovascular, respiratory, metabolic, and neuromuscular functions are dependent on the training volume, intensity and frequency (Vollaard et al. 2009; Laursen 2010). Therefore, training content may have an effect on the relationship between pretraining cardiac autonomic activity and subsequent training adaptation.

2.4 Monitoring endurance training adaptations

The essential feature of a successful training program is the optimal regulation of training load and recovery. If the training stimulus is too easy or too demanding in relation to recovery, training may lead to undesirable adaptations. A possible method to improve training adaptations would be the precise and continuous monitoring of the processes of adaptation. Appropriate monitoring can aid in determining whether an athlete is adapting to a training program while also in minimizing the risk of developing overtraining, illness, and injury (Halson 2014). If undesirable adaptations appear, it is possible to modify a training program based on the collected information. Until recently, maximal laboratory tests were needed in order to get objective information about endurance training adaptations. However, continuous e.g. weekly monitoring by performing maximal laboratory tests is not done due to the impracticality, expensiveness, and interfering effects on normal training habits. Therefore, there is a need for a practical and valid method for regular monitoring of training adaptations. Training load monitoring methods can be divided into external and internal methods. External training load is defined as the work completed by an athlete measured independently of his or her internal characteristics, such the mean power of performance (Wallace, Slattery & Coutts 2009). On the other hand, internal load, the relative physiological and psychological stress imposed on the athlete, determines the stimulus for training adaptation. Typically, internal load is measured by perception of effort, HR, blood lactate, and training impulse. As both external and internal loads have some merit for understanding the athlete´s total training load, a combination of both are important for training monitoring (Halson 2014).

2.4.1 Exercise heart rate

Exercise HR is probably the most frequently used method to quantify training intensity and internal training load in running. It is generally observed that HR at submaximal exercise decreases after endurance training (Lambert, Mbambo & St Clair Gibson 1998; Skinner et al. 2003; Scharhag-Rosenberger et al. 2009; Buchheit et al. 2010; Vesterinen et al. 2014), which is mainly due to increased SV (Bellenger et al. 2016). Significant correlations between decreases in exercise HR and improvements in high-intensity or maximal endurance performance have been widely observed (Lamberts et al. 2010a; Buchheit et al. 2012; Buchheit et al. 2013; Vesterinen et al. 2014; Lamberts 2014). Thus, submaximal exercise HR may be an efficient method to track changes in maximal aerobic running speed. However, decreased HR after training does not automatically reflect improved endurance performance. Decreased HR has also been observed to be related to the negative training adaptations such as in the case of short-term overreaching or overtraining (Hedelin et al. 2000b; Le Meur et al. 2013b).

Lamberts et al. (2011) have developed a submaximal test called the Lamberts and Lambert submaximal cycle test for monitoring fatigue and predicting training adaptation in cycling. The protocol consists of three stages with fixed HRs of 6 min at 60% and 80% and 3 min at 90% of HR_{max}. Recently, Otter et al. (2015) tested the same protocol in rowing. Performance power at 90% of HR_{max} was the strongest predictor of maximal endurance performance in both cycling and rowing (Lamberts et al. 2011; Otter et al. 2015). In addition, the reliability was the highest at 90% HR_{max} with intra-class correlation coefficients of 0.90 in rowing and 1.00 in cycling (Lamberts et al. 2011; Otter et al. 2015). High reliability has also been reported in running performance at 80% of HR_{max} in a submaximal running test on treadmill (Wang et al. 2010).

The previous studies have been conducted using cross-sectional designs. Less is known whether submaximal performance tracks the changes in endurance performance during prolonged training sensitively enough and is it able to identify responders and non-responders during a training period. It has, however, been reported that the variables in the submaximal test were able to track fatigue and recovery state during an intensive training camp (Hammes et al. 2016) and a whole training year (Otter et al. 2016). In addition, a case study by Lamberts et al. (2010a) suggested that cycling power at 90% HR_{max} in the submaximal cycling test was able to monitor changes in maximal cycling performance of a world-class cyclist during a 10-week training period. Furthermore, in our previous study, we observed that HR / running speed (RS) – index, calculated from all constant speed running exercises, serves as a potential tool for daily monitoring of training adaptation (Vesterinen et al. 2014). However, there are many well-established factors (i.e. environmental factors such as wind, temperature, and terrain as well as duration and intensity of exercise), which may cause fluctuation in exercise HR, and thus, may disturb the relationship between HR and RS (Lambert, Mbambo & St Clair Gibson 1998; Achten & Jeukendrup 2003). It has been proposed that an exercise intensity between 85 to 90% of HR_{max} is associated with the least day-to-day variation (Lamberts & Lambert 2009). Submaximal exercise HR, as well as performance power at a fixed HR may provide more valid information about training adaptation, if the duration and intensity of exercise are standardized.

2.4.2 Heart rate variability and heart rate recovery

High aerobic capacity is widely known to be related to high vagal resting activity. In addition, faster cardiorespiratory recovery measured by post-exercise heart rate recovery (HRR) and HRV have been reported to be related to a greater aerobic capacity (Hautala et al. 2001; Seiler, Haugen & Kuffel 2007; Daanen et al. 2012; Stanley, Peake & Buchheit 2013). Increased resting HRV is often associated with the positive adaptation (increased VO_{2max} or maximal aerobic speed) to endurance training, but can also be related to impaired performance (Hautala et al. 2003; Buchheit et al. 2010; Nummela, Hynynen & Vesterinen 2010; Boutcher et al. 2013; Plews et al. 2013; Da Silva et al. 2014; Bellenger et al. 2016). The measurements of post-exercise HRV and HRR may also have potential for monitoring training load and fatigue (Lamberts et al. 2009; Lamberts et al. 2010b; Otter et al. 2016; Hammes et al. 2016) as well as endurance training adaptation (Yamamoto et al. 2001; Lamberts et al. 2009; Buchheit et al. 2010; Lamberts et al. 2010b). Yamamoto et al. (2001) proposed that changes in cardiac autonomic regulation induced by endurance training can be seen sooner in post-exercise HRV measurements than at rest. Lamberts et al. (2009) reported that an increased HRR was associated with improvements in endurance performance after four weeks of HIT. In contrast, Lamberts et al. (2010a) found subsequently that an increased HRR was related with increased rate of perceived exertion (RPE) during cycling at 80-90% of HR_{max} in a functionally overreached cyclist. Recently, Aubry et al. (2015) observed that HRR improved in overreached athletes during three weeks of high volume training and concluded that a faster

HRR is not systematically associated with improved endurance performance. A similar finding was observed also after 6 days of high volume and high-intensity training in cyclists (Hammes et al. 2016). The results of these previous studies are, in part, conflicting and thus, the applicability of post-exercise HRR and HRV to monitor training adaptation will need further research work.

2.4.3 Neuromuscular function

Measures of neuromuscular functions such as the counter movement jump (CMJ) and the squat jump have become popular in training monitoring, especially in team-sports, due to their simplicity and the minimal amount of additional training load required to complete them (Cormack et al. 2008; McLean et al. 2010; Twist & Highton 2013). Measuring neural activation of muscles and fast force production abilities may provide useful data about an athlete´s neuromuscular fatigue status. Gathercole et al. (2015) reported that CMJ variables showed high intraday and interday reliability while changes in neuromuscular function after fatiguing exercise can be sensitively detected. In addition, it has been proposed that a decrease in the flight time – contraction time –relationship of CMJ represented neuromuscular fatigue during the Australian football season (Cormack et al. 2008). Measuring force production ability of the neuromuscular system may serve as a possible method to monitor training adaptation in endurance sports. However, to the best of my knowledge, there is no previously published study about the relationship between changes in CMJ and endurance training adaptations.

2.5 Prescription of endurance training

The regulation of a training load and recovery balance is a main element of a successful endurance training program. Adequate and gradually increasing training load is needed for disturbing the homeostasis of the body to achieve further improvement in endurance performance. Varying the type, intensity, and volume (by modifying duration and frequency) of training sessions allows the body to recover after accumulated training load and further improvements in endurance performance are possible. The purposeful sequencing of different training units is called as training periodization (Issurin 2010).

2.5.1 Traditional predetermined training program

Although there is consensus on which factors contribute to endurance performance (Noakes, Myburgh & Schall 1990; Coyle 1995; Paavolainen, Nummela & Rusko 1999), the optimal training volume and intensity distribution is still indefinite (Stoggl & Sperlich 2015). The majority of training studies present a high proportion of high volume, LIT among endurance athletes (Seiler 2010). In addition, Seiler & Kjerland (2006) have reported two, typically used patterns of training intensity distribution in endurance training programs; the threshold and the polarized training models. The threshold training model has been used especially in short-term studies among untrained subjects showing that training at the lactate threshold intensity induces a significant training adaptation. The polarized training model has been reported to induce greater improvements in endurance performance especially in high level athletes (Esteve-Lanao et al. 2007; Neal et al. 2013; Munoz et al. 2014; Stoggl & Sperlich 2014). In that model, 75-80% of training is performed at intensities clearly below the lactate threshold, relatively little training at the lactate threshold, and approximately 10-20% of training at intensities clearly above the lactate threshold (Seiler & Kjerland 2006; Tonnessen et al. 2014). However, numerous training studies have showed conflicting results and the optimal training intensity distribution is still unclear.

Recent studies have shown that changing the periodization of LIT and HIT without changing the training intensity distribution may have an effect on performance improvement (Ronnestad, Hansen & Ellefsen 2014; Ronnestad et al. 2016). Traditionally periodized training periods have been argued to focus on developing many abilities simultaneously. In that case, HIT is performed, e.g. two times per week, simultaneously with LIT and MOD in order to develop many fitness components at the same time (Seiler & Kjerland 2006). However, it has been proposed that the traditional periodized training may be a suboptimal training stimulus and, thus lead to suboptimal adaptations (Issurin 2010).

In contrast, block training includes shorter training periods (1-4 weeks), when the aim is to develop a few selected fitness components (Issurin 2008). This has also been described as a training cycle of highly concentrated specialized workloads. It has been suggested that block periodization of HIT (3-5 HIT sessions per HIT-block week) may provide superior training adaptation compared with traditionally organized HIT (Ronnestad, Hansen & Ellefsen 2014; Ronnestad et al. 2016).

2.5.2 Individualized training program

Traditional endurance training models and programs are based on sports and scientific literature, general recommendations, experience of coaches and presumptions about an athlete’s training and recovery status. Furthermore, adaptation to endurance training is individual and similar training programs are not necessarily optimal for everyone despite their similar training background. It has been proposed that a training prescription according to the status of cardiac vagal activity may be beneficial for improving endurance training adaptation. In the studies of Kiviniemi et al. (2007; 2010) a HIT session was programmed, if vagal related HFP, measured every morning, was increased or remained the same relative to the reference value. Otherwise, LIT or rest was programmed. Individuals who trained according to HRV, showed greater improvement in VO_{2max} among moderately fit men (Kiviniemi et al. 2007) and in endurance performance among healthy subjects (Kiviniemi et al. 2010) compared with individuals who trained according to a traditional, predefined training program.

Women benefitted from the HRV guidance by achieving the same significant improvement in endurance performance with a lower amount of HIT compared with a predefined training program (Kiviniemi et al. 2007; Kiviniemi et al. 2010). In studies of Kiviniemi et al. (2007; 2010) training prescription was based on daily, single HRV measurements. However, Plews et al. (2013) suggested that it is more valuable to use longer trends of HRV, e.g. a week rolling average compared with assessing its value on a single day. In addition, Plews et al. (2012) proposed the use of an individual's own HRV profile, the individual smallest worthwhile change (SWC), which reflects normal values of HRV, in interpreting HRV values and training prescription.

Capostagno et al. (2014) investigated the use of a submaximal cycling test in prescribing the timing of HIT sessions during a 2-week training period. Both predetermined and customized training programs included 4 HIT sessions but the time frames were different. In the customized training program, HIT was not performed, if an increased RPE, a failure in target HR or a change in HRR (more than 2 bpm) occurred in the submaximal cycling test. No differences were found in the improvements in endurance performance between the customized and predetermined training groups. However, the training period was short and remarkable training effects induced by 4 HIT sessions were not expected. It seems that it is possible to improve endurance training adaptation by determining the timing of intensive endurance training sessions according to regulation of cardiac vagal activity during prolonged endurance training.

3 PURPOSE OF THE THESIS

The present study was designed to investigate potential factors that may be related to individual variation of endurance training adaptation and which may have the potential to improve the effectiveness of endurance training. The main purpose was to evaluate whether endurance performance, cardiac autonomic regulation, and neuromuscular performance can be used in predicting and monitoring endurance training adaptation and individualizing endurance training prescription.

The specific aims of the study were:

1) To assess whether pretraining characteristics of the subjects, such as age, sex, fitness level, training background, nocturnal HRV, or serum hormone concentrations are associated with individual adaptations to different endurance training programs including: increased training volume and intensity, increased volume of low intensity training, and high intensity training.

   The hypothesis was that pretraining HRV would be related to individual endurance training adaptation. (Original papers I and II)

2) To investigate whether a submaximal running test combined with post-exercise HRR, HRV, and CMJ measurements conducted in the laboratory and field conditions could be used in monitoring endurance training adaptation.

   The hypothesis was that increased running speeds at standardized submaximal HR levels and post-exercise cardiac vagal activity would be related to enhanced endurance performance and decreased neuromuscular function would be related to negative endurance training adaptation. (Original papers III and IV)

3) To evaluate whether the HRV based method could be used in individualization of endurance training prescription.

   The hypothesis was that the HRV-guided training program would result in greater improvement in endurance performance compared with a traditional predetermined training program. (Original paper V)

4 METHODS

4.1 Subjects

Recreational endurance runners were recruited to participate in these studies (Table 1). Healthy, 20- to 50-year old women and 20- to 45-year old men were non-obese (BMI < 30 kg · m^{-2}), they did not have any diseases, and they did not regularly use medication. Subjects had a background of at least 2 years of regular running training. A physician screened each subjects' health and resting electrocardiogram (ECG) prior to giving clearance to participate in the studies. After being fully informed about the study designs and possible risks, all subjects provided a written informed consent document. The studies were approved by the Ethics Committee of the University of Jyväskylä, Finland.

TABLE 1 Characteristics of the subjects.

Papers	I (n = 28)	II, III and IV (n = 40)		V (n = 40)	
Sex	28 men	20 women	20 men	20 women	20 men
Age (yrs)	36 ± 6	35 ± 10	35 ± 6	34 ± 8	35 ± 7
Height (m)	1.79 ± 0.05	1.66 ± 0.07	1.75 ± 6	1.67 ± 0.07	1.78 ± 0.05
Body mass (kg)	78 ± 6	60 ± 7	77 ± 8	61 ± 7	76 ± 8
Percentage of body fat	17.7 ± 5.1	23.7 ± 4.4	15.2 ± 4.5	24.8 ± 4.4	14.6 ± 4.0
VO_{2max} (ml · kg^{-1} · min^{-1})	49 ± 4	47 ± 5	53 ± 5	49 ± 4	56 ± 5
Training years	5 ± 4	14 ± 8	14 ± 8	13 ± 8	15 ± 8
Training times · wk^{-1}*	4.4 ± 0.8	5.6 ± 1.7	4.4 ± 2.0	5.5 ± 1.2	6.0 ± 1.7
Running km · wk^{-1}*	24 ± 13	38 ± 19	27 ± 15	34 ± 22	39 ± 19

The values are mean ± SD. VO_{2max}, maximal oxygen uptake. * during the previous two months before the study.

4.2 Experimental design

4.2.1 Paper I

A longitudinal study design was used to assess the contribution of pretraining characteristics of subjects to individual training adaptations during a 28-week training program. The training program was divided into a 14-week preparation period (PREP) and a 14-week intensive training period (INT). During PREP the subjects were asked to maintain the same training volume as before the study. Thereafter, training volume and intensity were planned to increase progressively during INT. Testing at baseline, week 14 and week 28 (post) included a maximal incremental treadmill running test, nocturnal HRV measurements, assessment of serum hormone concentrations and body composition measurements.

4.2.2 Papers II, III and IV

The controlled 18-week study design was used to investigate pretraining factors that might be able to predict individual adaptations to high-volume of LIT or HIT. In addition, the usefulness of a submaximal running test with post-exercise measurements in field and laboratory conditions in monitoring changes of endurance performance during training was examined. After 8 weeks of PREP, the runners were matched into pairs according their background (sex, age, training background), endurance performance characteristics (VO_{2max}, RS_{peak}), baseline HRV and improvement of endurance performance during PREP. The matching of the pairs was done so that the characteristics were as similar as possible between matched pairs (the mean differences in endurance performance variables between matched pairs < 2%) and there were no statistically significant differences between mean values of the groups. Thereafter, within each pair, the runners were randomly assigned to the high volume training group (HVT) and high-intensity training group (HIT). For the 8-week INT, the HVT-group was instructed to increase their running training volume by 30–50%, whereas training intensity remained the same as during PREP. The HIT-group replaced 3 LIT sessions during each intense training week with 3 MOD or HIT sessions, whereas training volume was remained the same.

Testing prior and after both 8-week training periods (at weeks 0, 9 and 18) included a maximal incremental treadmill running test, nocturnal HRV measurements, assessment of blood serum hormone concentrations, and body composition. A submaximal running test (SRT), with post-exercise HRR, HRV, and CMJ measures, was performed at weeks 0, 4, 9, 13 and 18 in the laboratory conditions. In addition, the subjects were instructed to perform weekly a submaximal control exercise (SCE), with post-exercise HRR, on an outside course.

4.2.3 Paper V

A longitudinal study design was used to investigate the effectiveness of using HRV in training prescription on adaptations to endurance training. The study protocol included two training periods; a 4-week PREP and an 8-week INT. For INT, the subjects were matched into pairs according their background (sex, age, training background), endurance performance characteristics (VO_{2max}, the peak treadmill running speed (RS_{peak}), 3000 m time) and HRV. Thereafter, within each pair, the runners were randomized into the HRV-guided experimental training group (EXP) and traditional, preprogrammed training group (TRAD).

Testing was performed before and after both training periods at weeks 0, 5 and 14. The testing included a maximal incremental running test on a treadmill, a 3000 m time trial on a track, and body composition measurements. In addition, a reactivity jump test (RJ) was performed every other week and all subjects in the EXP-group were instructed to measure their R-R interval data at home every morning after awakening.

4.3 Data collection

4.3.1 Endurance performance

Maximal incremental treadmill test

The subjects were asked not to perform any vigorous physical activity two days prior to the running test. An incremental treadmill test was performed at the same time (± 2 h) of each testing day. The subjects performed the test, starting at $7\ km \cdot h^{-1}$ for women and at $8\ km \cdot h^{-1}$ for men, which was followed by an increase of $1\ km \cdot h^{-1}$ every third minute until volitional exhaustion. The incline was kept at 0.5 degrees during the whole test. HR was recorded continuously using a heart rate monitor (Suunto t6, Suunto Ltd, Vantaa, Finland). Oxygen consumption was measured breath-by-breath throughout the test using a portable spiroergometer (Oxycon Mobile, Viasys Health Care, Würzburg, Germany). After each 3-min stage the treadmill was stopped for about 15-20 s for fingertip blood samples (20 µl) and blood lactate (La) analysis. Blood lactate was determined using the Biosen S_line Lab+ lactate analyzer (EKF Diagnostic, Magdeburg, Germany). The highest 60-s VO_2 value during the treadmill test was considered as maximal oxygen uptake (VO_{2max}). Maximal endurance performance was defined as the peak treadmill running speed (RS_{peak}) when the subject became exhausted. If a subject could not complete the whole 3 min of the last speed, RS_{peak} was calculated as follows: speed of the last completed stage ($km \cdot h^{-1}$) + (running time (s) of the speed at exhaustion – 30 s) / 180-30 s) * $1\ km \cdot h^{-1}$. RS_{peak} has been shown to be closely related to maximal endurance performance (Noakes, Myburgh & Schall 1990). Therefore, in the present studies (I-IV), RS_{peak}

was used as the main variable for describing the adaptation to endurance training during the training periods. In addition, RS_{peak} has been observed to be highly reliable with intraclass correlation coefficients of 0.99 ± 0.01 and the coefficient of variation of 1.2% measured in the incremental treadmill running test (Dupuy et al. 2012). The determination of lactate thresholds was based on the increase and change in the inclination of the blood lactate curve during the test (Faude, Kindermann & Meyer 2009) in papers II-V. The first lactate threshold (LT1) was set at 0.3 $mmol \cdot l^{-1}$ above the lowest lactate value in the test. The second lactate threshold (LT2) was set at the intersection point between 1) a linear model between LT1 and the next lactate point and 2) a linear model between the lactate points with La increase of at least 0.8 $mmol \cdot l^{-1}$. In paper I, aerobic (AerT) and anaerobic (AnT) thresholds were determined using La, ventilation, VO_2, and production of carbon dioxide (Aunola & Rusko 1986).

3000 m time trial (Paper V)

The subjects performed the 3000 m time trial on a 200-m indoor track before and after both training periods. Time and the mean running speed of the 3000 m (RS_{3000m}) were calculated. At least two easy training days were prescribed between the treadmill test and 3000 m time trial.

4.3.2 A submaximal running protocol with post-exercise measures (Papers III and IV)

A submaximal running test (SRT)

The present submaximal running test (SRT) was modified from the Lamberts and Lambert Submaximal Cycle Test (Lamberts et al. 2011) (III). SRT was designed to be a standardized warm-up protocol. The 17-minute SRT consisted of three stages (Figure 5). The speed of the treadmill was set according to heart rate corresponding to 70% (RS1), 80% (RS2), and 90% (RS3) of a subject's maximum heart rate (HR_{max}) for 6, 6, and 3 minutes, respectively. The target heart rates were calculated based on HR_{max} in the maximal incremental treadmill test at week 0. HR was recorded throughout the test using a heart rate monitor (Suunto t6, Suunto Ltd, Vantaa, Finland) but the data of the first minute of each stage was excluded from the analyses due to setting running speed (RS) to reach the target HR. Therefore, average RS and HR were calculated over a 5-minute period (1:00-6:00 and 7:00-12:00) for stage 1 and 2, and for a 2-minute period (13:00-15:00) of stage 3. Mean power of all three stages has been observed to be highly repeatable with intra class correlation coefficients of 0.91, 0.92 and 0.90 in rowing (Otter et al. 2015), and 0.91, 0.98 and 1.00 in cycling (Lamberts et al. 2011). RPE was recorded in the final minute of each stage (Borg 1982). After completing the running test, the subjects were asked to stand without moving and talking for 2 minutes for determining post-exercise HRR and

HRV. They were asked to breathe normally, with no control of the respiratory rate. Finally, CMJ test was performed 3 minutes after the end of SRT.

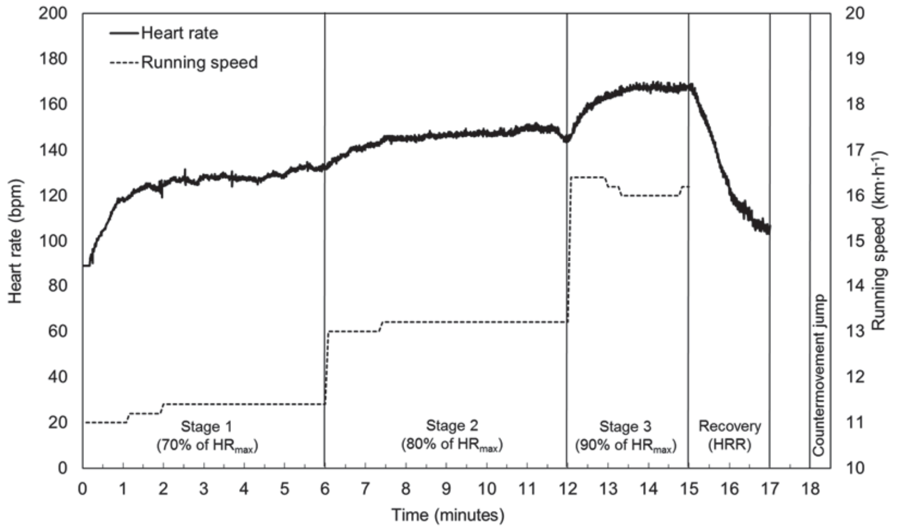


FIGURE 5 An example of an arbitrary subject’s training monitoring test including heart rate and running speed during the submaximal running test (SRT) and the countermovement jump test (CMJ).

Submaximal control exercise (SCE)

The protocol of the submaximal control exercise (SCE) was similar to SRT. SCE was performed as a standardized warm-up protocol for MOD and HIT sessions once per week in field conditions taking place after at least one easy training day (IV). The subjects were instructed to perform SCE on the same outdoor course each time. The 16-minute SCE consisted of same three stages as SRT. The subjects were asked to set their running speed (RS) according to HR corresponding to 70% (RS1), 80% (RS2) and 90% (RS3) of HR_{max} for 6, 6, and 3 minutes, by using the Garmin FR 610 heart rate monitors with global positioning system (GPS) (Garmin Ltd, Schaffhausen, Switzerland). The target HRs were calculated based on HR_{max} in the maximal incremental treadmill test at week 0. After completing the three stages, the subjects were asked to stand without moving or talking for 1 minute for determining HRR. A rate of perceived exertion with Borg´s 0-10 scale (Borg 1982) was estimated after the last stage. HR and RS were calculated over the same periods as in SRT.

4.3.3 Heart rate variability measurements and analysis

Resting ECG (Cardiofax ECG-9 320, Tokyo, Japan) was analyzed before the studies to screen each subjects’ health and to ensure the subjects had no cardiac abnormalities which would have effects on the HRV analysis.

Nocturnal HRV (Papers I and II)

Nocturnal RRI recordings were taken during three consecutive nights before and after both training periods during the testing weeks in paper I, with the Suunto Memory Belt (Suunto Ltd, Vantaa, Finland) having a sampling frequency of 1000 Hz. The measurements were done at home and were started just before going to bed to sleep and stopped after awakening in the morning. Four consecutive nights before the incremental treadmill test before both training periods were recorded in paper II, with the Garmin FR 610 heart rate monitor (Garmin Ltd, Schaffhausen, Switzerland) consisting of a chest belt (two-lead) with a sampling frequency of 1000 Hz. The measuring systems have been observed to be reliable for long-term HRV-analysis (Weippert et al. 2010).

RRI data was analyzed using the Firstbeat Sports software (Firstbeat Technologies Ltd, Jyväskylä, Finland). RRIs were checked by an artifact detection filter of the Firstbeat Sports software and subsequently excluded all falsely detected, missed, and premature heart beats (Saalasti 2003) caused by movement artifacts or any other artifacts of unknown origin. The consecutive RRI data were then resampled at the rate of 5 Hz by using linear interpolation to obtain equidistantly sampled time series. From the resampled data the software calculated HRV indices second-by-second using the short-time Fourier Transform method. For a given segment of data, a time window (Hanning) with a length of 256 samples was applied, the fast Fourier transform was calculated and a power spectrum was obtained. The window was then shifted one sample to another and the same process was repeated. The first 30-min after going to bed was excluded and the succeeding 4 h were accepted for the nocturnal HRV analysis. The following HRV indices were analyzed: average HR, low frequency power (LFP; 0.04-0.15 Hz), high frequency power (HFP; 0.15-0.40 Hz), total power (TP =LFP+HFP; 0.04-0.40 Hz) (Task Force, 1996). Nocturnal HRV indices are subject to a little day-to-day variation with intraclass correlation coefficients between 0.84–0.91 in 4 hours of nocturnal HRV analysis during two consecutive nights after a similar training day (Nummela, Hynynen & Vesterinen 2010). The results are provided as averages of two nights for reducing possible day-to-day variation in HRV indices. It was not possible to use averages of the three/four collected recordings because the recordings with an error percent higher than 33% (of 4 hours) were excluded from the analysis in some subjects for ensuring adequate quantity of RRI data for the reliable HRV analysis (Nummela, Hynynen & Vesterinen 2010).

Post-exercise HRR and HRV (Paper III and IV)

Post-exercise HRR was calculated by subtracting HR after 60 s recovery from HR at the end of third stage of SRT and SCE. A vagal-related HRV index, the natural logarithm of RMSSD, was calculated over the second recovery minute (16:00-17:00) in SRT for achieving a more stable HR compared to the first recovery minute. Kaikkonen et al. (2010) observed that the first 2-min recovery after exercise may give enough information on HRV recovery for evaluating training load. LnRMSSD has been suggested to provide the most reliable and practically applicable HRV variable for regular monitoring (Stanley, Peake & Buchheit 2013). RRI data was analyzed using a similar method as the nocturnal HRV analysis using the Firstbeat Sports software (Firstbeat Technologies Ltd, Jyväskylä, Finland).

Morning HRV (Paper V)

All subjects in EXP were instructed to measure their RRI data at home every morning after awakening and emptying their urinary bladder (paper V). Omegawave Pro Mobile System, with a two-lead chest belt (Omegawave Ltd., Helsinki, Finland) was used to record R-R intervals with a sampling frequency of 500 Hz. A 4-minute recording was performed in a supine position and the subjects were allowed to breathe naturally. RRI data was analyzed in the Omegawave cloud service and the vagal-mediated RMSSD was selected to be used in training prescription because of its greater reliability than other HRV spectral indices (Al Haddad et al. 2011; Bellenger et al. 2016). Further, a 7-day rolling average of RMSSD ($RMSSD_{7day}$) was calculated because it has been proposed to be more sensitive in tracking changes in training status compared with single-day values (Plews et al. 2013). The smallest worthwhile change (SWC) of $RMSSD_{7day}$ was calculated, as mean ± 0.5 * SD, from RMSSD values of the 4-week PREP for individual training prescription based on observations by Kiviniemi et al. (2007; 2010) and Plews et al. (2012, 2013). The SWC was updated after the first four weeks of INT based on the values collected over the previous four weeks due to previous findings about a relationship between an increase in resting cardiac autonomic activity and improved endurance performance (Buchheit et al. 2010; Nummela et al. 2010; Boutcher et al. 2013).

4.3.4 Neuromuscular measures (Papers III and V)

Countermovement jump

The CMJ test was performed 3 min after the end of SRT on a commercially available force plate (Accupower, Advanced Mechanical Technology, Watertown, USA) to measure CMJ height (CMJ_h) from the force time curve (paper III). The subjects performed three trials with their hands held on the hips throughout the entire movement, separated by 60 s recovery between the trials. Subjects were instructed to jump as high as possible. Countermovement depth was self-selected by the subject but no less than 90°. Force data were collected and analyzed by using custom-designed software (Research Institute for Olympic Sports, Jyväskylä, Finland), which used the equation $h = I^2 \cdot 2gm^{-2}$ to calculate jump height from impulse, where I is the impulse, g is gravity, and m is the mass of subject. Jump height was determined as an average of the two best jumps.

Reactivity jump (Paper V)

The RJ test was performed after the standardized warm-up procedure every second week during the 14-week training period on the same force plate as was used to measure CMJ in paper III. Before the beginning of training, the subjects performed a familiarization test for learning correct jumping technique. They were instructed to perform 10 continual vertical jumps (with as little bending of the knees as possible) with their hands held on their hips throughout the jumping set. The goal was to achieve the least possible contact time for a maximum height in every jump. The jumping set was performed twice, with a 2-minute recovery. Force data collection and analyses were conducted in the same way as in the CMJ analysis. Average height (RJ_h) and power (RJ_{power}) of the best two jumps of the best set was determined from the impulse.

4.3.5 Blood samples (Papers I and II)

Venous blood samples (10 ml (paper I), 3.5 ml (paper II)) were collected into serum-gel tubes (Venosafe, Terumo Medical Co., Leuven, Belgium) for the determination of basal serum testosterone and cortisol concentrations after 10 h of fasting in the morning between 7:30–8:30. The whole blood was centrifuged at 2700 rpm (Megafuge 1.0R, Heraeus, Germany) for ten minutes after which serum was removed and stored at -80 °C (paper I) /-20 °C (paper II) until analysis. The concentrations of testosterone and cortisol were determined by using a chemical luminescence technique (Immunlite 1000 Analyzer, DPC Diagnostics Corporation, Los Angeles, USA) and hormone specific immunoassay kits (Siemens, New York, NY, USA). The sensitivity of testosterone and cortisol assays were 0.05 $nmol \cdot l^{-1}$ and 5.5 $nmol \cdot l^{-1}$, respectively. The intra-assay coefficients of variation for testosterone and cortisol were 3.9% and 4.6%, respectively. All the assays were carried out according to instructions of the manufactures. All samples of the test subjects were analyzed in the same assay for each variable.

4.3.6 Body composition

Standing height was measured using standard laboratory techniques. Body mass and body composition were measured using a bioimpedance device (In body 720 body composition analyzer, Biospace Co. Ltd., Seoul, South Korea) in paper I. The measurements were performed after 10 h of fasting in the morning between 7:30–8:30. In papers II-V, percentage of body fat was assessed by a 4-point skinfold thickness measurement (Durnin & Rahaman 1967).

4.4 Training programs

4.4.1 Paper I

The subjects took part in the 28-week training program, which prepared them for a marathon or half-marathon at the end of the study (Table 2). The training program was divided into a 14-week PREP and a 14-week INT. During PREP the subjects were asked to maintain the same training volume as before the study (3-6 times a week). The subjects were instructed to train primarily below the aerobic threshold. The training program was periodized into cycles of four weeks, thus three weeks of intense training was followed by an easy training week. Endurance training consisted primarily of running but occasionally included cycling, Nordic walking and/or cross-country skiing. In addition, the subjects were asked to complete strength training 1-2 times a week.

TABLE 2 Week template of training over the 28-week training program.

	Preparation period	**Intense training period**		
	weeks 1-14	weeks 15-19	weeks 20-24	weeks 25-28
Week periodization (intense : recovery week)	3:1	2:1	2:1	2:1
High-intensity runs	none	none	1 x 4-5 km*	2 x 4-5 km*
Moderate-intensity runs	none	2 x 8-10 km*	1 x 8-10 km*	none
Long low-intensity run	1 x 15-20 km	1 x 20-25 km	1 x 20-30 km	1 x 25-30 km
Basic low-intensity runs	2-5 x 5-15 km	1-4 x 5-15 km	1-4 x 5-15 km	1-4 x 5-15 km
Strength training	1-2 sessions	1 session	1 session	1 session

* exercises were not performed during recovery weeks. High-intensity, intensity above anaerobic threshold; Moderate-intensity, the intensity between aerobic and anaerobic thresholds; Low-intensity, intensity below aerobic threshold.

The 14-week INT included higher running training volume (prolonged duration of the training sessions) and intensity compared with PREP. The training utilized the 3-week training cycles (two intense weeks followed by a recovery week). During the recovery weeks the subjects were asked to train at a low-intensity (below the AerT), whereas during the first three intense weeks the subjects replaced two LIT sessions with MOD (between the AerT and AnT) training sessions. During the next three intense weeks the subjects were asked to complete one MOD and one HIT (above the AnT) sessions per week in addition to LIT sessions. During the last three intense weeks subjects replaced two LIT sessions with two HIT sessions each week. In addition, the subjects were asked to complete one strength training session per week throughout INT for maintaining strength abilities and injury prevention.

4.4.2 Papers II, III and IV

The controlled 18-week training program included two 8-week training periods. PREP was completed first to familiarize the subjects with the testing procedures and proper endurance training and to ensure that subjects had a similar background in training before the second 8-week period. The subjects were asked to train once per week at MOD (HR between LT1 and2) and otherwise at LIT (HR < LT1) during PREP. In addition, they were asked to maintain the same training volume as before the study.

For the 8-week INT, HVT were instructed to increase running training volume by 30–50%, whereas training intensity remained the same as during PREP. HIT replaced 3 LIT sessions during each intense training week with 3 MOD or HIT (HR > LT2) sessions; 1. constant speed run 20-40 min at 80-90% HR_{max}, 2. 4 x 4 min at 90–95% HR_{max}, with 3 min of recovery at intensity below LT1, 3. 6 x 2 min at 100% RS_{peak}, with 2 min of recovery at the intensity below LT1. Training volume remained the same. The training was periodized into cycles of four weeks, thus three weeks of intense training was followed by an easy training week. Endurance training consisted primarily of running but occasionally included also cycling, Nordic walking and/or cross-country skiing. A strength training session consisting of muscle endurance exercise was instructed to be performed once a week for maintaining strength abilities and injury prevention.

4.4.3 Paper V

The study protocol included two training periods: a 4-week PREP and an 8-week INT. During the first four weeks, all subjects were asked to maintain the same training volume as before the study using a periodization model of three hard training weeks followed by an easy training week with progressively increasing intensity throughout the period (Table 3).

For the 8-week INT, all subjects were instructed to maintain the same training volume as during PREP. The TRAD-group trained according to a pre-programmed training program, which included approximately 50% of weekly training sessions performed at LIT and the other 50% at MOD/HIT. The main training sessions at MOD and HIT were similar to training sessions during PREP. In addition, the periodization of the training weeks (3:1) remained same compared with PREP. Endurance training was mainly running but the subjects were encouraged to perform at least one easy session per week using some other training mode than running (i.e. cycling or cross-country skiing) during both training periods. A strength training session consisting of muscle endurance exercise was instructed to be performed once a week for maintaining strength abilities and injury prevention.

TABLE 3 Week template of the preprogrammed training program for both groups during the preparation period (weeks 1 – 4) and for TRAD-group during the intense period (weeks 6 – 13).

Week		High-intensity training		Moderate run	Low-intensity runs	Test runs
		Constant run	Intervals		(HR < LT1)	
0	Test					3000 m run VO_{2max} test
1	Int			30´at 80-85%	3-6 x 6-12 km	
2	Int		4x4´at 90-95%/rec 3´	40´at 80-85%	2-5 x 6-12 km	
3	Int	30´at 85-90%	4x4´at 90-95%/rec 3´	40´at 80-85%	2-5 x 6-12 km	
4	Rec				3-5 x 6-12 km	
5	Test				3-5 x 6-12 km	VO_{2max} test
6	Int	30´at 85-90%		40´at 80-85%	2-4 x 6-12 km	3000 m run
7	Int	30´at 85-90%	4x4´at 90-95%/rec 3´	40´at 80-85%	2-4 x 6-12 km	
8	Int	30´at 85-90%	4x4´at 90-95%/rec 3´	40´at 80-85%	2-4 x 6-12 km	
9	Rec				3-5 x 6-12 km	
10	Int	30´at 85-90%	4x4´at 90-95%/rec 3´	40´at 80-85%	2-4 x 6-12 km	
11	Int	30´at 85-90%	4x4´at 90-95%/rec 3´	40´at 80-85%	2-4 x 6-12 km	
12	Int	30´at 85-90%	4x4´at 90-95%/rec 3´	40´at 80-85%	2-4 x 6-12 km	
13	Rec		4x4´at 90-95%/rec 3´		3-4 x 6-12 km	
14	Test				2-4 x 6-12 km	3000 m run VO_{2max} test

Training intensity are expressed as a percentage of maximal heart rate. Int, Intensive training week; Rec, recovery week / time between intervals; Test, testing week; LT1, lactate threshold 1; VO_{2max} test, maximal incremental treadmill test. All moderate- and high-intensity sessions started with a 15-20-min warm-up and were followed by a 15-min cool down. Moderate- and high-intensity runs were instructed to perform after a rest or easy training day. If the number of all training sessions per week was ≤ 4, only two moderate-/high-intensity runs were instructed to perform per week.

The EXP-group trained according to HRV from the morning measurements during INT (Figure 6). The basic idea of using HRV in training prescription was to decrease training intensity when cardiac vagal activity differed markedly from the baseline level (SWC = mean ± 0.5 * SD). When $\text{RMSSD}_{7\text{day}}$ was within the SWC, only MOD and HIT session were performed. If $\text{RMSSD}_{7\text{day}}$ fell outside the SWC, the subjects trained only at LIT or rested. When $\text{RMSSD}_{7\text{day}}$ returned to the mean level of the SWC, the subjects started to perform MOD and HIT sessions and continued training until $\text{RMSSD}_{7\text{day}}$ fell outside the SWC. The subjects maintained the same number of training sessions and rest days for every week as they did in PREP.

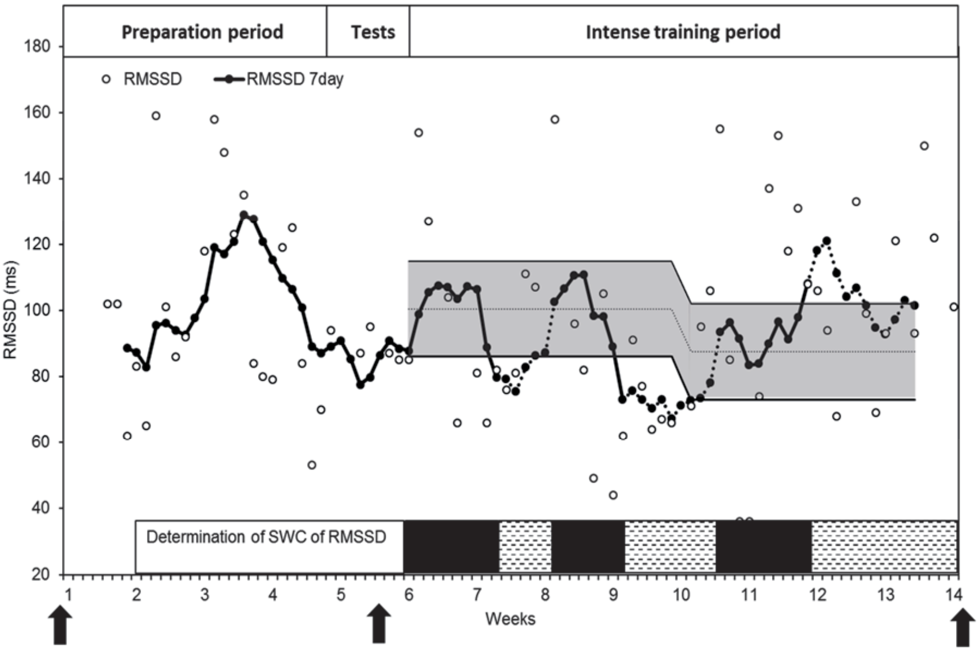


FIGURE 6 Example of programming moderate and high-intensity sessions in the EXP-group during the intense period. The grey area indicates the individual optimal area of RMSSD. The black area indicates timing of moderate- and high-intensity training. The dashed line area indicates timing of low-intensity training. The arrows represent timing of the running tests.

4.5 Training monitoring

The main weekly training sessions were supervised by experienced members of the research group. The subjects controlled their training intensity by measuring their HR during all exercises using a heart rate monitor with built-in GPS (Suunto t6 in I, Garmin FR 610 in II-V). Subjects kept a training diary throughout the study to record training mode, duration of the training session, average HR, and running distance. In addition, the subjects rated their perceived exertion (RPE) and recovery feelings using a scale from 0–10 after each training session (Borg 1982) and reported possible other stress factors e.g. sicknesses, injuries, and work/school stress in their training diary. HR data was used for determining the times at the three different training intensity zones; low (below aerobic threshold/LT1), moderate (between aerobic/LT1 and anaerobic thresholds/LT2) and high (above anaerobic threshold/LT2) intensities. Training load was quantified by session RPE (RPE x exercise duration in minutes) (Foster et al. 1996) (V).

4.6 Statistical analyses

Statistical analyses were carried out using SPSS software (PASW Statistics 18.0; SPSS Inc, Chicago, IL; IBM SPSS Statistics 20, IBM, New York, USA). Values are expressed as mean ± standard deviation (SD). The Gaussian distribution of the data was assessed with the Shapiro–Wilk goodness-of-fit test and homogeneity of variance was assessed by Levene's variance test. Ln-transformation was used with the nocturnal HRV variables, in order to meet the assumptions of the parametric statistical analysis. Statistical significance was accepted as $p < 0.05$.

In papers I and II, Pearson product moment correlation coefficient was used to determine the relationships between the pretraining characteristics and the training adaptation (change in RS_{peak}). Correlations between HRV and the training adaptation were adjusted by age due to effects of age on HRV and correlations between pretraining testosterone and VO_{2max} to the training adaptation were adjusted by sex using partial correlation. In addition to the measures of statistical significance, the following criteria were adopted to interpret the magnitude of the correlation between measurement variables: < 0.1 (trivial), 0.1–0.3 (small), 0.3–0.5 (moderate), 0.5–0.7 (large), 0.7–0.9 (very large) and 0.9–1.0 (almost perfect) (Hopkins et al. 2009). For an additional analysis of the relationship between pretraining HRV and the training adaptation, the subjects were retrospectively divided into high (> 8.1 ln ms^2) (HVT: n = 8; HIT: n = 5) and low HRV (< 8.1 ln ms^2) (HVT: n = 5; HIT: n = 7) groups based on pretraining HFP (mean of pretraining HFP in all subjects was used as the threshold) in paper II. Group differences were analyzed using a one-way analysis of variance (One-way ANOVA) and within group differences (group-by-training interaction) were analyzed using repeated measures analysis of variance (ANOVA), followed by Bonferroni as a post hoc test. In addition, multiple linear regression analysis with backward method was used to evaluate the amount of explained variance in training adaptation to the HVT and HIT programs (I-II). Pretraining predictors, which were previously reported to be possible predictors of training adaptation (Bouchard & Rankinen 2001; Hautala et al. 2003) and showed correlations to training adaptation in the present studies (I-II) were selected as independent variables for multiple linear regression analysis while the change in RS_{peak} was used as the dependent variable.

In paper III, the subjects were retrospectively divided into quartiles (the 1st quartile, Q_1, the highest response (n = 9); the 2nd quartile, Q_2, moderate response (n = 9); the 3rd quartile, Q_3, low response (n = 9), the 4th quartile, Q_4, the lowest response (n = 8)) of percentage change in RS_{peak} from week 0 to week 18. Differences between the quartiles were analyzed using a one-way analysis of variance (One-way ANOVA) and changes in the maximal running test, SRT and CMJ_h (group-by-training interaction) were analyzed using a repeated measures ANOVA, followed by Bonferroni as a post hoc test. In addition, standardized effects sizes (ES) were calculated using the partial eta square with the following threshold values: < 0.2 (trivial), 0.2–0.5 (small), 0.5–0.8 (moderate) and > 0.8 (large) (Cohen 1988, 40). Pearson product moment correlation coefficient was used to determine relationships between absolute values of SRT and CMJ_h, and endurance performance variables at week 9. In addition, relationships were analyzed between changes in SRT, CMJ_h, and RS_{peak}. In addition to the measures of statistical significance, the criteria were adopted to interpret the magnitude of the correlation between measurement variables (described in the previous paragraph).

In paper IV, the subjects were retrospectively grouped into four clusters according to changes in SCE results. Due to the presence of missing data values (due to sicknesses, mild injuries or poor HR data) in time-series of RS1, RS2, RS3 and HRR, a self-implemented (MATLAB R2013a) variant of the classical K-means method (MacQueen 1967), in which missing values are handled using the available case strategy (Little & Rubin 1987), was applied in the cluster analysis. The detailed algorithmic description of the K-means method for incomplete data can be found in Äyrämö (2006). In order to avoid locally optimal cluster models, 1000 clustering models were generated for each set of time-series by using random restarts and the ones with the least sum of squared within cluster errors were selected for further analysis. Differences of changes in the maximal running test between the clusters were analyzed using Kruskal Wallis test, followed by Dunn-Bonferroni post hoc method, due to the small number of the subjects in the clusters. Pearson product moment correlation coefficient was used the same way as in paper III for determining the relationships between the absolute values of SCE and endurance performance variables at week 9, as well as between changes in SCE and endurance training adaptation after 18-weeks of training.

In paper V, the adaptation to training was analyzed using repeated measures of ANOVA followed by Bonferroni as a post hoc test. Differences in the training adaptation between EXP and TRAD were analyzed by Student's t-test for independent samples and between sex by the Kruskal Wallis test. In addition, the magnitude of changes during training and differences between groups were expressed as standardized mean differences (effect size, ES), calculated from pooled means and standard deviations (Hopkins et al. 2009). Threshold values for Cohen's ES statistics were < 0.2 (trivial), 0.2–0.5 (small), 0.5–0.8 (moderate) and > 0.8 (large) (Cohen 1988, 40). Pearson's product-moment correlation coefficient was used to determine the relationships between the amount of MOD/HIT sessions and the training adaptation (change of RS_{3000m} and VO_{2max}).

5 RESULTS

5.1 Drop-outs and compliance with the training programs

In paper I, a total of 25 men completed the whole 28-week training program. One subject dropped out because of a lack of motivation, and two subjects were excluded because of insufficient compliance with the training during the study.

In paper II, a total of 29 subjects (16 women, 13 men) completed the whole 18-week training program including all tests and sufficient compliance with the training program. Exclusion of 11 subjects were due to injuries (n = 6), sickness (n = 3) and insufficient compliance with the training program (n = 2). Five of 40 subjects did not complete all tests related to monitoring of training adaptation (papers III and IV) due to injuries (n = 4) and lack of motivation (n = 1).

In paper V, a total of 31 subjects (14 women, 17 men) completed the whole training period. Nine subjects dropped out due to injuries (n = 2), sickness (n = 2) and insufficient compliance with daily HRV recordings and the training program (i.e. < 90% of all training sessions in the EXP-group and more than 2 main training sessions missing in the TRAD-group during the experimental period, n = 5).

5.2 Training (I-V)

During 28-weeks of training (I), total training volume (hours per week, times per week) did not differ between the two training periods (Table 4). Running volume and training intensity at moderate and high intensities were greater in INT compared with PREP.

In the 18-week training period (II-IV), total training time and distance during PREP remained similar compared with the training before the study (7.0 ± 2.8 vs 6.7 ± 2.7 $h \cdot wk^{-1}$, $p = 0.59$; 34.0 ± 18.2 vs 36.1 ± 22.0 running $km \cdot wk^{-1}$, $p = 0.41$). The HVT-group increased running volume by 35% during INT with no change in training intensity. The HIT-group increased proportion of training time at the high-intensity zone from 2 ± 2% to 7 ± 2%, while training volume remained similar.

No differences were observed between the EXP- and TRAD-group in training during PREP (V). Training volume and proportions of times in different training zones remained similar during PREP and INT in both groups. The number of MOD and HIT sessions during INT was significantly higher (p = 0.021) in TRAD (17.7 ± 2.5 sessions) compared to EXP (13.2 ± 6.0 sessions).

TABLE 4 Training data over the training periods.

	Training $h \cdot wk^{-1}$	Training $times \cdot wk^{-1}$	Running $km \cdot wk^{-1}$	Low (%)	Mod (%)	High (%)
14+14 weeks (I)						
PREP	5.8 ± 1.8	4.6 ± 0.9	26 ± 12	86 ± 12	13 ± 12	1 ± 1
INT	5.5 ± 1.7	4.2 ± 0.9	40 ± 15***	73 ± 14***	24 ± 14***	2 ± 3**
8+8 weeks (II-IV)						
PREP_{HVT}	7.0 ± 1.7	5.6 ± 0.9	35 ± 15	83 ± 10	15 ± 9	2 ± 2
PREP_{HIT}	6.9 ± 3.6	6.3 ± 3.1	33 ± 21	87 ± 8	12 ± 7	1 ± 1
INT_{HVT}	6.9 ± 1.3	5.8 ± 0.7	47 ± 13***	81 ± 10	17 ± 9	2 ± 2
INT_{HIT}	6.0 ± 2.4	6.5 ± 3.0	39 ± 18	87 ± 5#	6 ± 3***,###	7 ± 2***,###
4+8 weeks (V)						
PREP_{EXP}	7.1 ± 3.0	6.0 ± 1.7	43 ± 18	89 ± 8	10 ± 7	2 ± 3
$\text{PREP}_{\text{TRAD}}$	7.0 ± 2.7	5.9 ± 1.8	40 ± 23	88 ± 9	10 ± 8	1 ± 2
INT_{EXP}	6.5 ± 2.8	6.1 ± 1.8	42 ± 22	83 ± 27	14 ± 25	3 ± 5
INT_{TRAD}	6.3 ± 2.5	5.6 ± 1.6	41 ± 20	84 ± 12	13 ± 10	3 ± 4

Significant difference between the preparation and intense training periods, *p < 0.05, **p < 0.01, ***p < 0.001 and between the groups within the periods, #p < 0.05, ###p < 0.001. Low, low-intensity training; Mod, moderate-intensity training; High, high-intensity training; PREP, preparation period; INT, intense training period; HVT, high volume training group; HIT, high intensity training group; EXP, HRV-guided training group; TRAD, traditional, preprogrammed training group.

5.3 Training adaptation (I, II)

5.3.1 Endurance measures

During PREP, endurance characteristics showed improvements in most of the variables (Table 5). The largest improvements were observed in RS_{LT2} (2-8%)

and RS$_{LT1}$ (1-9%), while smaller changes were observed in VO$_{2max}$ (-1-4%) and RS$_{peak}$ (2-4%). No changes were observed in RE during PREP in any studies.

TABLE 5 Endurance characteristics over the preparation periods.

		14 weeks (I)	8 weeks (II-IV)	
			Women	Men
VO$_{2max}$	pre	49.6 ± 3.6	48.2 ± 5.1	53.5 ± 5.1
(ml · kg^{-1} · min^{-1})	mid	51.5 ± 4.5	48.0 ± 5.7	52.5 ± 3.3
	% change	3.6 ± 5.3**	-0.6 ± 4.5	-3.4 ± 4.8
RS$_{peak}$	pre	14.7 ± 1.0	14.3 ± 1.0	15.8 ± 0.9
(km · h^{-1})	mid	15.3 ± 1.1	14.6 ± 1.0	16.0 ± 0.6
	% change	4.1 ± 3.1***	2.5 ± 2.3***	1.8 ± 4.2
RS$_{LT2}$	pre	12.0 ± 1.2	11.8 ± 1.0	12.5 ± 1.0
(km · h^{-1})	mid	12.9 ± 1.1	12.1 ± 0.9	13.1 ± 0.7
	% change	8.2 ± 6.4***	2.2 ± 3.3*	5.0 ± 5.4**
RS$_{LT1}$	pre	9.4 ± 0.9	10.0 ± 0.9	10.3 ± 0.9
(km · h^{-1})	mid	10.2 ± 1.0	10.2 ± 1.1	10.6 ± 0.9
	% change	9.1 ± 7.3***	1.3 ± 5.3	2.9 ± 4.1*
RE$_{10}$	pre	221 ± 13	212 ± 13	215 ± 11
(ml · kg^{-1} · km^{-1})	mid	219 ± 16	211 ± 12	214 ± 14
	% change	-0.6 ± 5.7	-0.6 ± 4.5	-0.1 ± 4.6

Significant change during the period, *$p < 0.05$, **$p < 0.01$, ***$p < 0.001$. VO$_{2max}$, maximal oxygen uptake; RS$_{peak}$, peak treadmill running speed; RS$_{LT2}$, running speed at lactate threshold 2; RS$_{LT1}$, running speed at lactate threshold 1; RE$_{10}$, running economy at 10 km · h^{-1}.

All endurance performance variables improved significantly during the 14-week intense training period (INT), except VO$_{2max}$, which remained at the same level as after PREP (Table 6) (I). All in all, RS$_{peak}$ improved by 7.5 ± 4.5% ($p < 0.001$, min-max: -3.7-13.2%) and VO$_{2max}$ by 5.1 ± 6.2% ($p < 0.001$, min-max: -3.9-20.2%) during the whole 28-week training program. RS$_{LT2}$ and RS$_{LT1}$ increased by 12.4 ± 6.5% ($p < 0.001$) and 15.5 ± 8.4% ($p < 0.001$), respectively.

VO$_{2max}$, RS$_{peak}$, RS$_{LT2}$ and RS$_{LT1}$ improved after 8 weeks of HIT, while no significant changes were observed after HVT (II). No differences were observed between sexes in the changes in any of the endurance variables, except RS$_{peak}$ improved more in men (1.7 ± 1.7%) than in women (-0.6 ± 1.4%) ($p = 0.021$) after HVT. Individual changes in RS$_{peak}$ after the 14-week INT, the 8-week HVT and HIT are presented in Figure 7.

TABLE 6 Endurance characteristics over the intense periods (14 and 8 weeks)

		I (14 weeks)	II-IV (8 weeks)	
		INT	HVT	HIT
VO_{2max}	mid	51.5 ± 4.5	49.3 ± 3.9	50.7 ± 6.6
(ml · kg^{-1} · min^{-1})	post	52.2 ± 5.1	50.5 ± 4.7	52.8 ± 6.7
	% change	1.4 ± 5.1	2.6 ± 7.0	4.3 ± 4.0**
RS_{peak}	mid	15.3 ± 1.1	15.3 ± 0.9	15.2 ± 1.3
(km · h^{-1})	post	15.8 ± 1.2	15.3 ± 1.1	15.7 ± 1.4
	% change	3.3 ± 3.6***	0.5 ± 1.9	3.0 ± 2.8**
RS_{LT2}	mid	12.9 ± 1.1	12.5 ± 0.8	12.6 ± 1.2
(km · h^{-1})	post	13.4 ± 1.0	12.6 ± 1.1	13.0 ± 1.3
	% change	4.0 ± 4.5***	1.0 ± 3.9	3.6 ± 4.5*
RS_{LT1}	mid	10.2 ± 1.0	10.2 ± 1.0	10.3 ± 1.0
(km · h^{-1})	post	10.8 ± 0.9	10.3 ± 0.9	10.7 ± 1.0*
	% change	5.9 ± 5.3***	1.4 ± 4.6	3.7 ± 4.7*
RE_{10}	pre	219 ± 16	211 ± 14	215 ± 9
(ml · kg^{-1} · km^{-1})	mid	208 ± 13	214 ± 13	213 ± 12
	% change	-4.7 ± 6.2**	1.4 ± 2.7	-0.8 ± 3.7

Significant change during the period, *$p < 0.05$, **$p < 0.01$, ***$p < 0.001$. INT, intense training (increased running volume and intensity); HVT, high volume training group; HIT, high-intensity training group; VO_{2max}, maximal oxygen uptake; RS_{peak}, peak treadmill running speed; RS_{LT2}, running speed at lactate threshold 2; RS_{LT1}, running speed at lactate threshold 1; RE_{10}, running economy at 10 km · h^{-1}.

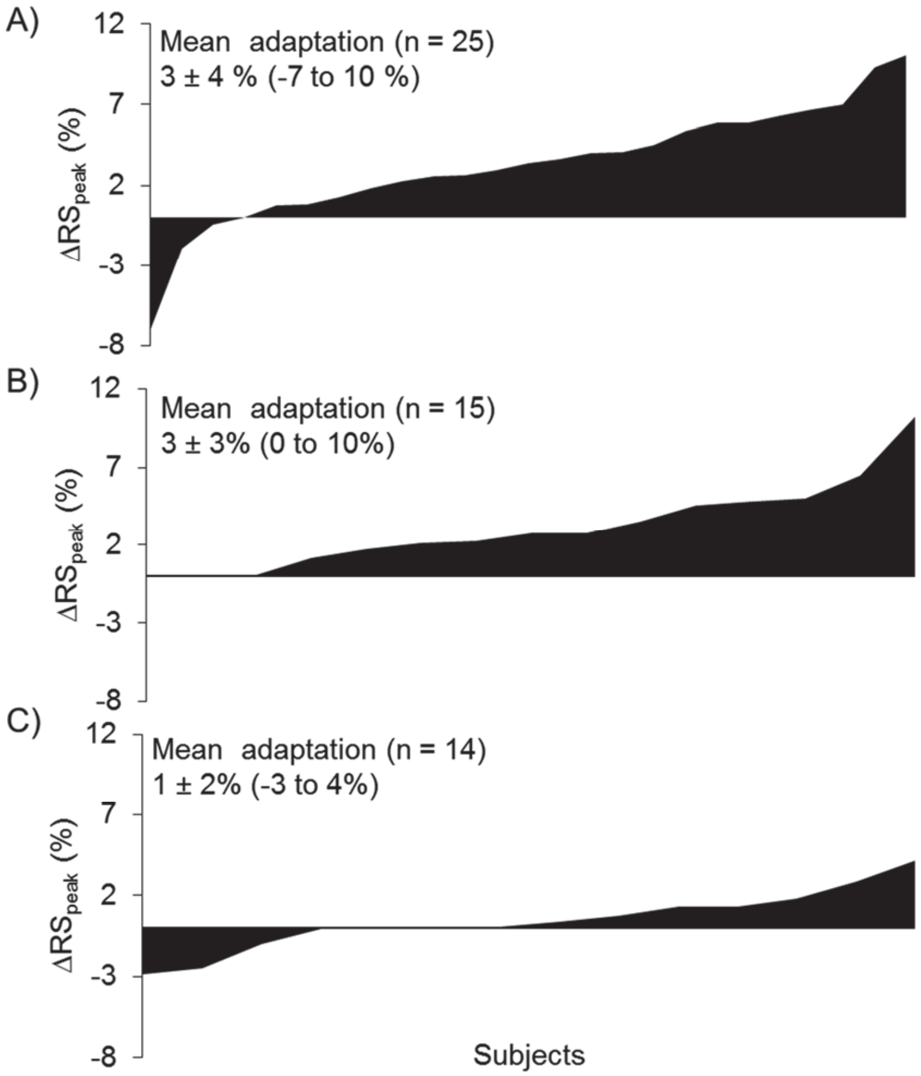


FIGURE 7 The individual heterogeneity of training adaptation (ΔRSpeak) to A) 14 weeks of intense training (INT, increased training volume and intensity), B) 8 weeks of high-intensity training and C) 8 weeks of high volume training (HVT).

5.3.2 Nocturnal HRV measures (I, II)

No changes were observed in nocturnal HR and HRV indices during the 14-week PREP (I) (Table 7), whereas HFP and TP increased significantly during the 14-week INT. HFP increased after the 8-week PREP and the intense training period in HVT compared with the baseline (II). None other HRV variables changed in either HVT or HIT during the training periods.

TABLE 7 Nocturnal HR and HRV over the preparation periods (8 to 14 weeks) and the experimental periods (8 to 14 weeks).

		I (14+14 weeks)	II (8+8 weeks)	
			HVT	HIT
HR (bpm)	pre	51.1 ± 4.4	51.2 ± 4.3	51.6 ± 7.6
	mid	49.9 ± 6.1	50.5 ± 4.1	52.5 ± 7.7
	post	48.9 ± 5.5*	49.0 ± 4.2	50.4 ± 7.1
LFP (ln ms^2)	pre	8.36 ± 0.47	8.15 ± 0.48	8.23 ± 0.58
	mid	8.29 ± 0.45	8.26 ± 0.44	8.16 ± 0.51
	post	8.42 ± 0.40	8.24 ± 0.36	8.33 ± 0.66
HFP (ln ms^2)	pre	8.02 ± 0.64	7.95 ± 0.66	7.88 ± 0.73
	mid	8.06 ± 0.68	8.23 ± 0.62*	7.75 ± 0.78
	post	8.21 ± 0.67$^{\#}$	8.24 ± 0.60*	7.93 ± 0.81
TP (ln ms^2)	pre	9.01 ± 0.50	8.81 ± 0.43	8.80 ± 0.57
	mid	8.99 ± 0.53	8.98 ± 0.44	8.71 ± 0.55
	post	9.14 ± 0.49$^{\#\#}$	8.95 ± 0.40	8.87 ± 0.67

Significant difference from pre, *p < 0.05; Significant difference from mid, $^{\#}p < 0.05$, $^{\#\#}p < 0.01$. HVT, high volume training; HIT, high-intensity training; HR, heart rate; LFP, low frequency power; HFP high frequency power; TP, total power

5.3.3 Body composition and serum hormone concentrations

Body composition and serum hormone concentrations are presented in Table 8. Body mass and percentage of body fat decreased during the 28-week training period (I). No changes were observed in body mass and percentage of body fat during the 18-week training period (II), except for a decrement in body mass in HVT men during PREP.

No changes were observed in basal levels of serum testosterone and cortisol during the 28-week study (I). Serum cortisol concentration decreased in HVT women and HIT men after PREP and INT compared baseline in study II. In addition, cortisol levels increased during INT in HVT men. Basal serum concentrations of testosterone decreased after PREP in HIT women, as well as in HVT women, which increased back to the baseline after HVT.

TABLE 8 Body composition and serum hormone concentrations over the preparation periods and the intense training periods.

		I (14+14 weeks)	II (8+8 weeks)			
			HVT		HIT	
			women (n = 8)	men (n = 6)	women (n = 8)	men (n = 6)
Body mass	pre	78.1 ± 5.6	60.1 ± 6.8	83.6 ± 6.7	59.7 ± 6.5	73.8 ± 6.1
(kg)	mid	77.5 ± 5.5**	59.2 ± 6.3	81.5 ± 6.6*	59.4 ± 6.8	72.1 ± 4.8
	post	76.5 ± 5.7***	59.3 ± 5.6	80.4 ± 7.7	59.3 ± 6.2	72.9 ± 5.5
Percentage of body fat	pre	17.7 ± 5.1	23.2 ± 3.6	14.9 ± 1.5	24.5 ± 4.7	14.5 ± 4.5
	mid	16.7 ± 5.1*	23.0 ± 3.4	14.2 ± 0.7	23.9 ± 5.2	13.6 ± 4.1
	post	16.3 ± 5.4*	22.7 ± 3.4	12.9 ± 1.0	23.8 ± 5.4	13.7 ± 4.1
Cortisol	pre	442 ± 79	624 ± 236	557 ± 191	532 ± 104	547 ± 77
$(\text{nmol} \cdot \text{l}^{-1})$	mid	437 ± 119	505 ± 167*	460 ± 139	452 ± 125	488 ± 67*
	post	438 ± 82	519 ± 202*	525 ± 139$^{\#}$	526 ± 126	457 ± 98*
Testosterone	pre	16.2 ± 3.4	1.0 ± 0.3	15.6 ± 4.8	0.9 ± 0.4	17.1 ± 2.9
$(\text{nmol} \cdot \text{l}^{-1})$	mid	17.1 ± 4.2	0.6 ± 0.3**	15.1 ± 4.9	0.6 ± 0.5*	15.2 ± 2.9
	post	16.5 ± 4.0	1.0 ± 0.3$^{\#}$	14.8 ± 3.0	0.6 ± 0.5	17.0 ± 3.4

Significant difference from pre,*$p < 0.05$, **$p < 0.01$, ***$p < 0.001$; Significant difference from mid, $^{\#}p < 0.05$. HVT, high volume training; HIT, high-intensity training.

5.4 Pretraining predictors of subsequent training adaptation (I, II)

Age and pretraining VO_{2max} did not correlate with the change in RS_{peak} in any training periods in studies I and II (Table 9). A negative correlation was observed between the previous training volume and the adaptation to HVT (II), but not in other training periods. The years of previous training tended to be related to the training adaptation in HVT.

No significant correlations were observed between pretraining basal hormonal concentrations and training adaptations in any of the training periods. Interestingly, a moderate trend was observed between pretraining testosterone levels and the training adaptation in PREP (I) and between pretraining cortisol and the training adaptation in HVT (II).

Large correlations were observed between nocturnal HRV at baseline and the change in RS_{peak} over INT, HVT, and HIT. The largest positive relationships were found between HFP at baseline and the change of RS_{peak} in INT and HIT (Figure 8). A negative correlation was observed between pretraining HFP and the change of RS_{peak} in HVT.

The change in RS_{peak} was greater in the low HRV group compared with the high HRV group after HVT (Figure 9). After HIT, the change of RS_{peak} was greater in the high HRV group compared with the low HRV group. In addition, the change of RS_{peak} was greater after HIT compared with HVT in the high HRV group, but no difference was found in the change of RS_{peak} between HIT and HVT in the low HRV group.

TABLE 9 Correlations between pretraining characteristics of subjects and endurance training adaptation (ΔRS_{peak}).

	I (14 + 14 weeks)		II (8 weeks)	
	PREP	INT	HVT	HIT
Age (years)	-0.11	0.16	-0.14	-0.21
Previous training years			-0.51 [b]	0.36 [c]
Previous training volume	-0.11	0.13	-0.62**, [b]	0.01
VO_{2max} ($ml \cdot kg^{-1} \cdot min^{-1}$)	-0.03	0.20	-0.02	0.15
RS_{peak} ($km \cdot h^{-1}$)	-0.06	0.02	0.49 [c]	0.02
Cortisol ($nmol \cdot l^{-1}$)	0.01	-0.18	0.40[c]	0.26
Testosterone ($nmol \cdot l^{-1}$)	0.32[c]	0.27	0.05	-0.02
HR_{rest}	-0.21	-0.44	0.14	-0.04
LFP (ln ms^2)	-0.17	0.69**, [b]	-0.16	0.05
HFP (ln ms^2)	-0.29	0.71***, [a]	-0.74**, [a]	0.63*, [b]
TP (ln ms^2)	-0.25	0.75***, [a]	-0.65*, [b]	0.38[c]

Significant correlation,* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$. [a] very large correlation, [b] large correlation, [c] moderate correlation. Correlations of HRV indices were adjusted for age and correlations of testosterone and VO_{2max} were adjusted by sex using partial correlation. PREP, preparation training; INT, intense training; HVT, high volume training; HIT, high-intensity training; previous training volume, times per week (I) and hours per week (II) during the previous two months before the study; HR_{rest}, resting heart rate; LFP, low frequency power; HFP high frequency power; TP, total power.

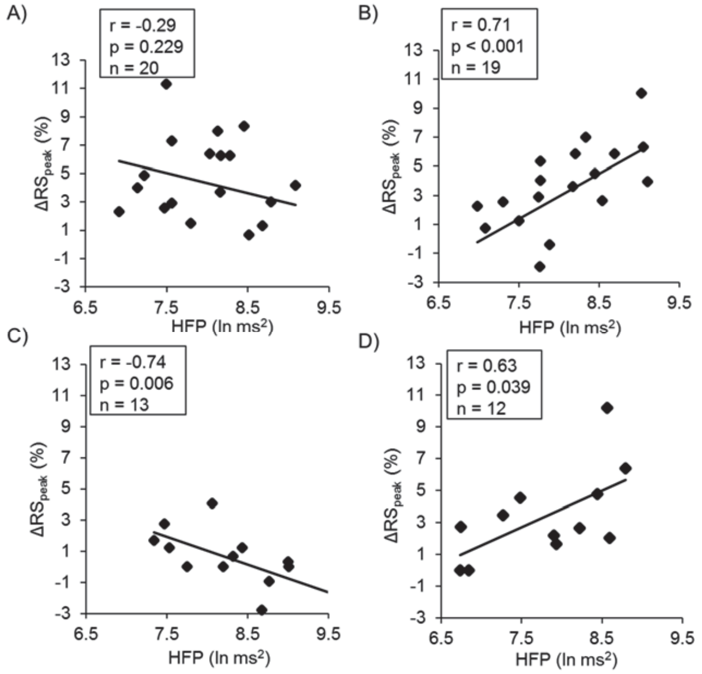


FIGURE 8 Relationships between training adaptation (ΔRS_{peak}) and pretraining nocturnal heart rate variability (HFP, high frequency power) over A) 14 weeks of preparation training (PREP), B) 14 weeks of intense training (INT, increased training volume and intensity), C) 8 weeks of high volume training (HVT) and D) 8 weeks of high-intensity training (HIT). Correlation coefficients are adjusted by age.

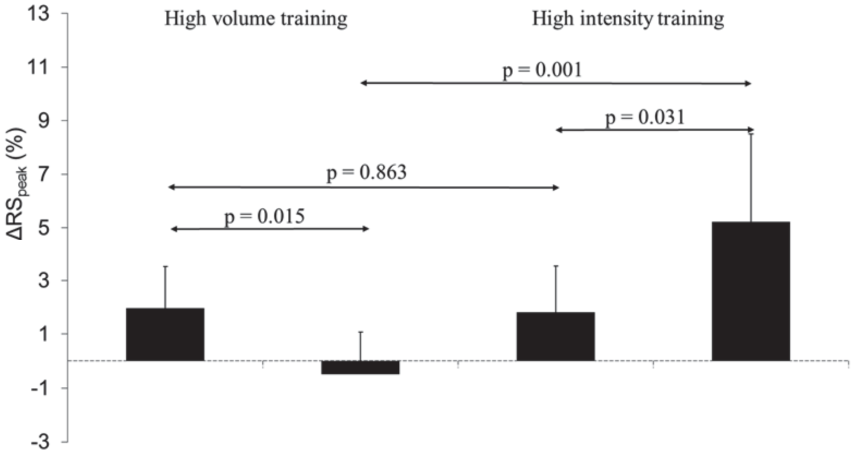


FIGURE 9 Training adaptation (ΔRS_{peak}) to 8 weeks of high volume (HVT) and high-intensity (HIT) endurance training in the low and high heart rate variability (HRV) groups (II).

The results of the multiple linear regression analysis showed significant relationships between actual training adaptation and predicted models (Table 10). HFP, previous training years and age explained 44% of the variance in change of RS_{peak} during HIT (Figure 10). HFP, age, RS_{peak}, previous training volume and previous training years explained 87% of the variance in training adaptation during HVT. Significant multicollinearity among the selected variables was not found (tolerance 0.83-1.00 in HIT and 0.56-0.83 in LIT; variance inflation factor 1.00-1.21 in HIT and 1.21-1.79 in LIT).

TABLE 10 Models to predict adaptation to high-intensity training (HIT) and high volume of low-intensity training (HVT) revealed by linear multiple regression analysis (backward method).

Model		r	r^2	Sig F change	p
HIT (I-II) (n = 31)					
1	HFP, previous training years, previous training volume, age, sex and RS_{peak}	0.70	0.49	0.007	0.007
2	HFP, previous training years, previous training volume, age and RS_{peak}	0.68	0.46	0.237	0.006
3	HFP, previous training years, previous training volume and age	0.67	0.45	0.453	0.003
4	HFP, previous training years and age	0.67	0.44	0.555	0.001
HVT (II) (n = 13)					
1	HFP, age, RS_{peak}, previous training volume, previous training years and sex	0.95	0.91	0.007	0.007
2	HFP, age, RS_{peak}, previous training volume and previous training years	0.93	0.87	0.176	0.005
3	HFP, age, RS_{peak} and previous training years	0.90	0.81	0.106	0.006
4	HFP, RS_{peak} and previous training years	0.86	0.73	0.118	0.006
5	RS_{peak} and previous training years	0.82	0.67	0.170	0.004

HVT, high volume of low-intensity training; HIT, high-intensity training; HFP, high frequency power; RS_{peak}, peak treadmill running speed; previous training volume, hours per week.

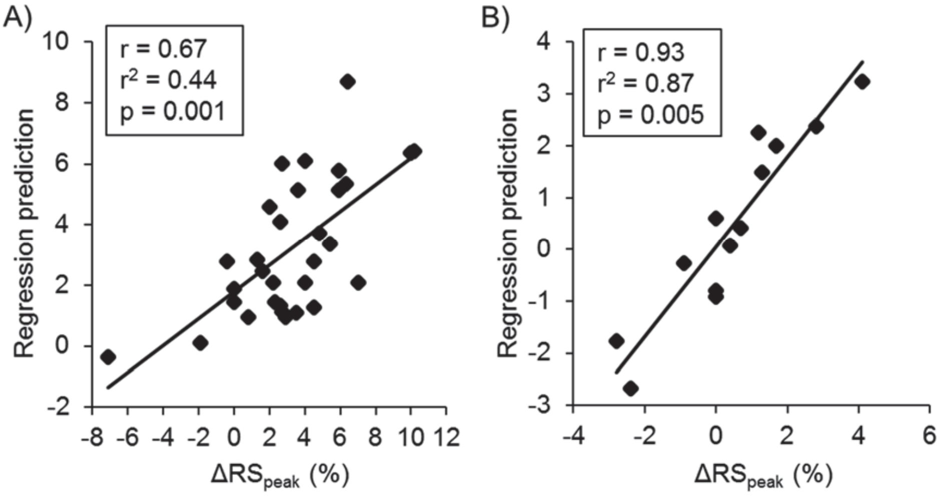


FIGURE 10 Relationships between actual training adaptation (ΔRS_{peak}) and regression predictions based on equations Y = -29.21 + 0.16*age + 0.13*training years + 3.22* HFP in HIT (n = 31) (A) and Y = 4.18 – 0.12*age – 0.09*training years – 0.38*training volume + 0.77*RS_{peak} – 1.01* HFP in HVT (n = 13) (B).

5.5 Submaximal running test with post-exercise cardiac autonomic and neuromuscular measures in monitoring training adaptation (III, IV)

5.5.1 SRT and SCE variables as predictors of endurance characteristics

RS of all stages in SRT and SCE were well correlated with RS_{peak}, VO_{2max}, RS_{LT2} and RS_{LT1} (Table 11). Post-exercise HRR and lnRMSSD in SRT and HRR after SCE correlated moderately with VO_{2max}, but not with RS_{peak}. Similar significances were observed in the correlation between sexes, except HRR, which correlated with both VO_{2max} and RS_{peak} in women after SRT (r = 0.62, p = 0.006; r = 0.64, p = 0.004, large) and after SCE (r = 0.66, p = 0.003; r = 0.63, p = 0.005), but not in men. A similar trend was found between VO_{2max} and HRR after SRT (r = 0.48, p = 0.098, moderate) and SCE (r = 0.56, p = 0.073, moderate) in men. In addition, CMJ_h correlated with RS_{peak}, when all that data was pooled the correlation separated for women and men were r = 0.44 (p = 0.052, moderate) and r = -0.23 (p = 0.418, small), respectively.

TABLE 11 Correlations between the results of SRT and SCE to endurance performance variables (n = 29).

	VO_{2max} ($ml \cdot kg^{-1} \cdot min^{-1}$)	RS_{peak} ($km \cdot h^{-1}$)	RS_{LT2} ($km \cdot h^{-1}$)	RS_{LT1} ($km \cdot h^{-1}$)
CMJ	$0.47^{**, c}$	$0.57^{***, b}$	$0.48^{**, c}$	$0.35^{*, c}$
SRT RS1 ($km \cdot h^{-1}$)	$0.68^{***, b}$	$0.71^{***, a}$	$0.76^{***, a}$	$0.79^{***, a}$
SRT RS2 ($km \cdot h^{-1}$)	$0.74^{***, a}$	$0.77^{***, a}$	$0.84^{***, a}$	$0.82^{***, a}$
SRT RS3 ($km \cdot h^{-1}$)	$0.75^{***, a}$	$0.85^{***, a}$	$0.86^{***, a}$	$0.80^{***, a}$
SRT HRR (bpm)	$0.44^{*, c}$	0.13	0.19	0.04
SRT lnRMSSD (ms)	$0.38^{*, c}$	0.13	0.14	0.05
SCE RS1 ($km \cdot h^{-1}$)	$0.60^{***, b}$	$0.74^{***, a}$	$0.83^{***, a}$	$0.87^{***, a}$
SCE RS2 ($km \cdot h^{-1}$)	$0.75^{***, a}$	$0.83^{***, a}$	$0.89^{***, a}$	$0.83^{***, a}$
SCE RS3 ($km \cdot h^{-1}$)	$0.58^{***, b}$	$0.79^{***, a}$	$0.78^{***, a}$	$0.71^{***, a}$
SCE HRR (bpm)	$0.46^{*, c}$	0.22	0.31^{c}	0.22

Pearson's correlation, * $p < 0.05$, *** $p < 0.001$. ^{a} very large correlation, ^{b} large correlation, ^{c} moderate correlation. SRT, submaximal running test; SCE, submaximal control exercise; VO_{2max}, maximal oxygen consumption; RS_{peak}, peak running speed in the maximal treadmill test; RS at LT2, running speed at lactate threshold 2; RS at LT1, running speed at lactate threshold 1; RS, running speed; HRR, heart rate recovery; lnRMSSD, the natural logarithm of the square root of the mean squared differences of successive R-R intervals.

5.5.2 Submaximal running test (SRT) in monitoring training adaptation (III)

The speed of the treadmill was successfully set for the target HR levels (70%, 80% and 90% of HR_{max}) in SRT (Table 12), with no changes between the five testing sessions. Individual ranges in HR were 67–74% during the first, 79–82% during the second and 88–93% of HR_{max} during the third stage. RPE, post-exercise HRR, and lnRMSSD remained similar during the whole training period, but a persistent increase was observed in RS of all stages after nine weeks of training.

TABLE 12 Physiological and performance variables of the submaximal running test (means ± SD)

	Week 0	Week 4	Week 9	Week 13	Week 18
Stage 1 (70% of HR_{max})					
Running speed ($km \cdot h^{-1}$)	8.2 ± 1.4	8.5 ± 1.4	8.9 ± 1.4***	8.8 ± 1.4***	9.0 ± 1.4***
Heart rate (bpm)	131 ± 8	132 ± 7	131 ± 7	132 ± 7	132 ± 7
% HR_{max}	70 ± 2	70 ± 1	70 ± 1	71 ± 1	70 ± 1
RPE (0-10)	2 ± 1	2 ± 1	1 ± 1	1 ± 1	2 ± 1
Stage 2 (80% of HR_{max})					
Running speed ($km \cdot h^{-1}$)	10.1 ± 1.5	10.3 ± 1.6	10.6 ± 1.6**	10.6 ± 1.5**	10.8 ± 1.5***
Heart rate (bpm)	150 ± 8	150 ± 8	150 ± 8	150 ± 8	150 ± 8
% HR_{max}	80 ± 1	81 ± 1	80 ± 1	80 ± 1	80 ± 1
RPE (0-10)	3 ± 1	3 ± 1	3 ± 1	3 ± 1	3 ± 1
Stage 3 (90% of HR_{max})					
Running speed ($km \cdot h^{-1}$)	12.6 ± 1.6	13.0 ± 1.7**	13.3 ± 1.7***	13.4 ± 1.7***	13.7 ± 1.7***
Heart rate (bpm)	168 ± 9	168 ± 8	168 ± 9	167 ± 9	168 ± 9
% HR_{max}	90 ± 1	90 ± 1	90 ± 1	90 ± 1	90 ± 1
RPE (0-10)	6 ± 2	5 ± 2	5 ± 2	5 ± 2	5 ± 1
Recovery period					
HRR (bpm)	42 ± 10	42 ± 9	43 ± 14	43 ± 12	43 ± 10
lnRMSSD (ms)	1.5 ± 0.7	1.6 ± 0.8	1.6 ± 0.8	1.6 ± 0.7	1.6 ± 0.7

Significant difference from week 0. ** $p < 0.01$, *** $p < 0.001$. HRR, heart rate recovery during the first minute after the end of the submaximal running test; lnRMSSD, the natural logarithm of the square root of the mean squared differences of successive R-R intervals as calculated during the last minute of the 2-min recovery period after the submaximal running test.

VO_{2max} increased moderately in Q1 (the highest responders) ($p = 0.004$), whereas only small or trivial changes were observed in other quartiles (Table 13). Large improvements of RS_{peak} were observed in Q1, Q2, and Q3, but not in Q4. The change in RS_{peak} was greater in Q1 compared with other quartiles. HR_{max} decreased (183 ± 10 vs. 180 ± 8; ES = 0.58, moderate; $p = 0.017$) in Q4, but remained unaltered in other quartiles. A large increase of RS3 was observed in Q1, whereas small or moderate changes were observed in other quartiles after the training period. The change in RS3 was greater in Q1 compared with Q4. Moderate or small increases were observed in SRT RS1 and RS2 in all quartiles, except in Q4. CMJ_h, post exercise HRR, and RMSSD showed trivial changes in all quartiles, except CMJ_h in Q2 (moderate).

TABLE 13 Performance changes after the 18-week training period in quartiles of the training adaptation (means ± SD).

	Percentage change at 18 weeks			
	1st quartile (n = 9)	2nd quartile (n = 9)	3rd quartile (n = 9)	4th quartile (n = 8)
VO_{2max} (%)	8.3 ± 0.8^{b}	2.9 ± 5.4^{c}	0.2 ± 4.3*, ^{d}	-2.6 ± 4.3***, ^{c}
RS_{peak} (%)	8.3 ± 6.2^{a}	$4.4 \pm 1.1^{***, a}$	$1.9 \pm 0.5^{***, a}$	-2.2 ± 2.7***, ^{c}
CMJ_h (%)	1.9 ± 5.3, ^{d}	4.1 ± 4.8^{b}	-2.2 ± 7.3, ^{d}	-1.2 ± 6.1, ^{d}
SRT RS1 (%)	11.4 ± 10.4^{b}	10.8 ± 9.1^{b}	10.7 ± 10.2^{b}	5.1 ± 5.3^{b}
SRT RS2 (%)	10.9 ± 8.4^{b}	5.9 ± 4.7^{b}	7.8 ± 9.2, ^{c}	1.3 ± 2.3, ^{c}
SRT RS3 (%)	13.5 ± 7.4^{a}	6.6 ± 3.9^{b}	9.1 ± 4.8^{b}	3.9 ± 2.0**, ^{b}
SRT HRR (%)	8.1 ± 19.5^{d}	8.2 ± 17.9^{d}	4.8 ± 13.6^{d}	11.8 ± 23.0^{d}
SRT RPE (%)	-7.1 ± 13.9^{c}	-5.9 ± 27.4^{d}	12.8 ± 34.0^{d}	-0.4 ± 13.4^{d}
SRT RMSSD (%)	15.7 ± 50.0^{d}	-4.2 ± 22.7^{d}	20.1 ± 51.1^{d}	6.2 ± 37.0^{d}

Significant difference from the first quartile. * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$. ^{a} large effect size, ^{b} moderate effect size, ^{c} small effect size, ^{d} trivial effect size. 1st quartile, the highest responders; 2nd quartile, moderate responders; 3rd quartile, low responders; 4th quartile, the lowest responders; VO_{2max}, maximal oxygen consumption; RS_{peak}, peak treadmill running speed; CMJh, the counter movement jump height; SRT, submaximal running test; RS, running speed; HRR, heart rate recovery; lnRMSSD, the natural logarithm of the square root of the mean squared differences of successive R-R intervals.

Relationships between the changes of RS in SRT, and the changes in VO_{2max} and RS_{peak} after 18 weeks of training are shown in Figure 11. The changes in RS2 and RS3 showed large or moderate correlations with the change of both VO_{2max} and RS_{peak}. No significant relationships were found between the changes of VO_{2max} and RS_{peak}, and the changes of CMJ_h ($r = 0.21$, small; $r = 0.15$, trivial), post exercise lnRMSSD ($r = 0.06$, $r = -0.02$, both trivial) and HRR ($r = 0.01$, $r = -0.09$, both trivial). No sex differences were observed in the correlations.

The changes of the variables in SRT and CMJ_h in the highest (Q1) and the lowest (Q4) responders at weeks 4, 9, 13, and 18 are presented in Figure 12. A significant training effect (test of within-subjects effect) between the measurement weeks was observed in RS of all stages in Q1 ($p < 0.005$, all), but only in RS3 ($p = 0.036$) in Q4. No changes were observed in either quartile in CMJ_h, RPE, HRR and lnRMSSD. Significant differences between Q1 and Q4 were observed in the change of RS3 at week 13 and 18. In addition, the change of RS2 tended to be greater in Q1 than Q4 at week 13 ($p = 0.076$) and 18 ($p = 0.136$).

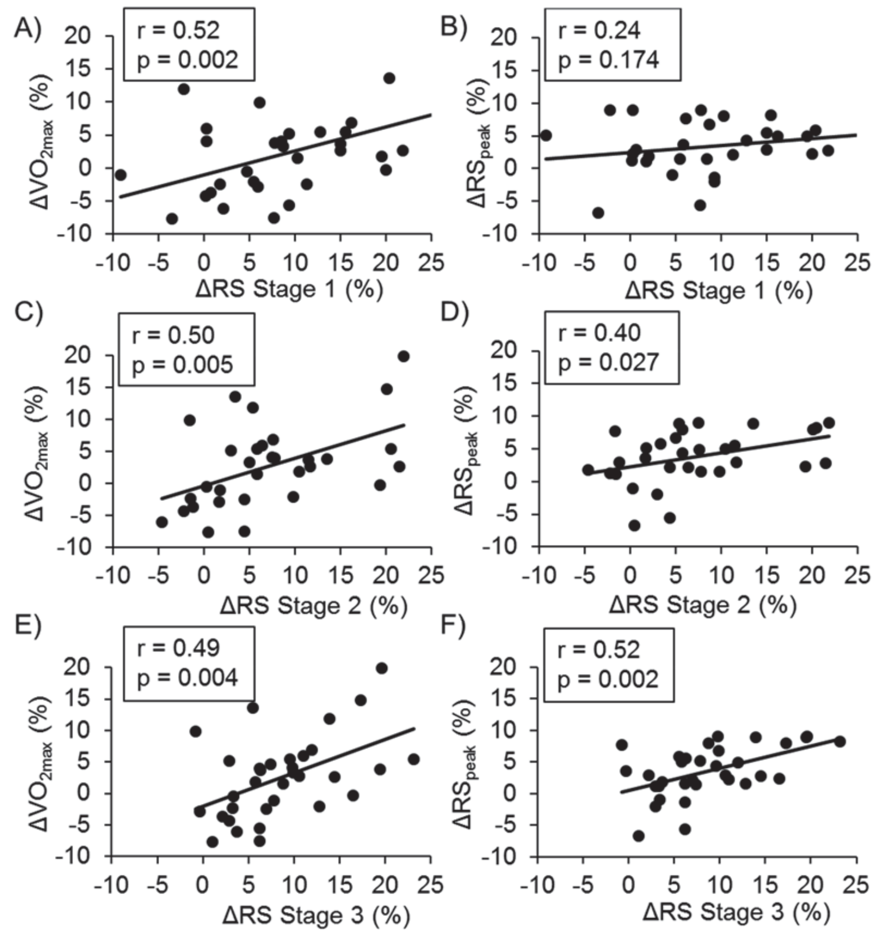


FIGURE 11 Correlations between the changes of maximal oxygen consumption (VO_{2max}) and peak running speed (RSpeak), and the changes of running speed during the first (70% HR_{max}) (A-B), second (80% HR_{max}) (C-D) and third stage (90% HR_{max}) (E-F) in the submaximal running test (n = 33) after 18 weeks of training.

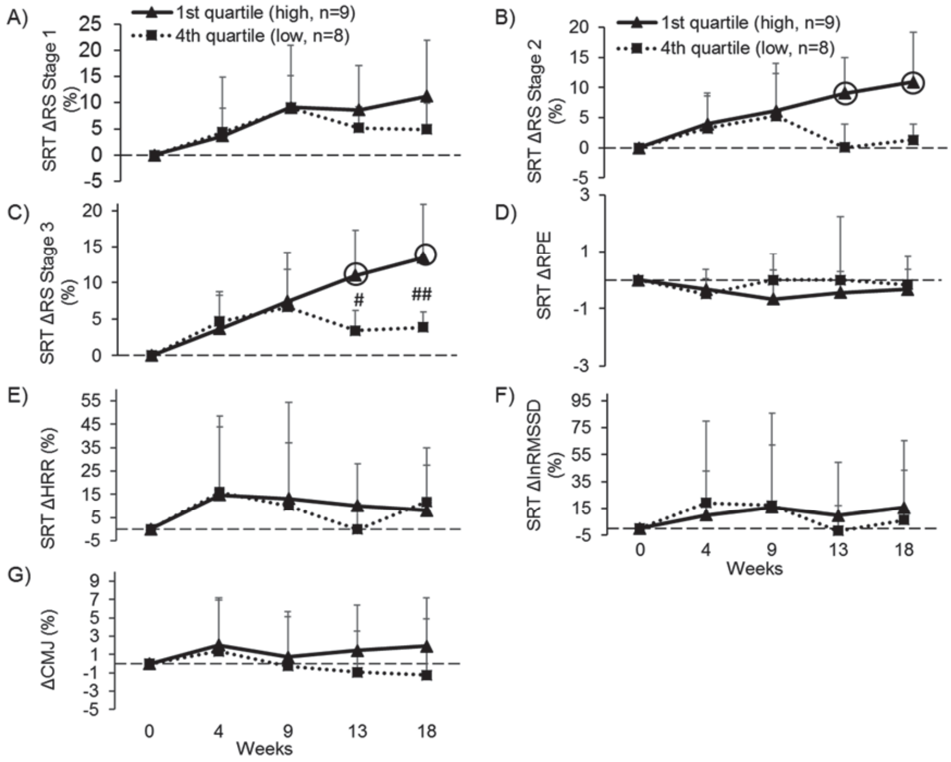


FIGURE 12 Changes in running speed (RS) in the first (A), second (B) and third stage (C) of the submaximal running test (SRT), rate of perceived exertion (RPE, D), post exercise heart rate recovery (HRR, E), the natural logarithm of the square root of the mean squared differences of successive R-R intervals (lnRMSSD, F) after the submaximal running test (SRT) and the counter movement jump height (CMJ_h, G) in 1st (the highest responders) and 4th (the lowest responders) quartiles of percentage training adaptation. Circles around symbols denote significant ($p<0.05$) within-group difference from week 0 and between groups differences: # $p<0.05$, ## $p<0.01$ (revealed by Bonferroni post hoc analysis).

5.5.3 Submaximal control exercise (SCE) in monitoring training adaptation (IV)

The subjects were not able to perform SCE every week due to sickness or mild injuries. In addition, some single test results were not approved for analysis due to poor HR signal. On average, they repeated SCE 13 times within 18 weeks. The presence of missing data values in the time-series of RS1, RS2, RS3, and HRR were 23.1%, 23.9%, 24.5% and 24.9%, respectively. The subjects were able to closely regulate their HR for the target HR levels by adjusting their RS according to GPS readings from the HR monitor. Mean HR for the three stages were 71 ± 3%, 81 ± 1% and 90 ± 1% of HR_{max}, respectively. Individual mean ranges were 69–75% during the first, 77–84% during the second and 87–92% of

HR_{max} during the third stage of SCE. Mean RPE after SCE was 5 ± 2 during the training period.

Relationships between the changes of variables in SCE and the changes in endurance performance variables after 18 weeks of training are shown in Table 14. The changes in RS2 and RS3 of SCE correlated significantly with the change in VO_{2max}, RS_{peak} and RS at lactate thresholds. Similar correlations were found in both sexes.

TABLE 14 Correlations between the changes in endurance performance variables and the changes in the submaximal control exercise (SCE, n = 26) after 18 weeks of training.

	VO_{2max} (%)	RS_{peak} (%)	RS_{LT2} (%)	RS_{LT1} (%)
SCE RS1 (%)	0.34^{c}	0.24	0.27	0.34^{c}
SCE RS2 (%)	$0.60^{**,b}$	$0.57^{**,b}$	$0.43^{*,c}$	$0.48^{*,c}$
SCE RS3 (%)	$0.62^{***,b}$	$0.79^{***,a}$	$0.74^{***,a}$	$0.52^{**,b}$
HRR (%)	0.13	-0.01	0.21	0.37^{c}

Pearson's correlation,$^{*}p < 0.05$, $^{**}p < 0.01$, $^{***}p < 0.001$. ^{a} very large correlation, ^{b} large correlation, ^{c} moderate correlation. VO_{2max}, maximal oxygen consumption; RS_{peak}, peak running speed in the maximal treadmill test; RS_{LT2}, running speed at lactate threshold 2; RS_{LT1}, running speed at lactate threshold 1; RS, running speed; HRR, heart rate recovery.

Time series of the changes in RS of SCE for the clusters are presented in Figure 13. The clusters based on the change in RS2, showed differences between the clusters in the change of VO_{2max} ($p = 0.038$) and RS_{peak} ($p = 0.008$). Cluster 1, which showed the greatest improvement in RS2, improved more in RS_{peak} compared with clusters 2 and 3 ($p = 0.004$). The clusters grouped by the change of RS3 also showed differences in the change of VO_{2max} ($p = 0.009$) and RS_{peak} ($p = 0.004$) and RS_{LT2} ($p = 0.042$). Clusters 1 and 2 showed significantly greater improvements in RS_{peak} compared with clusters 3 and 4. Clusters grouped by the changes of RS1, HRR, and RPE, showed no differences in the change of any endurance performance variables.

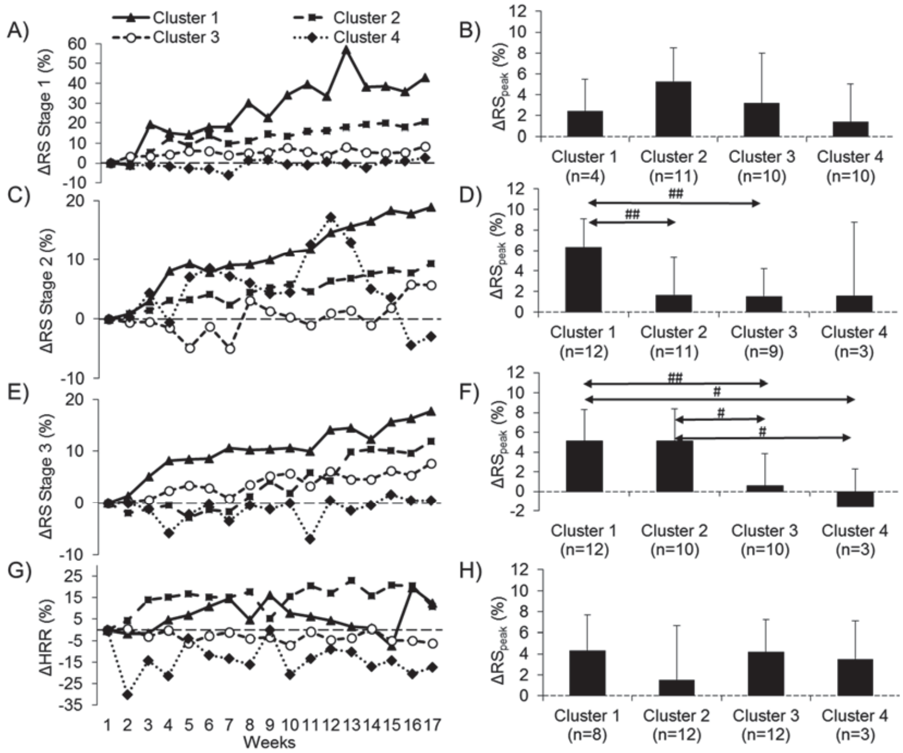


FIGURE 13 Representative time-series for the clusters based on the changes of running speed in the first (A), second (C), third stage (E) and heart rate recovery (G), and changes in peak running speed in the maximal treadmill test (RS_{peak}) for the clusters based on changes of RS1 (B), RS2 (D), RS3 (F) and HRR (H). Between cluster differences in change of RS_{peak}: # p<0.05, ## p<0.01 (revealed by Kruskal-Wallis test).

5.6 HRV-guided vs. preprogrammed endurance training (V)

5.6.1 Adaptations to training

Endurance performance of all subjects improved significantly during PREP as follows: RS_{3000m} by 2.7 ± 2.5% ($p < 0.001$), VO_{2max} by 2.9 ± 4.4% ($p = 0.003$), RS_{LT2} by 4.3 ± 7.4% ($p = 0.001$), and RS_{LT1} by 4.8 ± 8.0% ($p = 0.001$).

Running time for the 3000 m time trial improved in EXP (-14.3 ± 14.1 s, p = 0.005, ES = 0.53) but not in TRAD (-7.8 ± 19.8 s, p = 0.111. ES = 0.143) during INT. A small between-group difference was observed in the change of RS_{3000m} (Table 15, Figure 14). VO_{2max} and RS_{LT2} improved in both groups, with a small between-group difference, while RS_{LT1} improved in the EXP-group, but not in TRAD (a moderate between-group difference). No differences were observed in the changes of the endurance characteristics between sexes.

TABLE 15 Endurance performance variables in the EXP- and TRAD-groups before and after the 8-week intense training period. Values are means ± SD.

	RS_{3000m} $(km \cdot h^{-1})$	VO_{2max} $(ml \cdot kg^{-1} \cdot min^{-1})$	RS_{LT2} $(km \cdot h^{-1})$	RS_{LT1} $(km \cdot h^{-1})$
EXP (n=12)				
mid	15.4 ± 1.6	54.4 ± 6.2	13.4 ± 1.4	11.0 ± 1.2
post	15.7 ± 1.5	56.4 ± 7.0	13.8 ± 1.3	11.3 ± 1.2
% change	2.1 ± 2.0**	3.7 ± 4.6*	2.6 ± 3.3*	2.8 ± 3.7*
ES (rating)	0.54 (mod)	0.40 (small)	0.38 (small)	0.37 (small)
TRAD (n=18)				
mid	15.0 ± 1.6	53.0 ± 5.8	12.8 ± 1.6	10.6 ± 1.4
post	15.2 ± 1.5	55.5 ± 5.8	13.1 ± 1.5	10.8 ± 1.5
% change	1.1 ± 2.7^{ns}	5.0 ± 5.2**	1.9 ± 2.2**	1.0 ± 2.9^{ns}
ES (rating)	0.14 (trivial)	0.49 (small)	0.46 (small)	0.17 (trivial)
Between group differences in responses to training				
	0.42 (small)	0.26 (small)	0.25 (small)	0.54 (mod)

* $p < 0.05$, ** $p < 0.01$, (significant difference from mid); ES = effect size; EXP, heart rate variability guided training group; TRAD, preprogrammed training group; RS_{3000m}, mean running speed in 3000 m running test; VO_{2max}, maximal oxygen consumption; RS_{LT2}, running speed at lactate threshold 2; RS_{LT1}, running speed at lactate threshold 1.

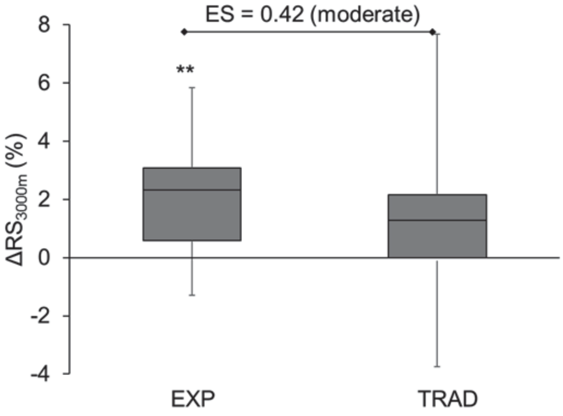


FIGURE 14 Changes (%) in running performance of 3000 m after the 8-week HRV guided training (EXP) and preprogrammed training (TRAD). Box plots represent median values (solid line), 50th percentile values (box outline), and minimal / maximal values (whiskers). ** $p < 0.01$, significant difference from mid, ES = effect size in the difference between the groups.

A significant training effect between the measurement weeks was observed in RJ_{power} in EXP ($p < 0.001$, ES = 0.398) but not in TRAD ($p = 0.364$, ES = 0.085) (Figure 15). Significant differences between the groups were observed in the change of RJ_{power} at week 13 (ES = 0.39, small) and after INT (ES = 0.50, moderate). No differences between the groups were observed in RJ_h. Weekly session RPE was similar for the groups during the training period, except a higher training load in TRAD compared with EXP at the second week of INT (week 7) (ES = 0.36, small). Higher weekly recovery feeling was observed in EXP compared with TRAD after the second week of INT (ES = 0.57) and remained higher (ES = 0.41–0.52) for the whole training period, excluding week 9.

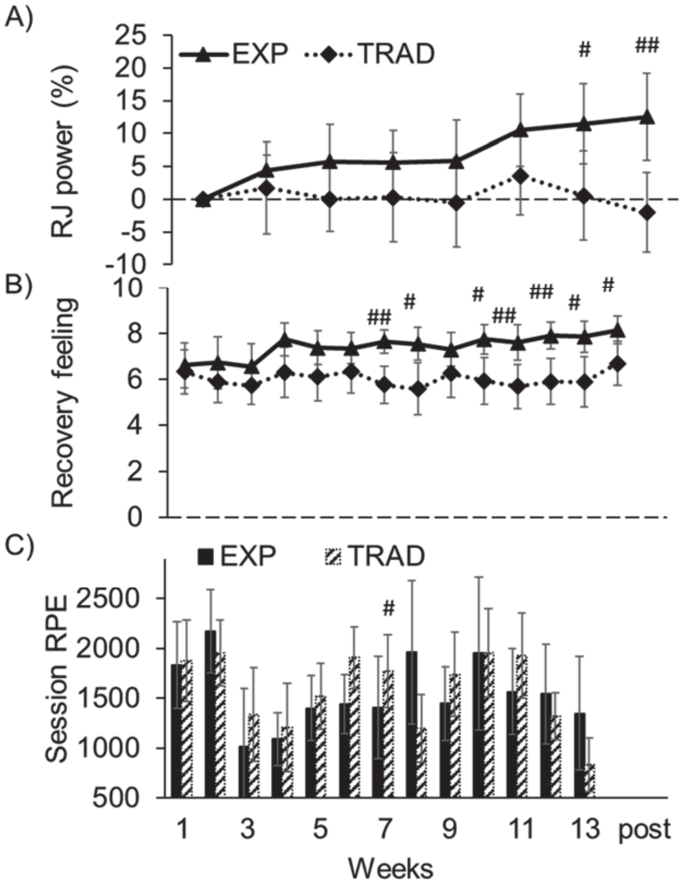


FIGURE 15 Changes (%) in reactivity jump power (A) and weekly recovery feeling (B) and session RPE (C) during the 14-week training period in the HRV guided (EXP) and preprogrammed training groups (TRAD). Circles around symbols denote significant ($p < 0.05$) within-group difference from week 0 and between groups differences: # $p < 0.05$, ## $p < 0.01$ between group differences (revealed by Bonferroni post hoc analysis).

Individual ranges in the change of RS_{3000m} were from -1 to 6% in EXP and from -4 to 8% in TRAD (Figure 16). One subject in HRV and five subjects in TRAD showed decrement in the 3000 m running performance, while other subjects improved or maintained their running performance in EXP over the 8-week training period.

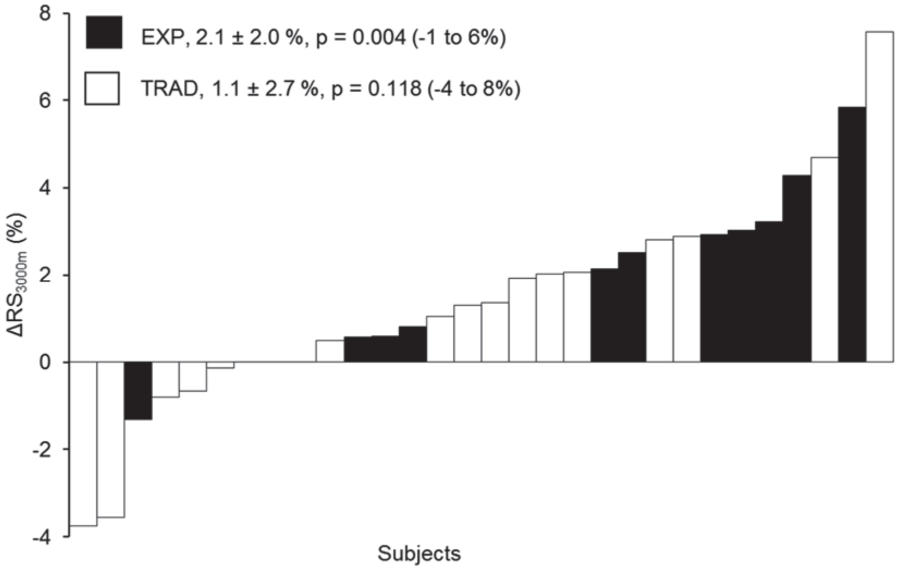


FIGURE 16 Individual changes (%) in endurance performance after the 8-week heart rate variability guided training (EXP, black bars) and preprogrammed training (TRAD, white bars).

5.6.2 Individualization of training in the HRV-guided group

The only difference in means between EXP and TRAD in training was a significantly higher (p = 0.021) amount of MOD and HIT sessions in TRAD (17.7 ± 2.5 sessions) compared to EXP (13.2 ± 6.0 sessions). Individual ranges in the amount of MOD and HIT sessions were from 11 to 21 sessions in TRAD and from 5 to 24 sessions in EXP. Figure 17 presents three examples of individualized programming of training according to HRV. Subject A responded well to a high amount of HIT training. The training program included three HIT blocks (34 days in total) during INT. Subject B also performed three HIT blocks but they were much shorter (15 days in total). However, the response to a high amount of LIT was positive. Subject C did only two 7-day blocks of HIT at the beginning of INT. After that, subject C's HRV was below SWC due to work stress and the training was solely LIT. Subject C was the only subject who showed a decrement in the 3000 m running performance during INT. No significant correlations were found between the number of MOD/HIT sessions and the change of RS_{3000m} (r = 0.42, p = 0.17) or VO_{2max} (r = 0.26, p = 0.43).

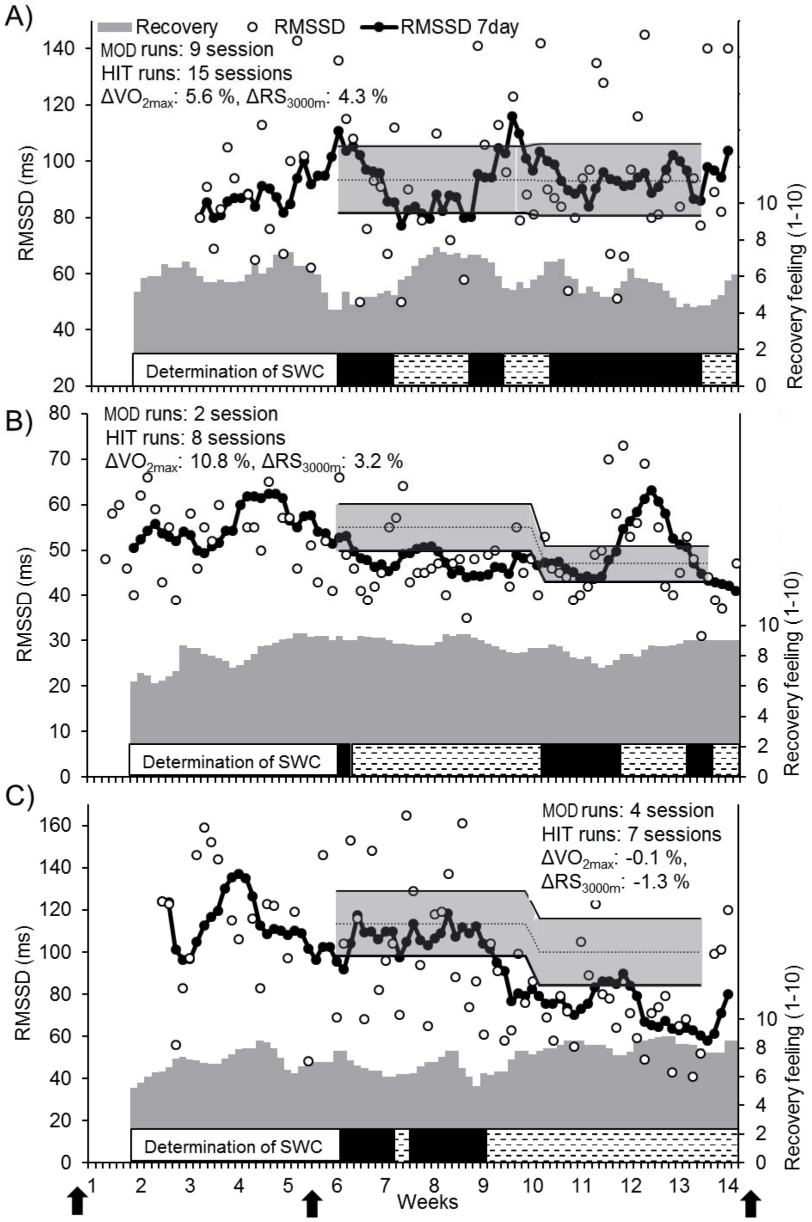


FIGURE 17 Daily changes in the square root of the mean squared differences of successive R-R intervals (RMSSD), 7-day rolling average of RMSSD and recovery feeling for subject A (positive response to a high amount of high-intensity training), subject B (positive response to a high amount of low-intensity training) and subject C (negative response to a high amount of low-intensity training). The grey area indicates the individual optimal area of RMSSD. The black area indicates timing of moderate- and high-intensity training. The dashed line area indicates timing of low-intensity training. The arrows represent timing of the running tests.

6 DISCUSSION

This thesis examined potential factors that could be related to individual variation in endurance training adaptations. The aim was to investigate whether pretraining characteristics of subjects such as age, sex, fitness level, training background, nocturnal HRV, and serum hormone concentrations were related to the subsequent improvement in endurance characteristics. Secondly, the usefulness of a submaximal running test with post-exercise cardiac autonomic and neuromuscular function in monitoring the progress of training adaptations was investigated during an 18-week training program. Thirdly, the aim was to evaluate the effectiveness of using HRV in individualization of endurance training prescription.

The main findings showed that pretraining nocturnal HRV was the strongest single predictor of improvement in maximal endurance performance. Secondly, the present results showed that running speeds at 80 and 90% of HR_{max} in the three-staged submaximal running test protocol were the most competent variables for tracking changes in maximal endurance performance. The third main finding showed that 3000 m running performance improved in the HRV-guided training group, while the performance in the traditional, predefined training group remained the same, although the HRV-guided group performed less moderate- and high-intensity training sessions.

6.1 Individual adaptation to predetermined endurance training (I, II)

Endurance performance

Maximal aerobic capacity and maximal endurance performance improved by 5 and 8% after the 28-week training program and by 2 and 4% after the 18-week training program. The greater improvements were found in the changes of lactate thresholds in both studies (12-16%, 5-6%, respectively). The changes are within the range of aerobic capacity and endurance performance improvements reported in trained endurance runners (Midgley, McNaughton & Jones 2007). The improvements in maximal endurance performance (~ 3%) during the 14-week intense (increased volume and intensity) and the 8-week HIT period were slightly smaller than reported after 8 weeks of LIT, MOD and HIT training (10%) (Buchheit et al. 2010) and after 10 weeks of HIT (6-8%) in moderately trained subjects (Esfarjani & Laursen 2007). After the 8-week HVT (II), a non-significant change (0.5%) was observed, which has been also reported after 10-week of LIT (Esfarjani & Laursen 2007). Contrary to the previously mentioned studies, the protocol of the present studies included preparatory periods, which already induced improvements of 2 to 4% in maximal endurance performance. It is reasonable that greater prolonged improvements are more challenging to achieve after this kind of training period.

Large individual differences in the training adaptations are typical after standardized training (Bouchard & Rankinen 2001; Mann, Lamberts & Lambert 2014). Large individual variation was also found in the changes of maximal endurance performance (-7 to 10%) over the intense training periods (papers I and II) in the present study regardless of the individualized training volume and frequency according to subjects' previous training background. Four of the 25 subjects (16%) did not improved their maximal endurance performance after the 14-week INT. Three (20%) non-responders were identified after 8 weeks of HIT, and seven non-responders (50%) were identified after HVT. Scharhag-Rosenberger et al. (2009; 2012) reported unchanged VO_{2max} in four of the 18 untrained subjects (22%) after 12 months of constant load (3 times/week, 45 min/session at 60% of heart rate reserve) training. The authors concluded that training load should be increased after 6 months of training to maintain the effectiveness of training among beginners (2009; 2012). The present results support the concept that progressively increasing training load, especially by increasing training intensity, is beneficial for prolonged improvements in endurance characteristics in recreational endurance runners. It seems that the increase in training volume alone is not an adequate training stimulus for making prolonged improvements. It also seems that the individualization in training volume and frequency according to previous training background is not enough for diminishing the large heterogeneity in training adaptations. Subjects may need more comprehensively individualized training based on individual physiological characteristics and the status of trainability.

Heart rate variability

Moderate endurance training load tends to increase vagal related HRV (Hautala et al. 2003; Buchheit et al. 2010; Nummela et al. 2010; Boutcher et al. 2013; Da Silva et al. 2014), while increased training intensity and/or load tends to cause a decrease in HRV (Pichot et al. 2000; Pichot et al. 2002; Baumert et al. 2006; Hynynen et al. 2007; Plews et al. 2014). However, an increase in HRV can also be observed after intensified training with decreased endurance performance in functionally overreached athletes (Le Meur et al. 2013b). In the present study, increases in HFP and TP were observed over the 14-week INT and in HFP over both of the present 8-week LIT periods in the HVT group, while no changes were observed in HIT. It seems that increased training volume was needed for the increase in cardiac vagal activity, which is in line with the observation by Plews et al. (2014), who showed a positive relationship between increased vagal activity and training time spent at low-intensity in Olympic level rowers. On the other hand, HIT without the change in training volume did not induce changes in cardiac autonomic regulation in the present study. However, it produced greater improvements in endurance performance, while no improvements were observed in HVT. HRV adaptations to endurance training seemed to be context dependent being related to training volume, intensity and individual training status.

Body composition and serum hormone concentrations

Body mass and percentage of body fat decreased constantly over the 28-week training period, while no changes in anthropometrics were observed over the 18-week training period. The initial percentage of body fat was a bit higher in paper I compared with the male subjects in paper II, which may explain the different findings. Nutritional counselling was given to all subjects and it was similar in both studies. It may be possible that energy consumption increased more during the intense training period in paper I because of the increase in both training volume and intensity.

It has been proposed that serum hormone concentrations can be used in training monitoring. Increased cortisol levels may suggest accumulated stress, overreaching, overtraining or psychological stress. In addition, the increase in serum testosterone may suggest a positive adaptation to the training load (Purge, Jurimae & Jurimae 2006; Grandys et al. 2009). In the present study, basal serum concentrations of testosterone and cortisol remained unaltered during 28 weeks of training. This is in line with the study by Schumann et al. (2015), who observed 13% improvement in endurance performance without changes in basal testosterone and cortisol concentrations during 24 weeks of endurance training in recreational endurance runners. During the 18-week training period, some fluctuations were found in concentrations of serum cortisol and testosterone. The highest cortisol concentrations were observed at baseline measurements in HVT women and in HIT men, which may be due to psychological stress (excitement of the first blood tests). On the other hand, a decrease in cortisol would also indicate a potential state of anabolism (Viru & Viru 2004). In the present study, unaltered basal testosterone levels during the 18 weeks of training do not suggest any changes in the anabolic/catabolic status. Many factors, such as circadian rhythms, pulsatile secretion, nutrition, training load, other stress factors and sleep may influence serum basal hormone concentrations and cause variation in single point measurements (Hackney & Viru 2008). Using hormonal profiles of multiple measurements made over 2-3 days might diminish large variation in hormone concentrations and would be more relevant for monitoring the anabolic/catabolic status.

6.2 Predictors of individual trainability (I, II)

In the present study, nocturnal HFP and TP at baseline correlated negatively with the change in maximal endurance performance after 8 weeks of HVT. In contrast, nocturnal HFP and TP were positively correlated with the adaptation to increased training intensity, while training volume remained same (paper II) or increased (paper I). Previous studies have also reported the positive relation between pretraining cardiac vagal activity and subsequent improvement in VO_{2max} (Hedelin, Bjerle & Henriksson-Larsen 2001; Hautala et al. 2003; Boutcher et al. 2013). Higher cardiac vagal activity has been related to greater improvement in aerobic capacity in highly-trained endurance athletes after 7 months of training and the competition season (Hedelin, Bjerle & Henriksson-Larsen 2001), in sedentary men after 8 weeks of MOD (Hautala et al. 2003) and in untrained women after 12 weeks of HIT (Boutcher et al. 2013). In addition, Boutcher & Stein (1995) reported greater VO_{2max} improvement in sedentary men with high pretraining HRV compared with individuals with low HRV following 24 sessions of MOD. On the contrary, Buchheit et al. (2010) reported a negative relationship between pretraining RMSSD and the change in 10 km running performance (high cardiac vagal activity predicted poor performance) after an 8-week period of LIT, MOD, and HIT.

To the best of current knowledge this is the first study, which proposed that training content has an effect on the relationship between pretraining cardiac vagal activity and subsequent training adaptations. It seems that the relationship is more dependent on training intensity than training volume. High cardiac vagal activity predicted positive adaptations if training load was increased by increasing training intensity. Individuals with higher vagal activity may have a better capacity to cope with increased training intensity and load for leading greater training adaptation. Greater adaptations of individuals with higher resting vagal activity may also be related to a greater adaptation capacity and an improved post-exercise metabolic recovery (Blasco-Lafarga, Martinez-Navarro & Mateo-March 2013). Furthermore, LIT may not sufficiently disturb the homeostasis of individuals with higher HRV, and therefore, does not lead to desirable training adaptations. On the other hand, individuals with lower vagal activity seemed to get a sufficient stimulus from LIT for achieving greater adaptations to training. Cardiac vagal activity has been proposed as a method to assess the vulnerability to stress (Porges 1992; Porges 1995). Thus, individuals with lower vagal activity may have a limited capacity to cope with stress induced by HIT. Unfortunately, the precise mechanisms underlying the relationship between the endurance training adaptation and cardiac autonomic activity are still unclear. It has been reported that genetic factors may determine much of the variation in the endurance training adaptation (Bouchard & Rankinen 2001; Bouchard et al. 2011; Perusse et al. 2013). These factors could partly explain the great variation in cardiac vagal activity. Singh et al. (2001) observed that genes accounted for 13-23% of the variation in the frequency domain HRV measures, while Golosheykin et al. (2016) suggested that 50-60% of the observed individual differences in HRV measures can be attributed to additive genetic factors. Therefore, a common genetic factor may explain the relationship between the endurance training adaptations and cardiac vagal activity (Hautala, Kiviniemi & Tulppo 2009).

Buchheit et al. (2010) expressed that the non-responders had a better pretraining fitness level than responders and speculated that training stimuli might not have been enough for the individuals with higher endurance capacities, although 8 weeks of training included HIT in addition to LIT and MOD. However, the same observation was not found in the present study in terms of the relationship between the baseline fitness level and subsequent training adaptations. In addition, age and sex, which have previously been reported to be predictors of training adaptations (Bouchard & Rankinen 2001; Hautala et al. 2003), were not associated with the adaptations in the correlation analysis. This might be explained by the relatively homogenous groups of subjects in terms of age and baseline fitness level. On the other hand, the multiple regression analysis revealed that the strongest relationship was found between actual training adaptations to HIT and the regression model, which included pretraining HFP, previous training years, and age. However, the amount of variance explained by the model remained relatively low (44%). Instead, a previous training background seemed to be a stronger predictor of training adaptation to LIT. The correlation results proposed that individuals with less training background, in terms of previous training volume and years, showed greater improvements in endurance performance after HVT. The multiple regression analysis showed that the model, which included pretraining HFP, age, RS_{peak}, and previous training background (training years and training volume) explained 87% of the variance in training adaptations to HVT. Lower age, training background, and HFP was together associated with greater training adaptations in the equation. In contrast, higher baseline RS_{peak} was associated with greater adaptation in the model, which can be explained by the higher baseline and improvement of RS_{peak} after HVT in men compared with women. However, the small sample sizes have to be taken into consideration in the interpretation of the regression analysis results. Nevertheless, it seems that many pretraining factors are together related to subsequent training adaptations.

Basal testosterone and cortisol levels have previously been reported to be related to positive training adaptations while lowered testosterone levels could disrupt some anabolic or androgenic processes (Hackney, Moore & Brownlee 2005; Hackney & Lane 2015). No significant correlations were found between pretraining hormone concentrations and the training adaptations in the present studies. Statistical trends were observed between pretraining testosterone level and the training adaptation during PREP (paper I) and between cortisol and the training adaptation in HVT (paper II). Nevertheless, the present results do not support the use of pretraining basal testosterone and cortisol concentrations as predictors of individual endurance training adaptation, at least in recreationally endurance trained subjects.

6.3 Submaximal running performance with post-exercise measurements in monitoring the progress of training adaptation (III, IV)

RS was set successfully for the target heart rate levels of the stages in SRT by the exercise physiologist and in SCE by the subjects. The individual range of HR were the smallest during the third stage (90% of HR_{max}), which expresses that the intensity around LT2 seems to be reasonable for exact regulation of HR. These findings are in line with the previous study related to a submaximal cycling test (Lamberts & Lambert 2009). Heart rates and RPEs of the stages showed that the submaximal running protocol was truly submaximal and did not cause remarkable training load. Furthermore, the submaximal running test seems to be a useful method for regular monitoring of training adaptations that does not interfere with normal training and is therefore, a suitable warm-up protocol.

Submaximal running performance with post-exercise measurements as predictors of endurance characteristics

The strongest predictor of maximal endurance performance was RS at 90% of HR_{max} in the laboratory conditions (r = 0.85) and RS at 80% of HR_{max} in field conditions (r = 0.83) (SCE) in the present study. Similar findings were also observed between aerobic capacity and submaximal running performance at the same intensities in laboratory and field conditions (r = 0.75, r = 0.75, respectively). The current findings support the idea that submaximal endurance performance is able to predict maximal endurance performance (Lamberts et al. 2011; Otter et al. 2015). It has been proposed that the intensity of submaximal performance should be around 80% and 90% of HR_{max} for achieving the highest reliability and for predicting peak cycling performance (r = 0.94) (Lamberts et al. 2011) and 2000-m maximal rowing time (r = -0.93) (Otter et al. 2015). Slightly smaller correlations in the present study may be explained by more challenging and rougher regulation of power (= running speed) on the treadmill compared to exercises with the ergometer, like cycling or rowing in the laboratory conditions. During SRT the speed of the treadmill was adjusted at every 5 seconds, if the HR was 3 beats higher or lower compared to the target HR level. Although, the target average HR levels were achieved in SRT, it is possible that more fluctuation was observed during running compared with the cycling or rowing ergometer tests. This may also explain partly higher correlations in SCE, when

RS was regulated continuously by the subjects according to data of the HR monitor, regardless other external factors (e.g. wind, temperature, terrain), which can interfere the results in field conditions.

The highest correlations between RS at LTs and the submaximal RSs were found between LT1 and RS at 80% of HR_{max} (r = 0.82) and between LT2 and RS at 90% of HR_{max} (r = 0.86) in the laboratory conditions. In the field conditions, the highest correlations were found between LT1 and RS at 70% of HR_{max} (r = 0.87) of HR_{max}, and between LT2 and RS at 80% of HR_{max} (r = 0.89). The findings are rational because RS at LT1 (~ 68% of RS_{peak}) closely corresponds with RS at 80% of HR_{max} (~ 69% of RS_{peak}), and LT2 (~ 84% of RS_{peak}) with RS at 90% of HR_{max} (~ 86% of RS_{peak}) in SRT. Furthermore, in the field conditions RSs were slightly higher (2-7%) at the same submaximal HR levels due to more natural running surface compared with the treadmill.

The present results showed that post-exercise HRR and HRV after SRT and HRR after SCE correlated moderately (r = 0.38–0.46) with VO_{2max}, but not with endurance performance, except in women (r = 0.64-0.66). The present results support that the higher post-exercise vagal activity measured by HRR and HRV is related with the higher aerobic capacity. HRR is generally faster in well-trained individuals compared with untrained subjects (Daanen et al. 2012). On the other hand, it seems that the relationship between HRR and aerobic capacity or maximal endurance performance is weaker in well-trained athletes. This lack of relationship has been observed in relatively homogenous groups of competitive endurance runners (Bosquet, Gamelin & Berthoin 2007) and in well-trained cross-country skiers (Mourot et al. 2015). In the present study, the association was stronger in women compared with men who showed a similar trend between HRR and VO_{2max}. Some differences have previously been observed in HRR between sexes. Arena et al. (2010) observed faster HRR in men, while Antelmi et al. (2008) found just the opposite. However, possible sexdifferences in post-exercise cardiac autonomic regulation still remain unclear and further studies are needed.

In addition to cardiorespiratory and metabolic factors, neuromuscular factors have an important role in endurance performance. A large correlation (r = 0.57) was observed between CMJ_h and RS_{peak} (all pooled) in the present study. The finding supports that muscle power of the lower extremities is related to running performance (Dumke et al. 2010; Hebert-Losier, Jensen & Holmberg 2014). Improvements in neuromuscular performance are thought to be beneficial for endurance performance via improved muscle efficiency and work economy (Mujika, Ronnestad & Martin 2016). However, a similar trend in the correlation was found only in women when sexes were analyzed separately. When the subjects were analyzed all pooled, the group was more heterogeneous in terms of maximal running and jumping performance, which may explain the larger correlation.

Submaximal running performance in monitoring training adaptation

Power or RS at certain submaximal HR levels has been suggested to predict endurance performance in the cross-sectional study design setup and decreased HR after the training period is generally a sign of positive training adaptations. However, less is known about whether submaximal performance is able to track the individual changes in endurance performance during longitudinal training sensitively enough in order to obtain important information about the progress of training adaptations. The present results demonstrated that the changes in RSs at 80 and 90% of HR_{max} stages in the laboratory and field conditions were related to the changes in both maximal endurance performance (r = 0.40-0.79) and aerobic capacity (r = 0.49-0.62) after the 18-week training period. This finding is in line with the previous observations about decreases in HR at the standardized submaximal intensity after endurance training (Borresen & Lambert 2008; Scharhag-Rosenberger et al. 2009; Buchheit et al. 2010), which is proposed to be due to a decrease in sympathetic activity to the heart (Borresen & Lambert 2008) and an increase in stroke volume, which allows for a decrease in HR to maintain cardiac output (Bellenger et al. 2016). However, Buchheit et al. (2010) observed similar decrements in HR at 60% of maximal aerobic speed in both responders and non-responders. The present study suggests that the submaximal intensity should be higher to be more valid in monitoring endurance training adaptation. RS at 90% of HR_{max} (86-88% of maximal aerobic speed) has been shown to be the most sensitive variable for identifying responders and non-responders during the 18-week training period measured either in the laboratory or field conditions. In our previous study, we observed slightly lower correlations (r = 0.43-0.61) between the change in HR-RS index calculated from every continuous-type running exercise and the change in maximal running speed during the 28-week endurance training (Vesterinen et al. 2014). It seems that by standardizing the intensity and duration of the submaximal performance, it is possible to enhance its ability to track individual training adaptations by decreasing internal factors (e.g. level of hydration, body temperature, cardiac drift). However, it seems that the laboratory conditions are not necessary if the outdoor track for submaximal running test is well standardized. Furthermore, the submaximal running performance allows the possibility to identify individuals who fail to make positive adaptations during training, which is essential information for coaches and athletes as this information enables them to adjust a training program to achieve better outcomes.

In the interpretation of the monitoring results, it is important to note that overload or overreaching is needed for achieving adequate homeostatic disturbances (and allowing subsequent, positive adaptations), which may cause temporary impairment in endurance performance. Furthermore, temporarily impaired submaximal performance can be a desirable outcome after an exhaustive training period. Therefore, the monitoring results should always be interpreted in the context of training data. In addition, it is important note that a decreased HR at a submaximal level or an increased power or RS at a submaximal HR level is not always a sign of a positive training adaptation. Decreased submaximal HR and HR_{max} can also be related to impaired endurance performance in the case of overreaching (Le Meur et al. 2013b) and overtraining (Hedelin et al. 2000b), which proposes cardiac vagal hyperactivity. In the present study, the moderate decrease in HR_{max} together with the poor improvement in endurance performance in the lowest responders, may have been a sign of overreaching. However, RPE remained relatively unaltered at submaximal levels. In the case of overreaching or overtraining, RPE would increase at submaximal levels because one would be working harder to achieve the same HR level due to higher relative intensity, if HR_{max} is reduced (Le Meur et al. 2013a). Thus, consideration of RPE is of great importance (Hammes et al. 2016) when interpreting results. Therefore, RPE together with the data of submaximal RS are needed for reasonable information about training adaptation.

Post-exercise cardiac autonomic regulation in monitoring training adaptation

Measurements of post-exercise HRV and HRR have been proposed to have potential for monitoring training load/fatigue (Lamberts et al. 2009; Lamberts et al. 2009; Lamberts et al. 2009; Lamberts et al. 2010a; Lamberts et al. 2010b; Aubry et al. 2015; Otter et al. 2016; Hammes et al. 2016; Otter et al. 2016; Hammes et al. 2016; Otter et al. 2016; Hammes et al. 2016) and endurance training adaptation (Yamamoto et al. 2001; Lamberts et al. 2009; Buchheit et al. 2010; Lamberts et al. 2010b) by reflecting cardiac autonomic regulation. An increased HRR has been reported to be related to improved VO_{2max} or endurance performance (Lamberts et al. 2009; Lamberts et al. 2010b; Daanen et al. 2012). However, no changes were observed in either post-exercise HRV or HRR in the present study. In addition, no differences were found between the highest and the lowest responders and, contrary to our hypothesis, no relationships were found between post-exercise cardiac autonomic regulation and individual training adaptations. This finding is in line with the studies by Buchheit et al. (2012; 2013), who also showed that changes in HRR were not related to changes in endurance performance in young soccer players. It seems that a faster HRR indicates rather a state of fatigue /or functional overreaching than an improved endurance performance (Lamberts et al. 2010a; Aubry et al. 2015; Hammes et al. 2016).

The absence of this relationship can be explained by the relatively homogenous group of subjects in the present study. It seems that the relationship is weaker in homogenous groups (Otter et al. 2015; Mourot et al. 2015), which may be due to the relationship between genetic polymorphism in acetylcholine receptor M2 and post-exercise HRR (Hautala et al. 2006). Thus, it may be possible that post-exercise cardiac autonomic regulation may indicate overall aerobic fitness or track changes in training load, but the change in post-exercise HRR or HRV is not sensitive enough to track changes in endurance performance and aerobic capacity, especially in homogeneous groups. The contradicting findings between the studies can also be explained by the different protocols used in the post-exercise measurements. The mode, duration, and intensity of exercise, as well as time frames when HRR or HRV is measured, may have an effect on post-exercise HRR and HRV measurements (Daanen et al. 2012). In interpreting post-exercise HRV results, it is very important to take into account the preceding exercise intensity because it has a graded effect on post-exercise HRV measures (Michael et al. 2016). In addition, post-exercise HRV is influenced by many factors such blood pressure regulation, baroreflex activity, and especially metaboreflex stimulation, which may complicate the interpretation of results regarding the actual cardiac autonomic regulation (Stanley, Peake & Buchheit 2013; Buchheit 2014). The applicability of post-exercise HRR and HRV to monitor training adaptation remain unclear and need future research work.

Neuromuscular function in monitoring training adaptation

The present results demonstrated that neuromuscular function measured by CMJ was related with maximal running performance in the cross-sectional analysis. However, the individual change in CMJ_h was not related with the change in RS_{peak} over the training period in women, men, or the whole group of subjects. A decreasing trend in CMJ_h was observed during weeks 4–18 only in the lowest responders. Impaired CMJ_h performance has been proposed to be an indicator of neuromuscular fatigue (Cormack et al. 2008; McLean et al. 2010; Gathercole et al. 2015). The change of CMJ_h in the lowest responders was statistically non-significant, but it is possible that it may be an early signal of neuromuscular fatigue. However, the present results cannot endorse the use of CMJ_h as a valid method for monitoring endurance training adaptations. In the study by Schumann et al. (2015), maximal dynamic strength in leg press decreased and CMJ_h remained unaltered during 24 weeks of endurance training, while endurance performance improved by 13%. Thus, decreased neuromuscular performance may not necessarily lead to impaired endurance performance. The use of a full CMJ-variable test battery (including e.g. peak power, flight time, ratio of flight time to contraction time) would be more sensitive for detecting neuromuscular fatigue than the sole use of jumping height, because the same fatiguing stimulus can elicit different effects between individuals and between CMJ variables (Gathercole et al. 2015). More detailed analysis of the neuromuscular status by determining neural activation of muscles and force-time curves might be more sensitive for monitoring training adaptation and therefore should be investigated in future studies. In addition, Gathercole et al. (2015) suggested that monitoring of neuromuscular fatigue by CMJ should be individualized by identifying individual interday variability and fatigue-detection thresholds.

6.4 HRV-guided training prescription (V)

The present results demonstrated that the 3000 m running performance and running speed at LT1 improved in the HRV-guided EXP-group, but not in the traditionally predefined TRAD-group, whereas VO_{2max} and running speed at LT2 improved in both groups over the 8-week INT. To the best of current knowledge, only a few previous studies have examined the use of HRV in endurance training prescription (Kiviniemi et al. 2007; Kiviniemi et al. 2010; Botek et al. 2014). In the study by Kiviniemi et al. (2007), a HIT session was programmed in the HRV-guided group if HFP, measured on every morning, was increased or remained the same compared with the reference value of HFP (average of 10 days – SD). Otherwise, LIT or rest was programmed. They observed that the HRV-guided group showed greater improvements in maximal running performance (6%) compared with a predefined group (4%) after four weeks of training (Kiviniemi et al. 2007). In the present study, the group difference in the change of maximal running performance (2.1% in EXP vs 1.1% in TRAD) was rated as small in qualitative and as non-significant in the t-test analyses. However, in practice the difference of 1% in sport performance can make the difference between winning and losing (Currell & Jeukendrup 2008). The finding that VO_{2max} improved in both groups but 3000 m running performance only in HRV, may be explained by improved neuromuscular function after HRV-guided training. Improved power in RJ in the EXP-group may suggest that the timing of HIT according to HRV was more beneficial in terms of neuromuscular performance. Muscle endurance exercise was performed once a week in both groups for maintaining strength abilities and injury prevention. Therefore, it may not explain improved neuromuscular function in the EXP-group. The results of RJ also showed that power seems to be a more sensitive variable than jumping height to track training adaptations to endurance running.

Training volume and training load as quantified by the session RPE were similar for the groups. However, the feeling about recovery was greater in EXP after the first two weeks of INT. It is important to note that the slightly greater improvement in the 3000 m running performance in EXP was achieved by performing less MOD and HIT sessions compared with TRAD. Furthermore, training focused more on LIT in EXP, which may explain the greater improvement in RS_{LT1} compared with TRAD. The previous finding is in line with the observations of Kiviniemi et al. (2010), who did not find any differences in the training adaptation between the HRV-guided and predefined groups among moderately trained women, but the HRV-group performed less HIT sessions (1.8 vs 2.8 sessions per week). In addition, they proposed that a different HRV-guided program is needed for women because they are more susceptible to needing a longer recovery for HRV (Kiviniemi et al. 2010). In the present study, no differences were observed between sexes in training adaptations. Kiviniemi et al. (2010) proposed that the sex-differences in HRV responses to HIT could be explained by a lower relative fitness level in women compared with men. In the present study, the relative fitness level was even a bit higher in women (Shvartz & Reibold 1990), which can explain the contradictory findings in sex-differences between the present study and the study by Kiviniemi et al. (2010). However, clarification of possible sex differences needs more investigations with larger sample sizes.

Individual adaptation to HRV-based vs. traditional endurance training

It is widely known that standardized endurance training induces large individual variation in training adaptations. In the present study, HRV-guided training led to a slightly smaller range (-1 to 6%) in the change of maximal running performance compared with the predefined training (-4 to 8%), while the individual range in the amount of HIT sessions was larger in EXP (5 to 24 sessions) compared with TRAD (11 to 21 sessions). This finding suggests that HRV based individual timing of HIT may be beneficial for diminishing variation in the adaptation. However, one subject in EXP failed to improve running performance during INT (Figure 14.C). The subject trained only at low intensities during the last five weeks of INT because his RMSSD values were below the SWC. Reduced HRV was mainly induced by work stress and it created challenges for the HRV based training prescription method. Regardless, it might be assumed that neither the predefined HIT training would result in optimal training outcomes in that kind of stressed state and LIT would be recommended for enhancing recovery process. On the other hand, the non-significant correlation between the training adaptation and the number of MOD/HIT sessions showed that the adaptation to training was independent of the amount of vigorous sessions. Some individuals responded well to the high amount of MOD and HIT (Figure 14.A), while other individuals (Figure 14.B) achieved positive responses with a smaller dose of MOD/HIT sessions. This can be partly explained by our finding, which showed that some individuals respond better to LIT and some individuals to HIT (Figure 7, Figure 8). Individuals' recovery of cardiac autonomic regulation and further capacity to cope with vigorous training seems to be different. Subject A (Figure 14) performed three HIT blocks during INT. The longest one continued for 21 days and included 15 MOD/HIT sessions. During the blocks, recovery feeling decreased and HRV changed relatively slowly from the regular level, while some individuals' HIT blocks were remarkably shorter. Therefore, individualized training programs are needed for diminishing variation in the adaptation and increasing effectiveness of training.

Methodological issues in HRV-based training prescription

In the present study, HRV determined the timing of HIT blocks via the use of a 7-day rolling average of RMSSD, while in the previous studies by Kiviniemi et al. (2007; 2010) daily HRV determined the timing of a single HIT sessions. The 7-day rolling average was used in the present study because it provides a better representation of training adaptation by diminishing the large day-to-day variation in HRV compared with single-day values (Plews et al. 2013). Hence, the present method prescribes the timing of MOD/HIT blocks rather than single MOD/HIT sessions because an averaged value of HRV does not typically change more than SWC after the stimulus of one single training session. The present method enabled a training program, which could be practical for monitoring endurance athletes' training with vigorous training periods, such as training camps with multiple training sessions and not only monitoring of single hard training sessions. Block periodization of HIT has, in fact, been reported to provide superior training adaptation compared with traditionally organized HIT (Ronnestad, Hansen & Ellefsen 2014; Ronnestad et al. 2016). However, block training has mainly been used among high level athletes. Individually determined duration and timing of HIT blocks according to HRV may be a more approachable training model also for untrained individuals. It may be easier to avoid the imbalance between training load and recovery, when training prescription is based on the status of cardiac autonomic regulation. However, further studies are needed in different populations.

The individual SWC of HRV was used in the present study, which presents regular values of HRV (Plews et al. 2012; Plews et al. 2013). When HRV is below the SWC, it indicates increased sympathetic activity, which has been observed to occur after vigorous training periods reflecting an insufficient recovery state (Iellamo et al. 2002; Pichot et al. 2002). On the other hand, HRV values above the SWC reflect increased vagal activity, called parasympathetic hyperactivity, which could also be a sign of functional overreaching (Le Meur et al. 2013b) or overtraining (Uusitalo, Uusitalo & Rusko 2000; Hedelin et al. 2000b). The imbalance of cardiac autonomic regulation may indicate an unfavorable situation to adapt to HIT sessions. As it is unknown whether HRV should be expected to increase or decrease in the case of overreaching and overtraining, it is recommended that the HRV based training prescription method includes upper and lower limits for normal area of HRV.

Furthermore, one issue is related to the magnitude of the SWC. In the present study, SWC was defined as mean ± 0.5 * SD based on the previous findings by Plews et al. (2012) and Hopkins et al. (2009). The SWC should be wide enough for allowing to train sufficiently at high intensities to achieve adequate disturbances in homeostasis so that further training adaptation can be attained. On the other hand, it should give enough recovery time after HRV falls outside the SWC. Performance changes and recovery feelings during INT did not reveal any signs of overtraining in the present study. Future studies should examine whether a shorter recovery time results in greater adaptations. In addition, the time frame of baseline HRV recordings has the critical role in determining the SWC so that it presents normal situation without abnormal values due to e.g. stress factors and sicknesses.

6.5 Methodological strengths and limitations

The present study consisted of three longitudinal (28-, 18- and 14-week) training studies. The training, the testing, and the measurements were well instructed, controlled, and supervised during the studies. Training frequency and volume were individualized according to the previous training background of the subjects for the purpose of diminishing large variation in training adaptations, which has widely been observed after a standardized training program (Bouchard & Rankinen 2001; Hautala et al. 2003; Vollaard et al. 2009; Scharhag-Rosenberger et al. 2012). In addition to training, it is well known that nutrition, sleep, and all daily physical activity have a high role in the process of training adaptations. Nutritional counselling was given to all subjects in an attempt to standardize nutritional habits. However, the other factors noted here were not strictly controlled in the present studies. Controlling of nutrition and all physical activity during prolonged studies is very challenging and arduous. Drastic changes in body composition were not observed and thus, it is presumed that the subjects followed a normal diet. The subjects reported their perceived exertion, recovery feelings, and possible other stress factors e.g. sickness, injuries, work/school stress in their training diary. In addition, the subjects recorded nocturnal HRV collections regularly allowing for researchers to evaluate the recovery state of the subjects. Thus, it was possible to evaluate indirectly if some drastic changes have occurred in sleep or physical activity.

The nocturnal recordings of RRIs (papers I and II) were done with heart rate monitors consisting of a two-lead chest belt with a sampling frequency of 1000 Hz. The measuring system has been reported to be reliable for long-term HRV analysis (Weippert et al. 2010). Nevertheless, ECG data was not available, which probably increased noise in the recordings. RRI data was carefully checked and all falsely detected, missed, and premature heart beats were excluded with the help of automated detection software. In addition, the HRV results over the 4 hours analyzing periods were provided as averages of two nights for reducing possible day-to-day variation in HRV indices.

In paper II, the threshold for separating individuals with low and high HRV was the mean value of HFP (8.1 ln ms^2) in this population. However, a randomized study, where low and high HRV groups would be randomly divided to high volume or high-intensity training, with larger sample size would have given more information about differences in training adaptations between the low and high HRV groups. Future research should also aim to determine the relationship between cardiac autonomic vagal activity and training adaptation among individuals with different training background from untrained individuals to high level endurance athletes. It has been observed that individuals with higher aerobic capacity have greater vagal activity, which may have effects on the relation between cardiac autonomic vagal activity and training adaptation compared with recreational endurance runners with lower aerobic capacity.

In paper V, daily HRV measurements were performed at home, which may not be as highly standardized as those performed in laboratory conditions. However, it is impractical to perform the measurements in the laboratory on every morning during the training period. In addition, it is possible to avoid psychophysiological effects of laboratory conditions on HRV by performing the measurements at home. Respiratory rate was spontaneously chosen because it was impossible to control in a real-life situation. Respiration is known to affect HRV, but only small differences have been observed in vagal-related HRV indices during spontaneous and metronome-guided breathing (Bloomfield et al. 2001). The morning HRV measurements (paper V) were done with Omegawave Pro Mobile System with a sampling frequency of 500 Hz, which has been observed to be reliable for HRV analysis (Parrado et al. 2010). A 7-day rolling average of RMSSD was calculated, because it has been proposed to diminish large day-to-day variation, which is typical in short, single HRV recordings, and be more sensitive to track changes in training status compared with single-day values (Plews et al. 2013). Thus, the present HRV results are reliable.

The present studies are limited by their relatively small sample sizes, partly due to drop outs because of sickness, injuries, or lack of training program participation. However, the number of subjects who dropped out (11-28%) is within similar ranges reported in longitudinal training studies (Sloan et al. 2009; Scharhag-Rosenberger et al. 2009; Buchheit et al. 2010; Schumann et al. 2015). Some injuries occurred regardless the 4-14-week preparatory training period, which was performed in all studies for learning, becoming accustomed to training and standardizing training background, limiting the learning effect, and training-induced injuries during the subsequent main training period. In addition, the limit for sufficient compliance with the training programs were relatively strict for ensuring the high quality of training, but reduced the number of subjects in the analyses. Furthermore, comprehensively controlled and supervised longitudinal training studies are more troublesome to conduct with a high number of subjects compared with cross-sectional studies. However, larger sample sizes would give more statistical power to clarify individual adaptations, predictive regression models, and possible differences between sexes and sub-groups. In addition, missing values due to sicknesses, injuries or incorrect HR or GPS data in weekly measurements in monitoring training adaptation (paper IV) may cause some fluctuation in the trends because of large variation between individuals.

One limitation in papers III and IV was that the reliability of the submaximal running protocol was not measured. High reliability has, however, been observed in mean power of all three submaximal stages in similar submaximal protocols in cycling (Lamberts et al. 2011) and rowing (Otter et al. 2015). High reliability has also been reported in running performance at 80% of HR_{max} in a submaximal running test on the treadmill, which is corresponding with the intensity of the second stage in SRT (Wang et al. 2010). The subjects were accustomed to running on a treadmill. In addition, the running speed was set successfully for the target heart rate levels of the stages on the treadmill by the exercise physiologist and in field conditions by the subjects. Therefore, the present results can be considered reliable. Neuromuscular performance results measured by CMJ_h showed that it is not sensitive enough for tracking changes in training adaptation. CMJ_h was selected because it is easy and fast to conduct also in field-conditions with accelerometers and mobile applications. However, other CMJ variables or power production in RJ would give more valid information about the status of the neuromuscular system in terms of monitoring endurance training adaptations.

7 MAIN FINDINGS AND CONCLUSIONS

The main findings of this study were as follows:

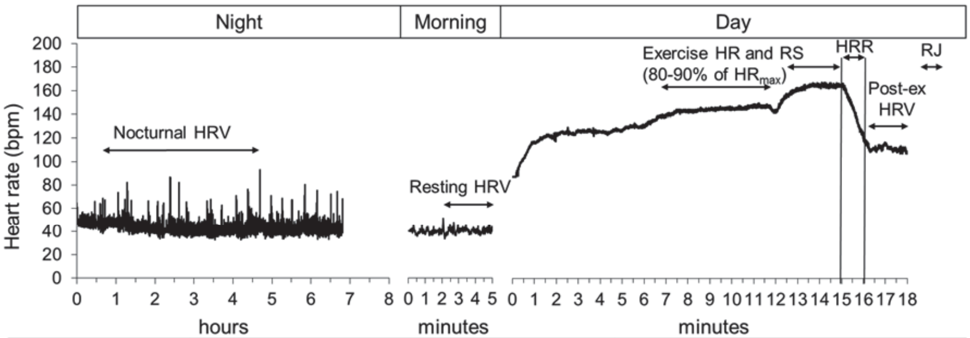
1) Pretraining nocturnal cardiac vagal activity was the strongest predictor of subsequent endurance training adaptations. The association was dependent on training contents. HRV was negatively correlated with improvements in endurance performance after an increase in volume of low-intensity training while HRV was positively correlated with the improvements in endurance performance after high-intensity training and intense endurance training (increased intensity and volume).
2) Running speeds at 80 and 90% of HR_{max} in the three-staged submaximal running test protocol were the most competent variables to track changes in maximal endurance performance during training. The highest responders according to the change in maximal endurance performance showed the greatest improvements in running speed at 80 and 90% of HR_{max} stages compared with the lowest responders.
3) The HRV-guided training group improved their 3000 m running performance over the 8-week intense training period, while 3000 m running performance in the traditional, predefined training group remained the same, although the HRV-guided group performed less moderate- and high-intensity training sessions. In addition, the individual range in the training adaptations was smaller in the HRV-guided group compared with the traditional, predefined training group.

Large inter-individual variation in training adaptations are widely reported after standardized training. For improving the effectiveness of training, the identification of low-responders would be worthwhile. The present results showed the potential of HRV in the identification of an individual´s trainability. Individuals with high pretraining vagal activity tended to respond better to high-intensity and intense (increased volume and intensity) training. These individuals may have a better capacity for coping with more intense training compared to individuals with lower HRV. In addition, the negative relationship between HFP and the adaptations to the increased volume of low-intensity training suggested that individuals with low HRV would respond better to low-intensity training compared with individuals with high HRV. Furthermore, HRV may be used in individualizing endurance training by adjusting training load and intensity so that individuals with higher resting HRV at baseline can be instructed to increase training load primarily by increasing training intensity rather than training volume. However, the findings are preliminary and further research is required before specific practical recommendations can be given to individuals.

The present submaximal running test appeared to be truly submaximal and did not cause a remarkable increase in training load. Furthermore, it is a suitable warm-up protocol for primary training sessions and it is possible to perform regularly for continuous monitoring of training. The stages with running speeds at 80 and 90% of HR_{max} in SRT/SCE give appropriate information about the progress of training adaptation. Therefore, the submaximal running test gives the possibility to identify individuals who fail to achieve positive adaptations during training, which is essential information for coaches and athletes and enables them to adjust training program to achieve better outcomes. Post-exercise HRR and HRV measurements gave information about the status of cardiac vagal activity and aerobic fitness but were not sensitive enough for tracking changes in endurance performance. Based on the neuromuscular measurements, it is recommended to use the reactivity jump power measurement in endurance training monitoring rather than the jumping height in CMJ.

Traditionally, endurance programs are based on sports and scientific literature, general recommendations, and experience of coaches. Training programs are typically predetermined regardless of the absence of objective information about athletes' training status and adaptations to previous training. The present results suggest that training prescription according to status of cardiac vagal activity may be a beneficial method to improve endurance training adaptation. The timing of moderate- and high-intensity training sessions according to HRV may be more optimal compared subjectively predefined training. Therefore, HRV shows a potential tool in endurance training prescription by optimizing the timing of vigorous training sessions.

It is widely established that standardized and predefined endurance training does not lead desirable outcomes in terms of improvements in health and endurance performance in all individuals. For avoiding poor adaptation to training and large inter-individual variation in the effectiveness of training, individualization in training prescription is needed. The findings of the present thesis propose that a training program can be individualized according to resting cardiac vagal activity for selecting the training content before a certain training period and for determining the timing of vigorous training sessions during training. In addition, submaximal running performance tests can be used for monitoring the progress of endurance training adaptations (Figure 18).



Measurement	**Possible use in optimizing endurance training**	**Recommendation for timing of measurements**
Resting HRV (night or morning)	1) Predicting trainability to different kinds of endurance training 2) Training prescription	1) At least 3 measurements before training period 2) Daily
Exercise HR and RS with RPE	Monitoring changes in maximal endurance performance	Once a week
HRR	Evaluating aerobic capacity and maximal endurance performance	Once a week
Post-exercise HRV	Evaluating aerobic capacity and maximal endurance performance	Once a week
Reactivity jump power	Evaluating neuromuscular function and monitoring trainability to HIT	Once a week

FIGURE 18 Use of heart rate and jump test measures in optimizing and individualizing an endurance training program.

YHTEENVETO (FINNISH SUMMARY)

Kestävyyssuorituskyky, sydämen autonominen säätely ja hermo-lihasjärjestelmän suorituskyky yksilöllisen kestävyysharjoitteluvasteen ennustamisessa ja seurannassa sekä harjoittelun ohjelmoinnissa.

Säännöllisen kestävyysharjoittelun positiiviset vaikutukset fyysiseen suorituskykyyn ovat laajasti tiedossa. Useimmat aikaisemmat tutkimukset ovat keskittyneet havainnoimaan keskimääräisiä harjoittelun aikaansaamia muutoksia esimerkiksi maksimaalisessa hapenottokyvyssä tai kestävyyssuorituskyvyssä. Tutkimuksissa on kuitenkin havaittu, että yksilöiden vaste kestävyysharjoitteluun vaihtelee hyvin paljon. Osa kehittyy harjoittelun myötä hyvinkin paljon, kun taas osalla vaikutukset voivat olla jopa negatiivisia.

Harjoitteluohjelman yksilöllistämisellä voi olla mahdollista parantaa harjoitteluvastetta ja pienentää suurta yksilöllistä vaihtelua. Haasteena on tunnistaa yksilöt, jotka eivät kehity tavanomaisella kestävyysharjoittelulla. Aiemmin on havaittu, että monet tekijät voivat olla yhteydessä suureen vaihteluun harjoittelun tuottavuudessa, kuten perimä, ikä, sukupuoli, aikaisempi harjoittelutausta, kuntotaso, uni, ravinto ja lepo. Lisäksi lähtötilanteessa mitatun sykevälivaihtelun, joka kuvaa sydämen autonomista säätelyä, on todettu olevan yhteydessä tulevaan harjoitteluvasteeseen.

Harjoitteluvastetta on mahdollista parantaa myös säännöllisellä kestävyysominaisuuksien kehityksen seurannalla. Tavallisesti urheilijat ja valmentajat seuraavat kestävyysharjoittelun aikaansaamia kuntomuutoksia erilaisin laboratoriossa tehtävin kuntotestein pari kertaa vuodessa. Se ei kuitenkaan anna säännöllistä tietoa kehityksen suunnasta. Tämän takia on tarvetta harjoitteluvastetta kuvaavalle seurantamenetelmälle, jolla pystytään seuraamaan harjoitteluvastetta viikkotasolla ilman, että se häiritsee normaalia harjoittelua. Tällöin on mahdollista muokata harjoitusohjelmaa, mikäli harjoitteluvaste ei ole toivottu. Aiempien tutkimusten mukaan submaksimaalinen suoritusteho vakiosykkeellä ja suorituksen jälkeinen sykkeen palautuminen ovat olleet yhteydessä maksimaaliseen hapenottokykyyn ja suorituskykyyn. Lisäksi madaltunut syketaso submaksimaalisessa vakiokuormituksessa harjoitusjakson jälkeen on ollut yhteydessä maksimaalisten kestävyysominaisuuksien kehitykseen. Useimmat aiemmat tutkimukset ovat kuitenkin poikkileikkaustutkimuksia ja vähemmän on tietoa siitä, miten edellä mainittujen muuttujien avulla voidaan seurata kunto-ominaisuuksien muutoksia harjoittelujakson aikana.

Perinteisesti harjoitusohjelmat perustuvat usein kirjallisuuteen, yleisiin suosituksiin ja valmentajien kokemuksiin. Harjoittelua ohjelmoidaan usein oletusten ja subjektiivisten näkemysten perusteella ilman objektiivista tietoa urheilijan harjoitus- ja palautumistilasta. Aiemmin on havaittu, että harjoittelun ohjelmointi sydämen autonomisen säätelyn perusteella saattaa tuottaa suuremmat hyödyt kuin perinteinen, ennakkoon laadittu harjoitusohjelma.

Ensimmäisessä vaiheessa tutkimuksen tarkoituksena oli selvittää lähtötilanteessa mitattujen muuttujien, kuten iän, kuntotason, harjoittelutaustan, yöllisen sykevälivaihtelun ja seerumin hormonitasojen yhteyttä erilaisten harjoittelujaksojen aikaansaamaan yksilölliseen harjoitteluvasteeseen. Yhteensä 28 kestävyysharjoittelutaustaista miestä toteutti 14 viikon perusharjoittelujakson jälkeen, 14 viikon intensiivisen harjoittelujakson, jolloin sekä juoksuharjoittelun määrä että teho lisääntyivät. Harjoittelujakson alussa mitatuista muuttujista yönaikainen autonomisen hermoston parasympaattista aktiivisuutta kuvaavat sykevälivaihtelumuuttujat (HFP, TP) olivat vahvimmin yhteydessä maksimikestävyyssuorituskyvyn muutokseen. Mitä suurempaa parasympaattinen aktiivisuus oli, sitä suurempaa oli myös kehitys. Sen sijaan muut lähtötilanteen muuttujat, kuten ikä, aiempi harjoittelutausta, kuntotaso ja hormonipitoisuudet eivät olleet yhteydessä harjoitteluvasteeseen. Toisessa harjoitustutkimuksessa kestävyysharjoitelleet miehet ja naiset satunnaistettiin kahteen harjoitteluryhmään 8 viikon perusharjoittelun jälkeen. Toinen ryhmä (n = 20) ohjeistettiin lisäämään juoksuharjoittelun määrää 30-50 % harjoitustehon pysyessä matalana. Toinen ryhmä (n=20) lisäsi harjoitteluohjelmaan viikoittain kolme vauhti-/ maksimikestävyysharjoitusta harjoitusmäärän pysyessä samana kuin perusharjoitusjaksolla. Jakson lähtötilanteessa mitatuista muuttujista autonomisen hermoston parasympaattista aktiivisuutta kuvaava HFP oli jälleen vahvimmin yhteydessä harjoitteluvasteeseen. Yhteys matalatehoisen määräpainotteisen harjoittelujakson aikaansaamaan muutokseen kestävyyssuorituskyvyssä oli negatiivinen (mitä matalampi HFP, sitä suurempi harjoitteluvaste) ja tehoharjoittelun aikaansaamaan vasteeseen positiivinen (mitä suurempi HFP, sitä suurempi harjoitteluvaste). Muista lähtötason muuttujista ainoastaan aikaisempi harjoittelu oli negatiivisesti yhteydessä määräpainotteisen harjoittelujakson aiheuttamaan kestävyyssuorituskyvyn muutokseen.

Toisessa vaiheessa tarkoituksena oli selvittää voiko 15 minuutin, kolmiportaisen submaksimaalisen juoksutestin sekä suorituksen jälkeisen sydämen autonomista säätelyä kuvaavan sykkeen palautumisen ja sykevälivaihtelun sekä hermo-lihasjärjestelmän suorituskykyä mittaavan kevennyshypyn avulla seurata harjoittelun aikaansaamaa muutosta maksimikestävyyssuorituskyvyssä sekä laboratorio että kenttäolosuhteissa mitattuna. Tulokset osoittivat, että 80-90 prosentin suoritustasot maksimisykkeestä kuvasivat parhaiten kestävyyssuorituskyvyssä tapahtuneita muutoksia 18-viikon harjoittelujakson aikana. Lisäksi tulokset osoittivat, että ko. kuormien juoksunopeuksien perusteella voitiin tunnistaa hyvin kehittyvät huonoimmin kehittyvistä jo harjoittelujakson aikana sekä laboratorio- että kenttäolosuhteissa tehdyistä mittauksista. Sen sijaan suorituksen jälkeinen sykkeen palautuminen, sykevälivaihtelu ja kevennyshyppytulos olivat yhteydessä maksimaaliseen hapenottokykyyn, mutta eivät harjoittelujakson aiheuttamiin muutoksiin.

Kolmannessa vaiheessa tarkoituksena oli selvittää, voiko sykevälivaihtelua käyttää harjoitusohjelman yksilöllisessä ohjelmoinnissa kestävyysharjoitelleilla naisilla (n = 20) ja miehillä (n = 20). Neljän viikon perusharjoittelujakson jälkeen tutkittavat satunnaistettiin kahteen harjoitteluryhmään. Perinteisesti, ennalta suunnitellun harjoittelun harjoituksista n. 50 % oli vauhti- ja maksimikestävyysharjoituksia ja 50 % peruskestävyysharjoituksia. Toisessa harjoitteluryhmässä olleet suorittivat aamuisin sykevälivaihtelumittauksen levossa. Sykevälivaihtelun 7 päivän keskiarvoa tarkasteltiin suhteessa yksilöllisesti määritettyyn normaaliin vaihteluväliin (keskiarvo ± 0.5*keskihajonta). Arvon ollessa vaihteluvälin sisäpuolella harjoittelu oli vauhti- ja maksimikestävyysharjoittelua. Arvon ollessa alueen ulkopuolella harjoittelu oli palauttavaa peruskestävyysharjoittelua, kunnes arvo oli palannut keskitasolle. 8-viikon harjoittelujakson aikana sykevälivaihteluun perusteella harjoitellut ryhmä paransi merkittävästi 3000 m suoritusta, kun taas toisella ryhmällä suoritus säilyi samalla tasolla. Maksimihapenotto kehittyi molemmilla ryhmillä, mutta hermo-lihasjärjestelmän suorituskykyä kuvaava reaktiivisuushypyn tehontuotto ainoastaan sykevälivaihtelun mukaan harjoitelleilla. Sykevälivaihteluun perustuva harjoitteluryhmä teki vähemmän vauhti- ja maksimikestävyysharjoittelua kuin ennakkoon ohjelmoitu harjoitteluryhmä.

Tutkimuksen perusteella voidaan todeta, että sydämen autonomisen säätelyn perusteella näyttäisi olevan mahdollista ennustaa tulevaa kestävyysharjoitteluvastetta kestävyysharjoitelleilla naisilla ja miehillä. Tämä tieto olisi erittäin hyödyllistä, jotta ei-kehittyvien harjoittelua pystyisi muokkaamaan jo ennen harjoittelun alkua. Näyttäisi, että tehopainotteinen harjoittelu hyödyttäisi enemmän yksilöitä, joilla on korkea parasympaattinen aktiivisuus lähtötilanteessa, kun taas matalatehoinen harjoittelu hyödyttäisi enemmän yksilöitä, joilla on matala parasympaattinen aktiivisuus. Aihe vaatii kuitenkin jatkotutkimuksia harjoittelutaustaltaan erilaisilla ryhmillä.

Tutkimuksen tulokset osoittivat myös, että kolmiportainen submaksimaalinen juoksutesti soveltuu säännölliseen harjoitteluvasteen seurantaan. Testin voi suorittaa verryttelynä pääharjoitukselle myös kenttäolosuhteissa, jolloin se ei häiritse normaaleja harjoittelurutiineja. Sen avulla on mahdollista havaita kestävyyssuorituskyvyssä tapahtuvia muutoksia jo harjoittelujakson aikana ja tarvittaessa muokata harjoitteluohjelmaa, mikäli tavoiteltuja muutoksia ei ole havaittavissa. Tulokset antoivat myös viitteitä siitä, sydämen autonomisen säätelyn avulla harjoittelun ohjelmoinnista voidaan saada tuottavampaa. Kovatehoisten harjoitusten aiheuttama vaste näyttäisi olevan parempi kestävyyssuorituskyvyn ja hermo-lihasjärjestelmän suorituskyvyn kannalta, kun harjoitukset ajoitetaan ajankohtaan, jolloin sydämen autonominen säätely on normaalitasolla. Tutkimuksissa käytetyt mittaukset ovat non-invasiivisia ja yksinkertaisia toteuttaa kenttäolosuhteissa, joten lähes kuka vain voi hyödyntää menetelmiä kestävyysominaisuuksien seurannassa ja harjoittelun optimoinnissa.

REFERENCES

Achten, J. & Jeukendrup, A. E. 2003. Heart rate monitoring: applications and limitations. Sports Medicine 33 (7), 517-538.

Al Haddad, H., Laursen, P. B., Chollet, D., Ahmaidi, S. & Buchheit, M. 2011. Reliability of resting and postexercise heart rate measures. International Journal of Sports Medicine 32 (8), 598-605.

Antelmi, I., Chuang, E. Y., Grupi, C. J., Latorre Mdo, R. & Mansur, A. J. 2008. Heart rate recovery after treadmill electrocardiographic exercise stress test and 24-hour heart rate variability in healthy individuals. Arquivos Brasileiros de Cardiologia 90 (6), 380-385.

Arena, R., Arrowood, J. A., Fei, D., Shelar, S., Helm, S. & Kraft, K. A. 2010. The influence of sex on the relationship between heart rate recovery and other cardiovascular risk factors in apparently healthy subjects. Scandinavian Journal of Medicine & Science in Sports 20 (2), 291-297.

Aubert, A. E., Seps, B. & Beckers, F. 2003. Heart rate variability in athletes. Sports Medicine 33 (12), 889-919.

Aubry, A., Hausswirth, C., Louis, J., Coutts, A. J., Buchheit, M. & Le Meur, Y. 2015. The Development of Functional Overreaching Is Associated with a Faster Heart Rate Recovery in Endurance Athletes. PloS ONE 10 (10), e0139754.

Aunola, S. & Rusko, H. 1986. Aerobic and anaerobic thresholds determined from venous lactate or from ventilation and gas exchange in relation to muscle fiber composition. International Journal of Sports Medicine 7 (3), 161-166.

Bassett, D. R.,Jr & Howley, E. T. 2000. Limiting factors for maximum oxygen uptake and determinants of endurance performance. Medicine and Science in Sports and Exercise 32 (1), 70-84.

Baumert, M., Brechtel, L., Lock, J., Hermsdorf, M., Wolff, R., Baier, V. & Voss, A. 2006. Heart rate variability, blood pressure variability, and baroreflex sensitivity in overtrained athletes. Clinical Journal of Sport Medicine 16 (5), 412-417.

Bellenger, C. R., Fuller, J. T., Thomson, R. L., Davison, K., Robertson, E. Y. & Buckley, J. D. 2016. Monitoring Athletic Training Status Through Autonomic Heart Rate Regulation: A Systematic Review and Meta-Analysis. Sports Medicine Feb 18. [Epub ahead of print].

Blasco-Lafarga, C., Martinez-Navarro, I. & Mateo-March, M. 2013. Is baseline cardiac autonomic modulation related to performance and physiological responses following a supramaximal Judo test? PloS ONE 8 (10), e78584.

Bloomfield, D. M., Magnano, A., Bigger, J. T.,Jr, Rivadeneira, H., Parides, M. & Steinman, R. C. 2001. Comparison of spontaneous vs. metronome-guided breathing on assessment of vagal modulation using RR variability. American Journal of Physiology. Heart and Circulatory Physiology 280 (3), H1145-50.

Borg, G. A. 1982. Psychophysical bases of perceived exertion. Medicine and Science in Sports and Exercise 14 (5), 377-381.

Borresen, J. & Lambert, M. I. 2008. Autonomic control of heart rate during and after exercise: measurements and implications for monitoring training status. Sports Medicine 38 (8), 633-646.

Bosquet, L., Gamelin, F. X. & Berthoin, S. 2007. Is aerobic endurance a determinant of cardiac autonomic regulation? European Journal of Applied Physiology 100 (3), 363-369.

Botek, M., McKune, A. J., Krejci, J., Stejskal, P. & Gaba, A. 2014. Change in performance in response to training load adjustment based on autonomic activity. International Journal of Sports Medicine 35 (6), 482-488.

Bouchard, C. & Rankinen, T. 2001. Individual differences in response to regular physical activity. Medicine and Science in Sports and Exercise 33 (6 Suppl), S446-51; discussion S452-3.

Bouchard, C., Sarzynski, M. A., Rice, T. K., Kraus, W. E., Church, T. S., Sung, Y. J., Rao, D. C. & Rankinen, T. 2011. Genomic predictors of the maximal O(2) uptake response to standardized exercise training programs. Journal of Applied Physiology 110 (5), 1160-1170.

Boutcher, S. H., Park, Y., Dunn, S. L. & Boutcher, Y. N. 2013. The relationship between cardiac autonomic function and maximal oxygen uptake response to high-intensity intermittent-exercise training. Journal of Sports Sciences 31 (9), 1024-1029.

Boutcher, S. H. & Stein, P. 1995. Association between heart rate variability and training response in sedentary middle-aged men. European Journal of Applied Physiology and Occupational Physiology 70 (1), 75-80.

Buchheit, M. 2014. Monitoring training status with HR measures: do all roads lead to Rome? Frontiers in Physiology 5, 73.

Buchheit, M., Chivot, A., Parouty, J., Mercier, D., Al Haddad, H., Laursen, P. B. & Ahmaidi, S. 2010. Monitoring endurance running performance using cardiac parasympathetic function. European Journal of Applied Physiology 108 (6), 1153-1167.

Buchheit, M., Racinais, S., Bilsborough, J. C., Bourdon, P. C., Voss, S. C., Hocking, J., Cordy, J., Mendez-Villanueva, A. & Coutts, A. J. 2013. Monitoring fitness, fatigue and running performance during a pre-season training camp in elite football players. Journal of Science and Medicine in Sport 16 (6), 550-555.

Buchheit, M., Simon, C., Piquard, F., Ehrhart, J. & Brandenberger, G. 2004. Effects of increased training load on vagal-related indexes of heart rate variability: a novel sleep approach. American Journal of Physiology. Heart and Circulatory Physiology 287 (6), H2813-8.

Buchheit, M., Simpson, M. B., Al Haddad, H., Bourdon, P. C. & Mendez-Villanueva, A. 2012. Monitoring changes in physical performance with heart rate measures in young soccer players. European Journal of Applied Physiology 112 (2), 711-723.

Capostagno, B., Lambert, M. I. & Lamberts, R. P. 2014. Standardized versus customized high-intensity training: effects on cycling performance. International Journal of Sports Physiology and Performance 9 (2), 292-301.

Cohen, J. 1988. Statistical power analysis for the behavioral sciences. New Jersey: Lawrence Erlbaum.

Cormack, S. J., Newton, R. U., McGuigan, M. R. & Cormie, P. 2008. Neuromuscular and endocrine responses of elite players during an Australian rules football season. International Journal of Sports Physiology and Performance 3 (4), 439-453.

Coyle, E. F. 1995. Integration of the physiological factors determining endurance performance ability. Exercise and Sport Sciences Reviews 23, 25-63.

Currell, K. & Jeukendrup, A. E. 2008. Validity, reliability and sensitivity of measures of sporting performance. Sports Medicine 38 (4), 297-316.

Da Silva, D. F., Verri, S. M., Nakamura, F. Y. & Machado, F. A. 2014. Longitudinal changes in cardiac autonomic function and aerobic fitness indices in endurance runners: a case study with a high-level team. European Journal of Sport Science 14 (5), 443-451.

Daanen, H. A., Lamberts, R. P., Kallen, V. L., Jin, A. & Van Meeteren, N. L. 2012. A systematic review on heart-rate recovery to monitor changes in training status in athletes. International Journal of Sports Physiology and Performance 7 (3), 251-260.

Daussin, F. N., Ponsot, E., Dufour, S. P., Lonsdorfer-Wolf, E., Doutreleau, S., Geny, B., Piquard, F. & Richard, R. 2007. Improvement of VO2max by cardiac output and oxygen extraction adaptation during intermittent versus continuous endurance training. European Journal of Applied Physiology 101 (3), 377-383.

Dudley, G. A., Abraham, W. M. & Terjung, R. L. 1982. Influence of exercise intensity and duration on biochemical adaptations in skeletal muscle. Journal of Applied Physiology: Respiratory, Environmental and Exercise Physiology 53 (4), 844-850.

Dumke, C. L., Pfaffenroth, C. M., McBride, J. M. & McCauley, G. O. 2010. Relationship between muscle strength, power and stiffness and running economy in trained male runners. International Journal of Sports Physiology and Performance 5 (2), 249-261.

Dupuy, O., Mekary, S., Berryman, N., Bherer, L., Audiffren, M. & Bosquet, L. 2012. Reliability of heart rate measures used to assess post-exercise parasympathetic reactivation. Clinical Physiology and Functional Imaging 32 (4), 296-304.

Durnin, J. V. & Rahaman, M. M. 1967. The assessment of the amount of fat in the human body from measurements of skinfold thickness. The British Journal of Nutrition 21 (3), 681-689.

Esfarjani, F. & Laursen, P. B. 2007. Manipulating high-intensity interval training: effects on VO2max, the lactate threshold and 3000 m running performance in moderately trained males. Journal of Science and Medicine in Sport 10 (1), 27-35.

Esteve-Lanao, J., Foster, C., Seiler, S. & Lucia, A. 2007. Impact of training intensity distribution on performance in endurance athletes. Journal of Strength and Conditioning Research 21 (3), 943-949.

Evertsen, F., Medbo, J. I., Jebens, E. & Gjovaag, T. F. 1999. Effect of training on the activity of five muscle enzymes studied on elite cross-country skiers. Acta Physiologica Scandinavica 167 (3), 247-257.

Faude, O., Kindermann, W. & Meyer, T. 2009. Lactate threshold concepts: how valid are they? Sports Medicine 39 (6), 469-490.

Foster, C., Daines, E., Hector, L., Snyder, A. C. & Welsh, R. 1996. Athletic performance in relation to training load. Wisconsin Medical Journal 95 (6), 370-374.

Gastin, P. B. 2001. Energy system interaction and relative contribution during maximal exercise. Sports Medicine 31 (10), 725-741.

Gathercole, R., Sporer, B., Stellingwerff, T. & Sleivert, G. 2015. Alternative countermovement-jump analysis to quantify acute neuromuscular fatigue. International Journal of Sports Physiology and Performance 10 (1), 84-92.

Goldsmith, R. L., Bigger, J. T.,Jr, Steinman, R. C. & Fleiss, J. L. 1992. Comparison of 24-hour parasympathetic activity in endurance-trained and untrained young men. Journal of the American College of Cardiology 20 (3), 552-558.

Golosheykin, S., Grant, J. D., Novak, O. V., Heath, A. C. & Anokhin, A. P. 2016. Genetic influences on heart rate variability. International Journal of Psychophysiology. Apr 22. [Epub ahead of print].

Gormley, S. E., Swain, D. P., High, R., Spina, R. J., Dowling, E. A., Kotipalli, U. S. & Gandrakota, R. 2008. Effect of intensity of aerobic training on VO2max. Medicine and Science in Sports and Exercise 40 (7), 1336-1343.

Grandys, M., Majerczak, J., Duda, K., Zapart-Bukowska, J., Kulpa, J. & Zoladz, J. A. 2009. Endurance training of moderate intensity increases testosterone concentration in young, healthy men. International Journal of Sports Medicine 30 (7), 489-495.

Green, H. J., Jones, L. L. & Painter, D. C. 1990. Effects of short-term training on cardiac function during prolonged exercise. Medicine and Science in Sports and Exercise 22 (4), 488-493.

Greiwe, J. S., Hickner, R. C., Hansen, P. A., Racette, S. B., Chen, M. M. & Holloszy, J. O. 1999. Effects of endurance exercise training on muscle glycogen accumulation in humans. Journal of Applied Physiology 87 (1), 222-226.

Hackney, A. C., Hosick, K. P., Myer, A., Rubin, D. A. & Battaglini, C. L. 2012. Testosterone responses to intensive interval versus steady-state endurance exercise. Journal of Endocrinological Investigation 35 (11), 947-950.

Hackney, A. C. & Lane, A. R. 2015. Exercise and the Regulation of Endocrine Hormones. Progress in Molecular Biology and Translational Science 135, 293-311.

Hackney, A. C., Moore, A. W. & Brownlee, K. K. 2005. Testosterone and endurance exercise: development of the "exercise-hypogonadal male condition". Acta Physiologica Hungarica 92 (2), 121-137.

Hackney, A. C., Sinning, W. E. & Bruot, B. C. 1988. Reproductive hormonal profiles of endurance-trained and untrained males. Medicine and Science in Sports and Exercise 20 (1), 60-65.

Hackney, A. C. & Viru, A. 2008. Research methodology: endocrinologic measurements in exercise science and sports medicine. Journal of Athletic Training 43 (6), 631-639.

Hainsworth, R. 1998. Physiology of the cardiac autonomic system. Teoksessa Clinical Guide to Cardiac Autonomic Tests. AA Dordrecht, The Netherlands: Kluwer Academic Publishers.

Halson, S. L. 2014. Monitoring training load to understand fatigue in athletes. Sports Medicine 44 Suppl 2, S139-47.

Hammes, D., Skorski, S., Schwindling, S., Ferrauti, A., Pfeiffer, M., Kellmann, M. & Meyer, T. 2016. Can the Lamberts and Lambert Submaximal Cycle Test (LSCT) Indicate Fatigue and Recovery in Trained Cyclists? International Journal of Sports Physiology and Performance 11 (3), 328-336.

Hautala, A., Tulppo, M. P., Mäkikallio, T. H., Laukkanen, R., Nissilä, S. & Huikuri, H. V. 2001. Changes in cardiac autonomic regulation after prolonged maximal exercise. Clinical Physiology 21 (2), 238-245.

Hautala, A. J., Kiviniemi, A. M. & Tulppo, M. P. 2009. Individual responses to aerobic exercise: the role of the autonomic nervous system. Neuroscience and Biobehavioral Reviews 33 (2), 107-115.

Hautala, A. J., Mäkikallio, T. H., Kiviniemi, A., Laukkanen, R. T., Nissilä, S., Huikuri, H. V. & Tulppo, M. P. 2003. Cardiovascular autonomic function correlates with the response to aerobic training in healthy sedentary subjects. American Journal of Physiology. Heart and Circulatory Physiology 285 (4), H1747-52.

Hautala, A. J., Rankinen, T., Kiviniemi, A. M., Mäkikallio, T. H., Huikuri, H. V., Bouchard, C. & Tulppo, M. P. 2006. Heart rate recovery after maximal exercise is associated with acetylcholine receptor M2 (CHRM2) gene polymorphism. American Journal of Physiology. Heart and Circulatory Physiology 291 (1), H459-66.

Hebert-Losier, K., Jensen, K. & Holmberg, H. C. 2014. Jumping and hopping in elite and amateur orienteering athletes and correlations to sprinting and running. International Journal of Sports Physiology and Performance 9 (6), 993-999.

Hedelin, R., Bjerle, P. & Henriksson-Larsen, K. 2001. Heart rate variability in athletes: relationship with central and peripheral performance. Medicine and Science in Sports and Exercise 33 (8), 1394-1398.

Hedelin, R., Kenttä, G., Wiklund, U., Bjerle, P. & Henriksson-Larsen, K. 2000a. Short-term overtraining: effects on performance, circulatory responses, and heart rate variability. Medicine and Science in Sports and Exercise 32 (8), 1480-1484.

Hedelin, R., Wiklund, U., Bjerle, P. & Henriksson-Larsen, K. 2000b. Cardiac autonomic imbalance in an overtrained athlete. Medicine and Science in Sports and Exercise 32 (9), 1531-1533.

Helgerud, J., Hoydal, K., Wang, E., Karlsen, T., Berg, P., Bjerkaas, M., Simonsen, T., Helgesen, C., Hjorth, N., Bach, R. & Hoff, J. 2007. Aerobic high-intensity intervals improve VO2max more than moderate training. Medicine and Science in Sports and Exercise 39 (4), 665-671.

Hickson, R. C. 1980. Interference of strength development by simultaneously training for strength and endurance. European Journal of Applied Physiology and Occupational Physiology 45 (2-3), 255-263.

Hill, D. W. & Rowell, A. L. 1997. Responses to exercise at the velocity associated with VO2max. Medicine and Science in Sports and Exercise 29 (1), 113-116.

Hoogeveen, A. R. & Zonderland, M. L. 1996. Relationships between testosterone, cortisol and performance in professional cyclists. International Journal of Sports Medicine 17 (6), 423-428.

Hopkins, W. G., Marshall, S. W., Batterham, A. M. & Hanin, J. 2009. Progressive statistics for studies in sports medicine and exercise science. Medicine and Science in Sports and Exercise 41 (1), 3-13.

Houmard, J. A., Costill, D. L., Mitchell, J. B., Park, S. H. & Chenier, T. C. 1991. The role of anaerobic ability in middle distance running performance. European Journal of Applied Physiology and Occupational Physiology 62 (1), 40-43.

Hynynen, E., Nummela, A., Rusko, H., Hämäläinen, I. & Jylhä, R. 2007. Effects of training on cardiac autonomic modulation during night sleep in cross country skiers. Teoksessa V. Linnamo, P. V. Komi & E. Müller (toim.) Science in Nordic Skiing.UK: Meyer & Meyer Sport Ltd., 90-98.

Iellamo, F., Legramante, J. M., Pigozzi, F., Spataro, A., Norbiato, G., Lucini, D. & Pagani, M. 2002. Conversion from vagal to sympathetic predominance with strenuous training in high-performance world class athletes. Circulation 105 (23), 2719-2724.

Issurin, V. 2008. Block periodization versus traditional training theory: a review. The Journal of Sports Medicine and Physical Fitness 48 (1), 65-75.

Issurin, V. B. 2010. New horizons for the methodology and physiology of training periodization. Sports Medicine 40 (3), 189-206.

Jones, A. M. & Carter, H. 2000. The effect of endurance training on parameters of aerobic fitness. Sports Medicine 29 (6), 373-386.

Joyner, M. J. & Coyle, E. F. 2008. Endurance exercise performance: the physiology of champions. The Journal of Physiology 586 (1), 35-44.

Kaikkonen, P., Hynynen, E., Mann, T., Rusko, H. & Nummela, A. 2010. Can HRV be used to evaluate training load in constant load exercises? European Journal of Applied Physiology 108 (3), 435-442.

Kiviniemi, A. M., Hautala, A. J., Kinnunen, H., Nissilä, J., Virtanen, P., Karjalainen, J. & Tulppo, M. P. 2010. Daily exercise prescription on the basis of HR variability among men and women. Medicine and Science in Sports and Exercise 42 (7), 1355-1363.

Kiviniemi, A. M., Hautala, A. J., Kinnunen, H. & Tulppo, M. P. 2007. Endurance training guided individually by daily heart rate variability measurements. European Journal of Applied Physiology 101 (6), 743-751.

Kraemer, W. J. & Ratamess, N. A. 2005. Hormonal responses and adaptations to resistance exercise and training. Sports Medicine 35 (4), 339-361.

Lambert, M. I., Mbambo, Z. H. & St Clair Gibson, A. 1998. Heart rate during training and competition for long-distance running. Journal of Sports Sciences 16 Suppl, S85-90.

Lamberts, R. P. 2014. Predicting cycling performance in trained to elite male and female cyclists. International Journal of Sports Physiology and Performance 9 (4), 610-614.

Lamberts, R. P. & Lambert, M. I. 2009. Day-to-day variation in heart rate at different levels of submaximal exertion: implications for monitoring training. Journal of Strength and Conditioning Research 23 (3), 1005-1010.

Lamberts, R. P., Rietjens, G. J., Tijdink, H. H., Noakes, T. D. & Lambert, M. I. 2010a. Measuring submaximal performance parameters to monitor fatigue and predict cycling performance: a case study of a world-class cyclo-cross cyclist. European Journal of Applied Physiology 108 (1), 183-190.

Lamberts, R. P., Swart, J., Capostagno, B., Noakes, T. D. & Lambert, M. I. 2010b. Heart rate recovery as a guide to monitor fatigue and predict changes in performance parameters. Scandinavian Journal of Medicine & Science in Sports 20 (3), 449-457.

Lamberts, R. P., Swart, J., Noakes, T. D. & Lambert, M. I. 2011. A novel submaximal cycle test to monitor fatigue and predict cycling performance. British Journal of Sports Medicine 45, 797-804.

Lamberts, R. P., Swart, J., Noakes, T. D. & Lambert, M. I. 2009. Changes in heart rate recovery after high-intensity training in well-trained cyclists. European Journal of Applied Physiology 105 (5), 705-713.

Laughlin, M. H. & Roseguini, B. 2008. Mechanisms for exercise training-induced increases in skeletal muscle blood flow capacity: differences with interval sprint training versus aerobic endurance training. Journal of Physiology and Pharmacology 59 Suppl 7, 71-88.

Laursen, P. B. 2010. Training for intense exercise performance: high-intensity or high-volume training? Scandinavian Journal of Medicine & Science in Sports 20 Suppl 2, 1-10.

Le Meur, Y., Hausswirth, C., Natta, F., Couturier, A., Bignet, F. & Vidal, P. P. 2013a. A multidisciplinary approach to overreaching detection in endurance trained athletes. Journal of Applied Physiology 114 (3), 411-420.

Le Meur, Y., Pichon, A., Schaal, K., Schmitt, L., Louis, J., Gueneron, J., Vidal, P. P. & Hausswirth, C. 2013b. Evidence of parasympathetic hyperactivity in functionally overreached athletes. Medicine and Science in Sports and Exercise 45 (11), 2061-2071.

Lee, C. L., Hsu, M., Astorino, T. A., Liu, T. W. & Chang, W. D. 2016. Effectiveness of 2 Weeks of high-intensity interval training on performance and hormone status in adolescent triathletes. The Journal of Sports Medicine and Physical Fitness Jan 21. [Epub ahead of print].

Little, R. J. & Rubin, D. B. 1987. Statistical analysis with missing data. New York: John Wiley & Sons, Inc.

MacQueen, J. 1967. Some methods for classification and analysis of multivariate observations. Teoksessa L. M. Le Cam & J. Neyman (toim.) Proceedings of the Fifth Berkeley Symposium on Mathematical Statistics and Probability. (1st. painos) University of California Press: Berkeley, CA, 281-297.

Malliani, A., Pagani, M., Lombardi, F. & Cerutti, S. 1991. Cardiovascular neural regulation explored in the frequency domain. Circulation 84 (2), 482-492.

Mann, T. N., Lamberts, R. P. & Lambert, M. I. 2014. High responders and low responders: factors associated with individual variation in response to standardized training. Sports Medicine 44 (8), 1113-1124.

Martinmäki, K., Rusko, H., Kooistra, L., Kettunen, J. & Saalasti, S. 2006. Intraindividual validation of heart rate variability indexes to measure vagal effects on hearts. American Journal of Physiology. Heart and Circulatory Physiology 290 (2), H640-7.

McCarthy, J. P., Pozniak, M. A. & Agre, J. C. 2002. Neuromuscular adaptations to concurrent strength and endurance training. Medicine and Science in Sports and Exercise 34 (3), 511-519.

McLean, B. D., Coutts, A. J., Kelly, V., McGuigan, M. R. & Cormack, S. J. 2010. Neuromuscular, endocrine, and perceptual fatigue responses during different length between-match microcycles in professional rugby league players. International Journal of Sports Physiology and Performance 5 (3), 367-383.

Meeusen, R., Duclos, M., Foster, C., Fry, A., Gleeson, M., Nieman, D., Raglin, J., Rietjens, G., Steinacker, J., Urhausen, A., European College of Sport Science & American College of Sports Medicine 2013. Prevention, diagnosis, and treatment of the overtraining syndrome: joint consensus statement of the European College of Sport Science and the American College of Sports Medicine. Medicine and Science in Sports and Exercise 45 (1), 186-205.

Michael, S., Jay, O., Halaki, M., Graham, K. & Davis, G. 2016. Submaximal exercise intensity modulates acute post-exercise heart rate variability. European Journal of Applied Physiology 116(4), 697-706.

Midgley, A. W., McNaughton, L. R. & Jones, A. M. 2007. Training to enhance the physiological determinants of long-distance running performance: can valid recommendations be given to runners and coaches based on current scientific knowledge? Sports Medicine 37 (10), 857-880.

Midgley, A. W., McNaughton, L. R. & Wilkinson, M. 2006. Is there an optimal training intensity for enhancing the maximal oxygen uptake of distance runners?: empirical research findings, current opinions, physiological rationale and practical recommendations. Sports Medicine 36 (2), 117-132.

Mikkola, J., Rusko, H., Nummela, A., Pollari, T. & Häkkinen, K. 2007. Concurrent endurance and explosive type strength training improves neuromuscular and anaerobic characteristics in young distance runners. International Journal of Sports Medicine 28 (7), 602-611.

Mourot, L., Fabre, N., Andersson, E., Willis, S., Buchheit, M. & Holmberg, H. C. 2015. Cross-country skiing and postexercise heart-rate recovery. International Journal of Sports Physiology and Performance 10 (1), 11-16.

Mujika, I., Ronnestad, B. R. & Martin, D. T. 2016. Effects of Increased Muscle Strength and Muscle Mass on Endurance-Cycling Performance. International Journal of Sports Physiology and Performance 11 (3), 283-289.

Munoz, I., Seiler, S., Bautista, J., Espana, J., Larumbe, E. & Esteve-Lanao, J. 2014. Does polarized training improve performance in recreational runners? International Journal of Sports Physiology and Performance 9 (2), 265-272.

Neal, C. M., Hunter, A. M., Brennan, L., O'Sullivan, A., Hamilton, D. L., De Vito, G. & Galloway, S. D. 2013. Six weeks of a polarized training-intensity distribution leads to greater physiological and performance adaptations than a threshold model in trained cyclists. Journal of Applied Physiology 114 (4), 461-471.

Noakes, T. D., Myburgh, K. H. & Schall, R. 1990. Peak treadmill running velocity during the VO2 max test predicts running performance. Journal of Sports Sciences 8 (1), 35-45.

Nummela, A., Hynynen, E. & Vesterinen, V. 2010. Nocturnal heart rate and heart rate variability as a method for monitoring training load. In: Kokusuz F., Ertan H. and Tsolakidis E. (eds) 15th Annual Congress of the European College of Sport Science, Book of Abstracts , 516.

Nummela, A., Hynynen, E., Kaikkonen, P. & Rusko, H. 2016. High-intensity endurance training increases nocturnal heart rate variability in sedentary participants. Biology of Sport 33 (1), 7-13.

Nummela, A., Hynynen, E., Kaikkonen, P. & Rusko, H. 2010. Endurance performance and nocturnal HRV indices. International Journal of Sports Medicine 31 (3), 154-159.

Nummela, A. T., Paavolainen, L. M., Sharwood, K. A., Lambert, M. I., Noakes, T. D. & Rusko, H. K. 2006. Neuromuscular factors determining 5 km running performance and running economy in well-trained athletes. European Journal of Applied Physiology 97 (1), 1-8.

Otter, R. T., Brink, M. S., Lamberts, R. P. & Lemmink, K. A. 2015. A new Submaximal Rowing Test to predict 2000 meter rowing ergometer performance. Journal of Strength and Conditioning Research 29 (9), 2426-2433.

Otter, R. T., Brink, M. S., van der Does, H. T. & Lemmink, K. A. 2016. Monitoring Perceived Stress and Recovery in Relation to Cycling Performance in Female Athletes. International Journal of Sports Medicine 37 (1), 12-18.

Paavolainen, L., Häkkinen, K., Hämäläinen, I., Nummela, A. & Rusko, H. 1999. Explosive-strength training improves 5-km running time by improving running economy and muscle power. Journal of Applied Physiology 86 (5), 1527-1533.

Paavolainen, L. M., Nummela, A. T. & Rusko, H. K. 1999. Neuromuscular characteristics and muscle power as determinants of 5-km running performance. Medicine and Science in Sports and Exercise 31 (1), 124-130.

Parrado, E., Garcia, M. A., Ramos, J., Cervantes, J. C., Rodas, G. & Capdevila, L. 2010. Comparison of Omega Wave System and Polar S810i to detect R-R intervals at rest. International Journal of Sports Medicine 31 (5), 336-341.

Perusse, L., Rankinen, T., Hagberg, J. M., Loos, R. J., Roth, S. M., Sarzynski, M. A., Wolfarth, B. & Bouchard, C. 2013. Advances in exercise, fitness, and performance genomics in 2012. Medicine and Science in Sports and Exercise 45 (5), 824-831.

Pichot, V., Busso, T., Roche, F., Garet, M., Costes, F., Duverney, D., Lacour, J. R. & Barthelemy, J. C. 2002. Autonomic adaptations to intensive and overload training periods: a laboratory study. Medicine and Science in Sports and Exercise 34 (10), 1660-1666.

Pichot, V., Roche, F., Gaspoz, J. M., Enjolras, F., Antoniadis, A., Minini, P., Costes, F., Busso, T., Lacour, J. R. & Barthelemy, J. C. 2000. Relation between heart rate variability and training load in middle-distance runners. Medicine and Science in Sports and Exercise 32 (10), 1729-1736.

Plews, D. J., Laursen, P. B., Kilding, A. E. & Buchheit, M. 2014. Heart-rate variability and training-intensity distribution in elite rowers. International Journal of Sports Physiology and Performance 9 (6), 1026-1032.

Plews, D. J., Laursen, P. B., Kilding, A. E. & Buchheit, M. 2013. Evaluating training adaptation with heart-rate measures: a methodological comparison. International Journal of Sports Physiology and Performance 8 (6), 688-691.

Plews, D. J., Laursen, P. B., Kilding, A. E. & Buchheit, M. 2012. Heart rate variability in elite triathletes, is variation in variability the key to effective training? A case comparison. European Journal of Applied Physiology 112, 3729-3741.

Porges, S. W. 1995. Cardiac vagal tone: a physiological index of stress. Neuroscience and Biobehavioral Reviews 19 (2), 225-233.

Porges, S. W. 1992. Vagal tone: a physiologic marker of stress vulnerability. Pediatrics 90 (3 Pt 2), 498-504.

Purge, P., Jurimae, J. & Jurimae, T. 2006. Hormonal and psychological adaptation in elite male rowers during prolonged training. Journal of Sports Sciences 24 (10), 1075-1082.

Ronnestad, B. R., Hansen, J. & Ellefsen, S. 2014. Block periodization of high-intensity aerobic intervals provides superior training effects in trained cyclists. Scandinavian Journal of Medicine & Science in Sports 24 (1), 34-42.

Ronnestad, B. R., Hansen, J., Thyli, V., Bakken, T. A. & Sandbakk, O. 2016. 5-Week Block Periodization Increases Aerobic Power in Elite Cross-Country Skiers. Scandinavian Journal of Medicine & Science in Sports 26 (2), 140-146.

Ronnestad, B. R. & Mujika, I. 2014. Optimizing strength training for running and cycling endurance performance: A review. Scandinavian Journal of Medicine & Science in Sports 24 (4), 603-612.

Saalasti, S. 2003. Neural networks for heart rate time series analysis. Department of Mathematical Information Technology, University of Jyväskylä, Jyväskylä Studies in Computing 33. PhD Thesis

Saunders, P. U., Pyne, D. B., Telford, R. D. & Hawley, J. A. 2004. Factors affecting running economy in trained distance runners. Sports Medicine 34 (7), 465-485.

Scharhag-Rosenberger, F., Meyer, T., Walitzek, S. & Kindermann, W. 2009. Time course of changes in endurance capacity: a 1-yr training study. Medicine and Science in Sports and Exercise 41 (5), 1130-1137.

Scharhag-Rosenberger, F., Walitzek, S., Kindermann, W. & Meyer, T. 2012. Differences in adaptations to 1 year of aerobic endurance training: individual patterns of nonresponse. Scandinavian Journal of Medicine & Science in Sports 22 (1), 113-118.

Schumann, M., Mykkänen, O. P., Doma, K., Mazzolari, R., Nyman, K. & Häkkinen, K. 2015. Effects of endurance training only versus same-session combined endurance and strength training on physical performance and serum hormone concentrations in recreational endurance runners. Applied Physiology, Nutrition, and Metabolism 40 (1), 28-36.

Seiler, K. S. & Kjerland, G. O. 2006. Quantifying training intensity distribution in elite endurance athletes: is there evidence for an "optimal" distribution? Scandinavian Journal of Medicine & Science in Sports 16 (1), 49-56.

Seiler, S. 2010. What is best practice for training intensity and duration distribution in endurance athletes? International Journal of Sports Physiology and Performance 5 (3), 276-291.

Seiler, S., Haugen, O. & Kuffel, E. 2007. Autonomic recovery after exercise in trained athletes: intensity and duration effects. Medicine and Science in Sports and Exercise 39 (8), 1366-1373.

Seiler, S., Joranson, K., Olesen, B. V. & Hetlelid, K. J. 2013. Adaptations to aerobic interval training: interactive effects of exercise intensity and total work duration. Scandinavian Journal of Medicine & Science in Sports 23 (1), 74-83.

Shvartz, E. & Reibold, R. C. 1990. Aerobic fitness norms for males and females aged 6 to 75 years: a review. Aviation, Space, and Environmental Medicine 61 (1), 3-11.

Singh, J. P., Larson, M. G., O'Donnell, C. J. & Levy, D. 2001. Genetic factors contribute to the variance in frequency domain measures of heart rate variability. Autonomic Neuroscience : Basic & Clinical 90 (1-2), 122-126.

Skinner, J. S., Gaskill, S. E., Rankinen, T., Leon, A. S., Rao, D. C., Wilmore, J. H. & Bouchard, C. 2003. Heart rate versus %VO2max: age, sex, race, initial fitness, and training response--HERITAGE. Medicine and Science in Sports and Exercise 35 (11), 1908-1913.

Sloan, R. P., Shapiro, P. A., DeMeersman, R. E., Bagiella, E., Brondolo, E. N., McKinley, P. S., Slavov, I., Fang, Y. & Myers, M. M. 2009. The effect of aerobic training and cardiac autonomic regulation in young adults. American Journal of Public Health 99 (5), 921-928.

Smith, M. L., Hudson, D. L., Graitzer, H. M. & Raven, P. B. 1989. Exercise training bradycardia: the role of autonomic balance. Medicine and Science in Sports and Exercise 21 (1), 40-44.

Spina, R. J. 1999. Cardiovascular adaptations to endurance exercise training in older men and women. Exercise and Sport Sciences Reviews 27, 317-332.

Stanley, J., Peake, J. M. & Buchheit, M. 2013. Cardiac parasympathetic reactivation following exercise: implications for training prescription. Sports Medicine 43 (12), 1259-1277.

Stoggl, T. & Sperlich, B. 2014. Polarized training has greater impact on key endurance variables than threshold, high intensity, or high volume training. Frontiers in Physiology 5, 33.

Stoggl, T. L. & Sperlich, B. 2015. The training intensity distribution among well-trained and elite endurance athletes. Frontiers in Physiology 6, 295.

Sztajzel, J., Jung, M., Sievert, K. & Bayes De Luna, A. 2008. Cardiac autonomic profile in different sports disciplines during all-day activity. The Journal of Sports Medicine and Physical Fitness 48 (4), 495-501.

Taipale, R. S., Mikkola, J., Nummela, A., Vesterinen, V., Capostagno, B., Walker, S., Gitonga, D., Kraemer, W. J. & Häkkinen, K. 2010. Strength training in endurance runners. International Journal of Sports Medicine 31 (7), 468-476.

Taipale, R. S., Mikkola, J., Salo, T., Hokka, L., Vesterinen, V., Kraemer, W. J., Nummela, A. & Häkkinen, K. 2014. Mixed maximal and explosive strength training in recreational endurance runners. Journal of Strength and Conditioning Research 28 (3), 689-699.

Task Force 1996. Heart rate variability: standards of measurement, physiological interpretation and clinical use.Task Force of the European Society of Cardiology and the North American Society of Pacing and Electrophysiology. Circulation 93 (5), 1043-1065.

Tonnessen, E., Sylta, O., Haugen, T. A., Hem, E., Svendsen, I. S. & Seiler, S. 2014. The road to gold: training and peaking characteristics in the year prior to a gold medal endurance performance. PloS ONE 9 (7), e101796.

Twist, C. & Highton, J. 2013. Monitoring fatigue and recovery in rugby league players. International Journal of Sports Physiology and Performance 8 (5), 467-474.

Urhausen, A., Gabriel, H. & Kindermann, W. 1995. Blood hormones as markers of training stress and overtraining. Sports Medicine 20 (4), 251-276.

Uusitalo, A. L. 2001. Overtraining: making a difficult diagnosis and implementing targeted treatment. The Physician and Sportsmedicine 29 (5), 35-50.

Uusitalo, A. L., Huttunen, P., Hanin, Y., Uusitalo, A. J. & Rusko, H. K. 1998. Hormonal responses to endurance training and overtraining in female athletes. Clinical Journal of Sport Medicine 8 (3), 178-186.

Uusitalo, A. L., Tahvanainen, K. U., Uusitalo, A. J. & Rusko, H. K. 1996. Non-invasive evaluation of sympathovagal balance in athletes by time and frequency domain analyses of heart rate and blood pressure variability. Clinical Physiology 16 (6), 575-588.

Uusitalo, A. L., Uusitalo, A. J. & Rusko, H. K. 2000. Heart rate and blood pressure variability during heavy training and overtraining in the female athlete. International Journal of Sports Medicine 21 (1), 45-53.

Vesterinen, V., Hokka, L., Hynynen, E., Mikkola, J., Häkkinen, K. & Nummela, A. 2014. Heart rate-running speed index may be an efficient method of monitoring endurance training adaptation. Journal of Strength and Conditioning Research 28 (4), 902-908.

Vikmoen, O., Ellefsen, S., Troen, O., Hollan, I., Hanestadhaugen, M., Raastad, T. & Ronnestad, B. R. 2016a. Strength training improves cycling performance, fractional utilization of VO2max and cycling economy in female cyclists. Scandinavian Journal of Medicine & Science in Sports 26 (4), 384-396.

Vikmoen, O., Raastad, T., Seynnes, O., Bergstrom, K., Ellefsen, S. & Ronnestad, B. R. 2016b. Effects of Heavy Strength Training on Running Performance and Determinants of Running Performance in Female Endurance Athletes. PloS ONE 11 (3), e0150799.

Viru, A. & Viru, M. 2004. Cortisol--essential adaptation hormone in exercise. International Journal of Sports Medicine 25 (6), 461-464.

Vollaard, N. B., Constantin-Teodosiu, D., Fredriksson, K., Rooyackers, O., Jansson, E., Greenhaff, P. L., Timmons, J. A. & Sundberg, C. J. 2009. Systematic analysis of adaptations in aerobic capacity and submaximal energy metabolism provides a unique insight into determinants of human aerobic performance. Journal of Applied Physiology 106 (5), 1479-1486.

Wahl, P., Mathes, S., Kohler, K., Achtzehn, S., Bloch, W. & Mester, J. 2013. Acute metabolic, hormonal, and psychological responses to different endurance training protocols. Hormone and Metabolic Research 45 (11), 827-833.

Wallace, L. K., Slattery, K. M. & Coutts, A. J. 2009. The ecological validity and application of the session-RPE method for quantifying training loads in swimming. Journal of Strength and Conditioning Research 23 (1), 33-38.

Wang, E., Solli, G. S., Nyberg, S. K., Hoff, J. & Helgerud, J. 2012. Stroke volume does not plateau in female endurance athletes. International Journal of Sports Medicine 33 (9), 734-739.

Wang, S. C., Lin, H. F., Wu, C. F., Lin, B. N., Wang, Y. S. & Huang, Y. J. 2010. Aerobic power assessment by using a 10 min heart rate control running on treadmill. The Journal of Sports Medicine and Physical Fitness 50 (1), 32-36.

Weippert, M., Kumar, M., Kreuzfeld, S., Arndt, D., Rieger, A. & Stoll, R. 2010. Comparison of three mobile devices for measuring R-R intervals and heart rate variability: Polar S810i, Suunto t6 and an ambulatory ECG system. European Journal of Applied Physiology 109 (4), 779-786.

Wheeler, G. D., Singh, M., Pierce, W. D., Epling, W. F. & Cumming, D. C. 1991. Endurance training decreases serum testosterone levels in men without change in luteinizing hormone pulsatile release. The Journal of Clinical Endocrinology and Metabolism 72 (2), 422-425.

Yamamoto, K., Miyachi, M., Saitoh, T., Yoshioka, A. & Onodera, S. 2001. Effects of endurance training on resting and post-exercise cardiac autonomic control. Medicine and Science in Sports and Exercise 33 (9), 1496-1502.

Yeo, W. K., Carey, A. L., Burke, L., Spriet, L. L. & Hawley, J. A. 2011. Fat adaptation in well-trained athletes: effects on cell metabolism. Applied Physiology, Nutrition, and Metabolism 36 (1), 12-22.

Zatsiorsky, V. M. & Kraemer, W. J. 2006. Science and Practice of Strength Training (2nd ed.). Champaign, IL: Human Kinetics.

Zhang, J. 2007. Effect of age and sex on heart rate variability in healthy subjects. Journal of Manipulative and Physiological Therapeutics 30 (5), 374-379.

Zinner, C., Wahl, P., Achtzehn, S., Reed, J. L. & Mester, J. 2014. Acute hormonal responses before and after 2 weeks of HIT in well trained junior triathletes. International Journal of Sports Medicine 35 (4), 316-322.

Äyrämö, S. 2006. Knowledge mining using robust clustering. Department of Mathematical Information Technology, University of Jyväskylä, Jyväskylä Studies in Computing 63. PhD Thesis

ORIGINAL PAPERS

I

Heart rate variability in prediction of individual adaptation to endurance training in recreational endurance runners

by

V. Vesterinen, K. Häkkinen, E. Hynynen, J. Mikkola, L. Hokka &
A. Nummela. 2013

Scandinavian Journal of Medicine and Science in Sports 23, 171-180

Scand J Med Sci Sports 2013: 23: 171–180
doi: 10.1111/j.1600-0838.2011.01365.x

SCANDINAVIAN JOURNAL OF
MEDICINE & SCIENCE
IN SPORTS

Heart rate variability in prediction of individual adaptation to endurance training in recreational endurance runners

V. Vesterinen[1], K. Häkkinen[2], E. Hynynen[1], J. Mikkola[1], L. Hokka[1], A. Nummela[1]

[1]KIHU-Research Institute for Olympic Sports, Jyväskylä, Finland, [2]Department of Biology of Physical Activity, University of Jyväskylä, Jyväskylä, Finland
Corresponding author: Ville Vesterinen, MSc, KIHU-Research Institute for Olympic Sports, Rautpohjankatu 6, 40700 Jyväskylä, Finland. Tel: +358 40 543 1273, Fax: +358 20 781 1501, E-mail: ville.vesterinen@kihu.fi

Accepted for publication 1 June 2011

The aim of this study was to investigate whether nocturnal heart rate variability (HRV) can be used to predict changes in endurance performance during 28 weeks of endurance training. The training was divided into 14 weeks of basic training (BTP) and 14 weeks of intensive training periods (ITP). Endurance performance characteristics, nocturnal HRV, and serum hormone concentrations were measured before and after both training periods in 28 recreational endurance runners. During the study peak treadmill running speed (V_{peak}) improved by 7.5 ± 4.5%. No changes were observed in HRV indices after BTP, but after ITP, these indices increased significantly (HFP: 1.9%, $P = 0.026$; TP: 1.7%, $P = 0.007$). Significant correlations were observed between the change of V_{peak} and HRV indices (TP: $r = 0.75$, $P < 0.001$; HFP: $r = 0.71$, $P < 0.001$; LFP: $r = 0.69$, $P = 0.01$) at baseline during ITP. In order to lead to significant changes in HRV among recreational endurance runners, it seems that moderate- and high-intensity training are needed. This study showed that recreational endurance runners with a high HRV at baseline improved their endurance running performance after ITP more than runners with low baseline HRV.

Regular aerobic endurance training and good maximal aerobic performance are widely accepted as factors that reduce all-cause mortality and improve a number of health outcomes (Kesaniemi et al., 2001). Numerous studies have shown that long-term endurance training induces many physiological adaptations leading to improved endurance performance (McArdle et al., 1996; Iwasaki et al., 2003; Purge et al., 2006; Scharhag-Rosenberger et al., 2009). The majority of the published studies have focused on main effects of endurance training and group differences while paying little attention to individual differences in training adaptation. However, it has been shown that individuals may adapt differently after exposure to very similar training loads. Although mean improvements in maximal oxygen uptake (VO_{2max}) following 6–20 weeks of standardized training have been within 10–15% of baseline values, individual adaptations have been shown to range from negative values to over 40% improvement (Bouchard & Rankinen, 2001; Hautala et al., 2003, 2009; Vollaard et al., 2009; Buchheit et al., 2010).

Physiological mechanisms causing the remarkable heterogeneity in the responsiveness to endurance training remain partly unclear. It has been proposed that many factors, like genetics, age, gender, nutrition, prior training, fitness level, sleep, rest, and stress can result in great variation in the adaptation to endurance training (Bouchard & Rankinen, 2001; Hedelin et al., 2001; Hautala et al., 2003, 2009; Buchheit et al., 2010; Nummela et al., 2010). However, Bouchard and Rankinen (2001) summarized that age, gender, race, and baseline fitness level together accounted for only 11% of the variance in the adaptation to standardized endurance training. In addition, it has been reported that serum hormone concentrations may be associated with the endurance training adaptation. Endurance training which has led to a negative training adaptation also results in decreased basal levels of serum testosterone concentration (Wheeler et al., 1991; Urhausen et al., 1995; Hoogeveen & Zonderland, 1996; Uusitalo et al., 1998). It has also been suggested that the increase in serum testosterone represents a positive adaptation to the training load (Purge et al., 2006). However, previous studies are partly contradictory and the possible association between hormone concentrations and the endurance training adaptation may be rather complicated.

It has been suggested that cardiovascular autonomic regulation is an important determinant of training adaptation (Hautala et al., 2009). Several studies have shown that endurance training increases heart rate variability (HRV) (Buchheit et al., 2004; Kiviniemi et al., 2006; Nummela et al., 2010). In addition, increased HRV and high baseline HRV have been observed to be associated with improvement in endurance performance (Boutcher & Stein, 1995; Hedelin et al., 2001; Hautala et al., 2003; Buchheit et al., 2010; Nummela et al., 2010). Hautala et al. (2003) found that high frequency power (HFP) was the most powerful determinant associated with future training adaptation, accounting for 27% of the variance in the adaptation to endurance training.

However, most of the previous studies which have investigated determinants of endurance training adaptation have used relatively short training periods (<8 weeks). Less is known about predictors of the adaptation to long-term endurance training. Loimaala et al. (2000) investigated effects of 5 months of high- and low-intensity endurance training on HRV, but did not find any changes in nocturnal or 24 h HRV indices regardless of improvements in endurance performance. Iwasaki et al. (2003) observed that previously sedentary people improved endurance performance over a whole 1-year training period but resting HRV, as measured during a 6-min period in the morning, increased only during the first 3 months. Association between the training adaptation and HRV after prolonged endurance training is partly unclear. In addition, sedentary people have been subjects in the major part of the previous studies but less is known about determinants of the long-term endurance training adaptation among recreationally trained endurance runners. Previous studies have reported that cardiac vagal modulation of HR during exercise and at rest, as determined by HRV, is higher in trained than in sedentary subjects (Buchheit & Gindre, 2006; Hautala et al., 2009; Buchheit et al., 2010). It is also clear that fitness level differs greatly between sedentary people and endurance trained runners. Based on the previous findings, determinants of the adaptation to endurance training may be different among different populations.

The aims of this study were (1) to investigate whether nocturnal HRV can be used to predict changes in endurance performance and (2) to assess baseline determinants which are associated with the training adaptation and can be used to predict the individual training adaptation during long-term endurance training in recreational endurance runners. It was hypothesized that nocturnal HRV at baseline will be correlated to the individual training adaptation.

Methods

Subjects

Twenty-eight male recreational endurance runners were recruited to the study. All subjects (age: 36 ± 6 years, height: 1.79 ± 0.05 m, body mass: 78.1 ± 5.6 kg) participated in a marathon-training project, which prepared them for a marathon run at the end of the project. All subjects were healthy, non-smokers, non-obese (BMI <30 kg/kg), and they did not have any diseases or use regular medication. In addition, resting ECG (Cardiofax ECG-9 320, Tokyo, Japan) was analyzed to ensure they had no cardiac abnormalities, which would have affected the HRV analysis or preclude them from participating in intense endurance training. According to a questionnaire about prior endurance training activity, the subjects had trained primarily running on average 4.4 ± 0.8 times/week during the last 2 months before the study. Most of the subjects had a training background of many years and had already run at least one half or full marathon before they volunteered for this study. One subject dropped out because of a lack of motivation, and two subjects were excluded because of insufficient compliance with the training during the study. Finally, 25 men were included in the study. Subjects were fully informed about the study design, including information on the possible risks and benefits, before signing an informed consent document. The study was approved by the Ethics Committee of the University of Jyväskylä, Finland.

Experimental design and training

The subjects took part in a 28-week training program (Table 1). The training program was divided into a 14-week basic training period (BTP) and a 14-week intense (increased running volume and intensity) training period (ITP). In BTP, the subjects were asked to maintain the same training volume as before the study (3–6 times/week). During BTP, training was

Table 1. Week template of training over 28 weeks of training program

	Basic training period	Intense training period		
	Weeks 1–14	Weeks 15–19	Weeks 20–24	Weeks 25–28
Week periodization (intense weeks : recovery week)	3:1	2:1	2:1	2:1
High-intensity runs	None	None	1 session*, 4–5 km	2 sessions*, 4–5 km
Moderate-intensity runs	None	2 sessions*, 8–10 km	1 session*, 8–10 km	None
Long low-intensity run	1 session, 15–20 km	1 session, 20–25 km	1 session, 20–30 km	1 session, 25–30 km
Basic low-intensity runs	2–5 sessions, 5–15 km	1–4 sessions, 5–15 km	1–4 sessions, 5–15 km	1–4 sessions, 5–15 km
Strength training	1–2 sessions	1 session	1 session	1 session

*Exercises were not performed during recovery weeks.

High-intensity, intensity above anaerobic threshold; Moderate-intensity, intensity between aerobic and anaerobic thresholds; Low-intensity, intensity below aerobic threshold.

performed primarily below the aerobic threshold (avg. 64% V_{peak}), which was individually determined for each subject from the incremental treadmill test (Aunola & Rusko, 1986). The training program of BTP was periodized to cycles of 4 weeks, thus 3 weeks of intense training was followed by an easy training week. Endurance training consisted primarily of running but occasionally included also cycling, nordic walking and/or cross country skiing. In addition, the subjects were asked to complete strength training 1–2 times/week. A training program of the 14-week ITP included higher running training volume (prolonged duration of the training sessions) and intensity compared with the basic training period. The training utilized the 3-week training cycles (2 intense weeks followed a recovery week). During the recovery weeks the subjects were asked to train at low-intensity [below the aerobic threshold, Aunola & Rusko (1986)], but during the first 3 intense weeks the subjects replaced two low-intensity training sessions with moderate-intensity [between the aerobic and anaerobic thresholds (avg. 67–84% V_{peak}); Aunola & Rusko, 1986] training sessions per week. During the next 3 intense weeks the subjects were asked to complete one moderate- and one high-intensity (above anaerobic threshold) training sessions per week beyond low-intensity sessions. During the last 3 intense weeks they replaced two low-intensity training sessions with high-intensity training sessions per week. In addition, the subjects were asked to complete one strength training session per week throughout the intense training period.

The subjects controlled their training intensity by measuring their HR during all exercises using Suunto t6 heart rate monitors and GPS pod speed/distance sensors (Suunto Ltd., Vantaa, Finland). Subjects kept a training diary throughout the study recording training mode, duration of the training session, average HR and running distance. In addition, the subjects rated their perceived exertion (RPE) using the scale from 0 to 10 after each training session (Borg, 1982). HR data was used for determining the times at the three different intensity zones; low (below aerobic threshold), moderate (between aerobic and anaerobic thresholds) and high (above anaerobic threshold) intensities. Training impulse (TRIMP), an index of training load, was calculated by using the following formula (Banister, 1991):

$$\begin{aligned}\text{TRIMP} = {} & t\,[\text{exercise duration (min)}] \\ & \times (\text{HR}_{\text{exercise}}\text{HR}_{\text{rest}})/(\text{HR}_{\text{max}} - \text{HR}_{\text{rest}}) \\ & \times (0.64 \times e[1.92 \times (\text{HR}_{\text{exercise}} - \text{HR}_{\text{rest}}) \\ & /(\text{HR}_{\text{max}} - \text{HR}_{\text{rest}})])\end{aligned}$$

.

Anthropometry and resting blood samples

All measurements were performed before and after both training periods (at weeks 0, 14 and 28). In addition to height; body mass and body composition were measured using bioimpedance (In body 720 body composition analyzer, Biospace Co. Ltd., Seoul, South Korea). The measurements were performed after 10 h of fasting in the morning between 7:30 and 8:30 hours. After the bioimpedance measurements, venous blood samples (10 mL) were collected into serum tubes (Venosafe, Terumo Medical Co., Leuven, Belgium) for the determination of basal serum testosterone and cortisol concentrations. The whole blood was centrifuged at 2500 *g* (Megafuge 1.0R, Heraeus, Germany) for 10 min after which serum was removed and stored at – 80 °C until analysis. The concentrations of testosterone and cortisol were determined by using a chemical luminescence techniques (Immunlite 1 000, DPC Diagnostics Corporation, Los Angeles, California, USA) and hormone-specific immunoassay kits (Siemens, New York, New York, USA). The sensitivity of testosterone and cortisol assays was 0.05 and 5.5 nmol/L, respectively. The intra-assay coefficients of variation for testosterone and cortisol were 3.9% and 4.6%, respectively. All the assays were carried out according to instructions of the manufactures. All samples of the test subject were analyzed in the same assay for each hormone.

Incremental treadmill test

The initial velocity was 8 km/h and was increased by 1 km/h every third minute until exhaustion. The incline was kept at 0.5° during the whole test. HR was recorded continuously using a heart rate monitor (Suunto t6, Suunto Ltd.). Oxygen consumption was measured breath-by-breath throughout the test using a portable gas analyzer (Oxycon Mobile®, Jaeger, Hoechberg, Germany). After each 3-min stage, the treadmill was stopped for about 15–20 s for fingertip blood samples (20 μL) and blood lactate (La) analysis. Blood lactate was determined using Biosen S_line Lab+lactate analyzer (EKF Diagnostic, Magdeburg, Germany). The highest 60-s VO_2 value during the treadmill test was considered as maximal oxygen uptake ($VO_{2\text{max}}$). The maximal endurance performance was determined as the peak treadmill running speed (V_{peak}) when the subject became exhausted. If the subject could not complete the whole 3 min of the last velocity, V_{peak} was calculated as follows: speed of the last completed stage (km/h)+(running time (s) of the speed at exhaustion − 30 s/180–30 s) × 1 km/h. In the present study a change of $V_{\text{peak},}$ which has been shown to be closely related to maximal endurance performance (Noakes et al., 1990), was used as the main variable for describing the adaptation to endurance training during the training periods. Aerobic (AerT) and anaerobic (AnT) thresholds were determined using La, ventilation, VO_2 and VCO_2 (production of carbon dioxide) (Aunola & Rusko, 1986). The running economy (RE) was determined as the average VO_2 from the last minute at the velocity of 10 km/h.

Nocturnal HRV

Nocturnal R–R interval (RRI) recordings were taken during three consecutive nights before and after both training periods with Suunto Memory Belt (Suunto Ltd.) having a sampling frequency of 1000 Hz. Nocturnal RRI data were recorded after a light training day according to TRIMP. RRI recordings were started before going to bed to sleep and stopped after waking up in the morning. The first 30 min after going to bed was excluded and the succeeding 4 h were accepted for the analysis. RRI data was analyzed using the Firstbeat Health software (version 3.0.1.0, Firstbeat Technologies Ltd., Jyväskylä, Finland). RRIs were checked and edited by an artifact detection filter of the Firstbeat Health software and subsequently verified by visual inspection to exclude all falsely detected, missed, and premature heart beats (Saalasti, 2003). The consecutive artifact corrected RRI data were then resampled at the rate of 5 Hz by using linear interpolation to obtain equidistantly sampled time series. From the resampled data, the software calculated HRV indices second-by-second using the short-time Fourier Transform method. For a given segment of data, a time window (Hanning) with a length of 256 samples was applied, fast Fourier transform was calculated and a power spectrum was obtained. The window was then shifted one sample to another and the same process was repeated. The following HRV indices were analyzed with time and frequency domain methods: average HR, standard deviation of RRI (SDNN), root mean square of differences between adjacent R–R intervals (RMSSD), low frequency power (LFP; 0.04–0.15 Hz), high frequency power (HFP; > 0.15–0.40 Hz), total power (TP = LFP+HFP; 0.04–0.40 Hz). The results are provided as averages of two nights, since there were so many erroneous RRI recordings that it was not possible to use averages of three nights on all subjects.

Statistical analysis

Values are expressed as mean ± standard deviation (SD) and 95% confidence interval (CI) for mean. The Gaussian distribution of the data was assessed with the Shapiro–Wilk goodness-of-fit test. Ln-transformation was used with the nocturnal HRV variables, in order to meet the assumptions of parametric statistical analysis. Repeated-measures analysis of variance (ANOVA) was used for statistical testing, followed by Bonferroni as a *post hoc* test. Pearson's product moment correlation coefficient was used to determine the relationships between the baseline characteristics and the training adaptation. Correlations between HRV and the training adaptation were adjusted by age using partial correlations due to effects of age on baseline HRV. The data were analyzed using SPSS software (PASW Statistics 18.0; SPSS Inc., Chicago, Illinois). Statistical significance was accepted as $P < 0.05$.

Results

Training volume variables (h/week, times/week) did not differ between the two training periods (Table 2). TRIMP ($P = 0.027$), running volume ($P < 0.001$) and training intensity variables [average HR ($P < 0.001$), $\%HR_{max}$ ($P < 0.001$), percentage at moderate ($P < 0.001$) and high intensities ($P = 0.004$)] were greater in ITP compared with BTP.

Body mass at weeks 0, 14 and 28 were 78.1 ± 5.6, 77.5 ± 5.5 and 76.5 ± 5.7 kg. Body mass after ITP was significantly smaller compared with the baseline level ($P < 0.001$) and after BTP ($P = 0.009$). Body fat% was lower after BTP (16.7 ± 5.1%, $P = 0.011$) and ITP (16.3 ± 5.4%, $P = 0.012$) compared with the baseline value (17.7 ± 5.1). There were no differences in basal levels of serum testosterone at weeks 0, 14 and 28 (16.2 ± 3.4, 17.1 ± 4.2, 16.5 ± 4.0 nmol/L) and cortisol (442 ± 79, 437 ± 119, 438 ± 82 nmol/L, respectively).

Table 2. Training data of the subjects in the training periods are means ± SD (95% CI)

	Basic training period	Intense training period
Training volume		
h/week	5.8 ± 1.8 (5.1–6.6)	5.5 ± 1.7 (4.8–6.2)
times/week	4.6 ± 0.9 (4.2–5.0)	4.2 ± 0.9 (3.8–4.5)
TRIMP (a week)	379 ± 113 (333–426)	421 ± 119* (372–470)
Running km (a week)	26.4 ± 12.2 (21–31)	39.9 ± 14.6*** (34–46)
Average heart rate (bpm)	127 ± 7 (124–130)	133 ± 9*** (130–137)
Average heart rate ($\%HR_{max}$)	68 ± 3 (67–69)	72 ± 4*** (70–73)
RPE (0–10+)	4.6 ± 1.3 (4.1–5.2)	4.8 ± 1.3 (4.2–5.4)
HR below AerT in running (%)	86 ± 12 (81–91)	73 ± 14*** (67–79)
HR between AerT and AnT in running (%)	13 ± 12 (8–18)	24 ± 14*** (18–30)
HR above AnT in running (%)	1 ± 1 (0–2)	2 ± 3** (1–4)

Significant difference between the periods:

*$P < 0.05$, **$P < 0.01$, ***$P < 0.001$.

TRIMP, training impulse; RPE, rate of perceived exertion; HR, heart rate; AerT, aerobic threshold; AnT, anaerobic threshold.

All subjects successfully completed a marathon ($n = 22$) or half-marathon ($n = 3$) as the main performance goal of the training program. Mean marathon time improved by 8.2% compared with the previous personal best (241 ± 23 vs 221 ± 24 min, $P < 0.001$). V_{peak} improved by 7.5 ± 4.5% ($P < 0.001$, min–max: − 3.7–13.2%) and VO_{2max} by 5.1 ± 6.2% ($P < 0.001$, min–max: − 3.9–20.2%) during the 28 weeks of training (Table 3). Velocities at anaerobic and aerobic thresholds increased by 12.4 ± 6.5% ($P < 0.001$) and 15.5 ± 8.4% ($P < 0.001$), respectively. The individual heterogeneity of training adaptation during both training periods is presented in Fig. 1. The mean increase in V_{peak} was 4.1 ± 3.1% ($P < 0.001$) during BTP and 3.3 ± 3.6% ($P < 0.001$) during ITP. The improvement did not differ between the training periods. In addition, velocities at AerT increased by 9.1 ± 7.3% ($P < 0.001$) in BTP and 5.9 ± 5.3% ($P < 0.001$) in ITP and AnT 8.2 ± 6.4% ($P < 0.001$), 4.0 ± 4.5% ($P < 0.001$), respectively. RE improved (3 ± 5%, $P = 0.002$) only during ITP.

No changes were observed in nocturnal HR and HRV indices during BTP (Table 4). After the 28-week training resting HR ($P = 0.037$) decreased and SDNN ($P = 0.013$) and RMSSD ($P = 0.001$) increased compared with the baseline level. In addition, HFP ($P = 0.026$) and TP ($P = 0.007$) increased significantly during ITP.

Age did not correlate with the training adaptation (the change in V_{peak}) in either BTP ($r = -0.11$) or ITP ($r = 0.16$). In addition, the previous training activity ($r = -0.11$, $r = 0.13$) and the baseline endurance performance ($r = -0.06$, $r = 0.02$), as well as any training volume or intensity variables did not correlate with the training adaptation in either periods. A good correlation was observed between the change in V_{peak} during ITP and HRV indices at the baseline measurement (Fig. 2, Table 5). The strongest relationship ($r = 0.75$, $P < 0.001$) was between the change in V_{peak} and TP at baseline [Fig. 2(b)]. No significant correlations between these parameters were found during BTP [Fig. 2(a)]. However, a weak trend was observed between the baseline testosterone level and the training adaptation ($r = 0.41$, $P = 0.085$). The change of RE did not correlate significantly to any baseline characteristics in either periods.

Discussion

The main findings of the present study showed that nocturnal HRV at baseline was associated with the endurance training adaptation in ITP, not in BTP (Table 5). The present results thus suggest that

Table 3. Performance parameters of the incremental treadmill test are means ± SD (95% CI)

	Baseline	Week 14	Week 28
VO_{2max} (mL/kg/min)	49 ± 4(48–51)	51 ± 4** (50–53)	52 ± 5** (50–54)
V_{peak} (km/h)	14.7 ± 1.0 (14.3–15.2)	15.3 ± 1.1*** (14.9–15.8)	15.8 ± 1.2$^{***,\#\#\#}$(15.3–16.3)
vAnT (km/h)	12.0 ± 1.2 (11.5–12.5)	12.9 ± 1.1*** (12.5–13.4)	13.4 ± 1.0$^{***,\#\#\#}$(13.0–13.8)
VAerT (km/h)	9.4 ± 0.9 (9.0–9.8)	10.2 ± 1.0*** (9.8–10.6)	10.8 ± 0.9$^{***,\#\#\#}$(10.4–11.2)
RE (mL/kg/km)	221 ± 13 (215–226)	219 ± 16 (213–225)	208 ± 13$^{***,\#\#}$(203–214)

Significant difference from baseline:

$^{**}P<0.01$, $^{***}P<0.001$.

Significant difference from week 14:

$^{\#\#}P<0.01$, $^{\#\#\#}P<0.001$.

VO_{2max}, maximal oxygen consumption; V_{peak}, peak treadmill running speed; vAnT, velocity at anaerobic threshold; vAerT, velocity at aerobic threshold; RE, running economy.

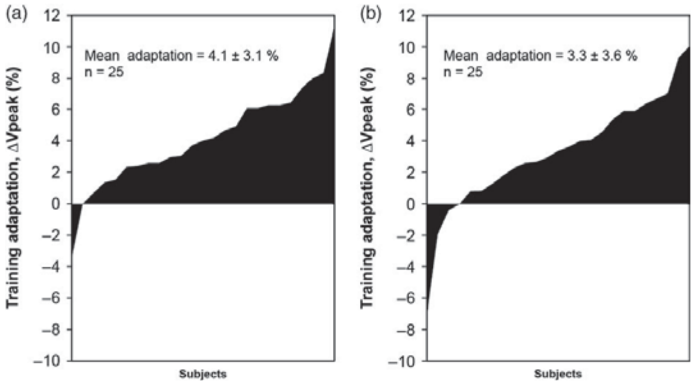


Fig. 1. Heterogeneity of training adaptations (ΔV_{peak}) during the basic training period (a) and the intense training period (b) in recreational endurance runners.

Table 4. Nocturnal HR and HRV values are means ± SD (95% CI)

	Baseline	Week 14	Week 28
HR (bpm)	51.1 ± 4.4 (49.0–53.3)	49.9 ± 6.1 (47.0–52.9)	48.9 ± 5.5* (46.3–51.6)
SDNN (ms)	134 ± 20 (124–143)	140 ± 28 (127–154)	152 ± 31* (137–167)
RMSSD (ms)	84 ± 25 (73–96)	93 ± 36 (76–111)	109 ± 41** (90–129)
LFP (ln ms^2)	8.36 ± 0.47 (8.14–8.59)	8.29 ± 0.45 (8.08–8.51)	8.42 ± 0.40 (8.23–8.62)
HFP (ln ms^2)	8.02 ± 0.64 (7.72–8.33)	8.06 ± 0.68 (7.73–8.39)	8.21 ± 0.67$^{\#}$ (7.89–8.54)
TP (ln ms^2)	9.01 ± 0.50 (8.77–9.25)	8.99 ± 0.53 (8.74–9.25)	9.14 ± 0.49$^{\#\#}$ (8.91–9.38)

Significant difference from baseline:

$^{*}P<0.05$, $^{**}P<0.01$.

Significant difference from week 14:

$^{\#}P<0.05$, $^{\#\#}P<0.01$.

HR, heart rate; SDNN, standard deviation of RRI; RMSSD, square root of the mean of the sum of the squares of differences between adjacent RRI; LFP, low-frequency power; HFP, high-frequency power; TP, total power.

moderate- and high-intensity training is needed for significant changes in vagal activity of cardiovascular autonomic regulation to occur among recreational endurance runners. In addition, the present results suggest that progressively increased training load led to the prolonged endurance training adaptation during 28 weeks of endurance training.

Individual adaptation to training

In the present study, recreational endurance runners trained the first 14 weeks at low-intensity followed by 14 weeks of a combination of low-, moderate- (11 sessions) and high-intensity (seven sessions) training. All endurance performance characteristics improved

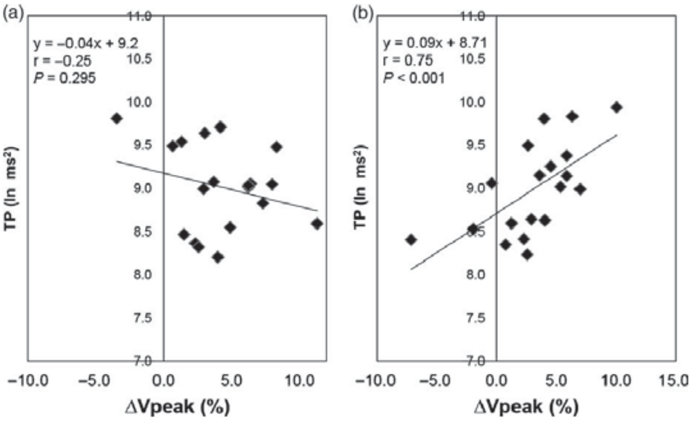


Fig. 2. Correlation between the interindividual training adaptation (ΔV_{peak}) and baseline heart rate variability (TP, total power) after adjustment on age in the basic training period (a) and the intense training period (b).

Table 5. Correlations between endurance training adaptation (ΔV_{peak}) and baseline hormones and heart rate variability

	Basic training period	Intense training period
Cortisol (nmol/L)	0.01	−0.18
Testosterone (nmol/L)	0.32	0.27
HR (bpm)	−0.21	−0.44
SDNN (ms)	−0.02	0.48*
RMSSD (ms)	−0.11	0.57*
LFP (ln ms^2)	−0.17	0.69**
HFP (ln ms^2)	−0.29	0.71***
TP (ln ms^2)	−0.25	0.75***

Significant correlation:
*$P<0.05$, **$P<0.01$, ***$P<0.001$.
Correlations to HRV indices were adjusted for age.
V_{peak}, peak treadmill running speed; HR, heart rate; SDNN, standard deviation of RRI; RMSSD, square root of the mean of the sum of the squares of differences between adjacent RRI; LFP, low-frequency power; HFP, high-frequency power; TP, total power.

continuously throughout the whole 28 weeks of training, except RE which improved only during ITP. Mean improvements were 5–8% in peak treadmill running speed ($VO_{2\max}$, V_{peak}) and 12–15% at submaximal velocities (vAnT, vAerT) including large individual variation in the training adaptation. Three subjects (12%) could not improve their endurance performance during the study. This possibly explains why the mean improvement in $VO_{2\max}$ was slightly smaller compared with previous long-term studies (Loimaala et al., 2000; Iwasaki et al., 2003; Scharhag-Rosenberger et al., 2009). In the study of Loimaala et al. (2000) an 11% improvement was observed in the low-intensity group (4–6 times/week at 55% of $HR_{\max}$) and 15% improvement in the high-intensity group (4–6 times/week at 75% of $HR_{\max}$) during 5 months of endurance training among previously untrained. Iwasaki et al. (2003) found that $VO_{2\max}$ increased 16% after 6 months and 20% after 1 year of progressive endurance training among sedentary subjects. It is rational that sedentary subjects in the previous studies (Loimaala et al., 2000; Iwasaki et al., 2003) improved more than recreational endurance runners in the present study because of remarkably lower baseline endurance performance level and minor training background. Scharhag-Rosenberger et al. (2009, 2010) reported a 10% increase in V_{peak} and unchanged $VO_{2\max}$ in four of the 18 untrained individuals (22%) after a 12 months endurance training period when training load remained constant (3 times/week, 45 min/session at 60% heart rate reserve) during whole 50 weeks of training. The authors concluded that beginners in recreational endurance exercise are advised to increase their training stimulus after 6 months of training to maintain the effectiveness of training (Scharhag-Rosenberger et al., 2009, 2010). The present results support the previous finding that progressively increased training load and intensity is beneficial for the continuous endurance training adaptation during long-term training.

HRV and endurance training adaptation

The association between HRV indices and the endurance training adaptation has been widely observed (Boutcher & Stein, 1995; Aubert et al., 2003; Hautala et al., 2003; Buchheit & Gindre, 2006; Buchheit et al., 2010; Nummela et al., 2010). However, most of the previous training studies have been relatively short (<8 weeks) and intensity of training have been mainly limited to moderate or vigorous intensity. We observed a significant correlation between the baseline HRV indices (LFP, HFP, TP) and the endurance training adaptation only during ITP. TP showed to have the strongest relationship with a change in V_{peak} ($r = 0.75$, $P < 0.001$), which accounts for 56% of the variance in the adaptation to endurance training. Our finding is in line with Hautala et al. (2003) and Boutcher & Stein (1995) who showed that high resting HRV at baseline was associated with good adaptation to 8-week endurance training period among sedentary males. Based on the present findings, the same association appeared among recreational endurance runners but only when training included moderate- and high-intensity training. In previous long-term (>5 months) endurance training studies, improvements in endurance performance were found but no associations between HRV indices and the adaptation (Loimaala et al., 2000; Iwasaki et al., 2003). However, Hedelin et al. (2001) found that subjects who increased their VO_{2max} during the 7-month training period showed higher HFP and TP values throughout the study compared with those who showed reduced VO_{2max} in regional and national level cross country skiers and canoeists. Manzi et al. (2009) found a curvilinear dose–response relationship between individualized training load and HRV indices. It was observed that an increase in normalized LFP at peak exercise training could predict improvement in recreational athletes, which the authors interpreted to reflect enhanced sympathetic modulation (Manzi et al., 2009). On the other hand, the opposite relationship (the subjects with the lower vagal modulation improved more, $r = 0.82$) has also been reported during an 8-week endurance training period in moderately trained runners (Buchheit et al., 2010). Buchheit et al. (2010) concluded that the association is more likely to be related to the interdependence of cardiac autonomic control and aerobic performance than to an individual trainability component *per se* which has been expressed by Hautala et al. (2003). However, the findings of the present study do not support the conclusion of Buchheit et al. (2010), because endurance performance at baseline was not associated with the endurance training adaptation. The differences between the studies might be partly explained by different HRV recording methods. In the study of Buchheit et al. (2010) HRV indices were calculated during a 5-min rest period immediately after awakening in the mornings, whereas in the study of Manzi et al. (2009) HRV recordings were performed over a 10-min rest period in the afternoon. In the present study HRV was analyzed over the 4-h period during nights. Hautala et al. (2003) reported that baseline HFP during nighttime was the most powerful HRV index associated with the future training adaptation compared with HRV during daytime or 24-h recording. As suggested previously (e.g. Pichot et al. 2000) the nighttime reflects a more standardized condition, and the results are less influenced by the subject's behavioral pattern. Based on these findings, it seems that high nocturnal HRV at the baseline is related to the positive adaptation to intensive endurance training. On the other hand, low HRV may reflect limitations in the capacity to improve the cardiorespiratory fitness, as suggested previously by Hautala et al. (2003). However, the mechanisms underlying the association between the baseline vagal activity and the training adaptation remain unclear and should be clarified in future studies.

It has been widely reported that endurance training increases HRV indices (Buchheit et al., 2004; Kiviniemi et al., 2006; Nummela et al., 2010). However, decrements have also been observed in HRV indices during very intensive training with insufficient recovery (Pichot et al., 2000; Portier et al., 2001; Iellamo et al., 2002; Manzi et al., 2009). Pichot et al. (2000) observed that a decrease in nocturnal HRV was followed by a significant increase during the easy training week in middle-distance runners. Effects of long-term endurance training on HRV are partly unclear. Loimaala et al. (2000) did not find any changes in HRV, measured over 24-h period, during 5 months of either high- or low-intensity endurance training, and Iwasaki et al. (2003) found increases in SDNN and LFP during the first 6 months but no changes in HRV during the last 6 months. The authors concluded that more prolonged and intense training does not necessarily lead to greater enhancement of the changes in LFP and HFP. The authors expressed an explanation that after 12 months of intense training, subjects may have been slightly overtrained which could explain unchanged HRV during the last 6 months of training (Iwasaki et al., 2003). Contrary to the study of Iwasaki et al. (2003), we observed unchanged HRV during the first 14 weeks of low-intensity training and significantly increased HRV indices (except in LFP) during ITP. However, it has to be taken into consideration that different HRV recording methods were used in the present study (nocturnal 4-h recording) compared with the study of Iwasaki et al. (2003) (6 min paced breathing recording in the mornings). The present findings suggest that moderate- and high-intensity training is needed for significant changes in markers of vagally mediated regulation of the cardiovascular system to occur among recreational endurance runners. It seems that low-intensity training had no effect on the homeostasis of cardiovascular autonomic function during nocturnal rest. On the other hand, endurance performance improved also during BTP although training frequency (4.6 ± 0.9 times/week) did not change compared with preceding training (4.4 ± 0.8 times/week) of the study. The observation that peak treadmill running speed improved without changes in nocturnal HRV during BTP may be partly explained by regular strength training which may have enhanced the function of the neuromuscular system, and by a learning effect between the first two running tests on treadmill. However, this protocol does not provide a comprehensive explanation for this observation.

Baseline characteristics in prediction of training adaptation

Age has been proposed to be one of the most powerful predictors of the training adaptation (Bouchard & Rankinen, 2001; Hautala et al., 2003). Bouchard & Rankinen (2001) observed that age accounted for 4% and Hautala et al. (2003) for 16% of the endurance training adaptation. Contrary to these previous studies (Bouchard & Rankinen, 2001; Hautala et al., 2003), age was not associated with the training adaptation, contributing only 1.1% to the adaptation in BTP and 2.6% in ITP. The longer duration of the present study compared with the studies of Bouchard & Rankinen (2001) (20 weeks) and Hautala et al. (2003) (8 weeks) may partly explain a smaller contribution of age. In addition, the relatively narrow range of age (20–45 years) in this study may explain that observation. On the other hand, the range of age has also been limited in the studies of Bouchard & Rankinen (2001) (17–29 years) and Hautala et al. (2003) (23–52 years). We also observed that the baseline endurance performance was not significantly associated with the training adaptation which is in agreement with Hautala et al. (2003) and Bouchard & Rankinen (2001). In addition, the previous training activity was not associated with the improvement in endurance performance. This might be explained by the homogenous group of subjects according to their training background, and the individualized training program used in this study.

Association between hormone concentrations and endurance training adaptation

It has been widely reported that endurance training decreases testosterone concentration, especially in the case of overtraining (Wheeler et al., 1991; Urhausen et al., 1995; Hoogeveen & Zonderland, 1996; Uusitalo et al., 1998). However, Purge et al. (2006) and Grandys et al. (2009) have found increases in testosterone and cortisol concentrations in elite male rowers during a 24-week training (Purge et al., 2006), and in physically active men during a 5-week low-intensity endurance training period (Grandys et al., 2009). Purge et al. (2006) concluded that the increase in testosterone represents a positive adaptation to the training load. In addition, an increase in testosterone concentration was observed during an 18–20-month training period in previously untrained males and females preparing for a marathon (Keizer et al., 1989). On the other hand, Hoogeveen & Zonderland (1996) found that a decrease in testosterone levels did not lead to a decrease in endurance performance among professional cyclists. In the present study, positive adaptation to training was found in both training periods but no changes in basal levels of testosterone and cortisol hormones were found. It is possible that training status and fitness level of the subjects may partly explain contradictory observations about effects of endurance training on the hormonal levels. In the present study, a trend was observed in association between the training adaptation and the baseline testosterone level in BTP but not in ITP. Based on that observation, it seems that high baseline testosterone level might be beneficial for the endurance training adaptation. The explanation for that might be related to a stimulatory effect of testosterone on erythropoiesis (Shahidi, 2001). On the other hand, the low level of blood testosterone may reflect limited trainability. However, Uusitalo et al. (1998) observed marked individual differences in hormonal changes during a heavy endurance training period and concluded that individual hormonal profiles are needed to follow-up training effects. However, in the present study basal serum testosterone and cortisol concentrations were determined only three times which did not provide reliable protocol to follow-up the training adaptation. Future studies are needed to show whether acute hormonal responses to standardized exercise sessions extend information about the importance of testosterone and cortisol concentrations for improvement in the endurance adaptation.

Perspectives

The current study shows that a 28-week program consisting of a combination of low-, moderate- and high-intensity training and a progressively increased training load led to improved endurance running performance in recreational endurance runners. While there is a general improvement, large variation exists in each individuals adaptation to training, supporting the results observed in previous studies (Bouchard & Rankinen, 2001; Hautala et al., 2003, 2009; Vollaard et al., 2009; Buchheit et al., 2010). Mechanisms resulting in remarkable variation in the responsiveness to endurance training remain partly unclear. It has been suggested that cardiovascular autonomic regulation is an important determinant of training adaptation (Hautala et al., 2009). However, most of the previous studies have used relatively short training periods and subjects have been sedentary people. The findings of this study support the hypothesis that cardiovascular autonomic regulation, as measured by HRV, is potentially an important tool for monitoring how individuals adapt to training programs. As high HRV at baseline was associated with good training adaptation after high-intensity training, low HRV seems to indicate poor training adaptation possibly caused by a state of fatigue. This is in line with the research by Lamberts et al. (2010a, b) and suggests that HRV at baseline can potentially be a useful method to prescribe training and monitor fatigue. The findings of this study also support this hypothesis among trained individuals during prolonged training as it shows that vagal activity of nocturnal cardiovascular autonomic regulation increases and high HRV at baseline is associated with improvements in endurance performance when training is intensive. It is possible that low HRV can predict an inability to cope with the training load and the accumulation of fatigue. It seems that nocturnal HRV may serve a useful method for predicting individual adaptation to prolonged endurance training.

Key words: endurance training, endurance performance, predicting training adaptation, autonomic nervous system.

Acknowledgements

Funding of the study was provided by the Finnish Funding Agency for Technology and Innovation (TEKES), KIHU – Research Institute for Olympic Sport and the Department of Biology of Physical Activity. The authors wish to thank the participating subjects for their collaboration.

References

Aubert AE, Seps B, Beckers F. Heart rate variability in athletes. Sports Med 2003: 33: 889–919.

Aunola S, Rusko H. Aerobic and anaerobic thresholds determined from venous lactate or from ventilation and gas exchange in relation to muscle fiber composition. Int J Sports Med 1986: 7: 161–166.

Banister EW. Modelling elite athletic performance. In: MacDougall JD, Wenger HA, Green HJ, eds. Physiological testing of the high-performance athlete. Champaign, IL: Human Kinetics Publishers Ltd., 1991: 403–424.

Borg GA. Psychophysical bases of perceived exertion. Med Sci Sports Exerc 1982: 14: 377–381.

Bouchard C, Rankinen T. Individual differences in response to regular physical activity. Med Sci Sports Exerc 2001: 33: 446–451.

Boutcher SH, Stein P. Association between heart rate variability and training response in sedentary middle-aged men. Eur J Appl Physiol Occup Physiol 1995: 70: 75–80.

Buchheit M, Chivot A, Parouty J, Mercier D, Al Haddad H, Laursen PB, Ahmaidi S. Monitoring endurance running performance using cardiac parasympathetic function. Eur J Appl Physiol 2010: 108: 1153–1167.

Buchheit M, Gindre C. Cardiac parasympathetic regulation: respective associations with cardiorespiratory fitness and training load. Am J Physiol Heart Circ Physiol 2006: 291: 451–458.

Buchheit M, Simon C, Piquard F, Ehrhart J, Brandenberger G. Effects of increased training load on vagal-related indexes of heart rate variability: a novel sleep approach. Am J Physiol Heart Circ Physiol 2004: 287: H2813–H2818.

Grandys M, Majerczak J, Duda K, Zapart-Bukowska J, Kulpa J, Zoladz JA. Endurance training of moderate intensity increases testosterone concentration in young, healthy men. Int J Sports Med 2009: 30: 489–495.

Hautala AJ, Kiviniemi AM, Tulppo MP. Individual responses to aerobic exercise: the role of the autonomic nervous system. Neurosci Biobehav Rev 2009: 33: 107–115.

Hautala AJ, Makikallio TH, Kiviniemi A, Laukkanen RT, Nissila S, Huikuri HV, Tulppo MP. Cardiovascular autonomic function correlates with the response to aerobic training in healthy sedentary subjects. Am J Physiol Heart Circ Physiol 2003: 285: H1747–H1752.

Hedelin R, Bjerle P, Henriksson-Larsen K. Heart rate variability in athletes: relationship with central and peripheral performance. Med Sci Sports Exerc 2001: 33: 1394–1398.

Hoogeveen AR, Zonderland ML. Relationships between testosterone, cortisol and performance in professional cyclists. Int J Sports Med 1996: 17: 423–428.

Iellamo F, Legramante JM, Pigozzi F, Spataro A, Norbiato G, Lucini D, Pagani M. Conversion from vagal to sympathetic predominance with strenuous training in high-performance world class athletes. Circulation 2002: 105: 2719–2724.

Iwasaki K, Zhang R, Zuckerman JH, Levine BD. Dose–response relationship of the cardiovascular adaptation to endurance training in healthy adults: how much training for what benefit? J Appl Physiol 2003: 95: 1575–1583.

Keizer H, Janssen GM, Menheere P, Kranenburg G. Changes in basal plasma testosterone, cortisol, and dehydroepiandrosterone sulfate in previously untrained males and females preparing for a marathon. Int J Sports Med 1989: 10(Suppl. 3): S139–S145.

Kesaniemi YK, Danforth E, , Jensen MD, Kopelman PG, Lefebvre P, Reeder BA. Dose–response issues concerning physical activity and health: an evidence-based symposium. Med Sci Sports Exerc 2001: 33: S351–S358.

Kiviniemi AM, Hautala AJ, Makikallio TH, Seppanen T, Huikuri HV, Tulppo MP. Cardiac vagal outflow after aerobic training by analysis of high-frequency oscillation of the R–R interval. Eur J Appl Physiol 2006: 96: 686–692.

Lamberts RP, Rietjens GJ, Tijdink HH, Noakes TD, Lambert MI. Measuring submaximal performance parameters to monitor fatigue and predict cycling performance: a case study of a world-class cyclo-cross cyclist. Eur J Appl Physiol 2010a: 108: 183–190.

Lamberts RP, Swart J, Capostagno B, Noakes TD, Lambert MI. Heart rate recovery as a guide to monitor fatigue and predict changes in performance parameters. Scand J Med Sci Sports 2010b: 20: 449–457.

Loimaala A, Huikuri H, Oja P, Pasanen M, Vuori I. Controlled 5-Mo aerobic training improves heart rate but not heart rate variability or baroreflex sensitivity. J Appl Physiol 2000: 89: 1825–1829.

Manzi V, Castagna C, Padua E, Lombardo M, D'Ottavio S, Massaro M, Volterrani M, Iellamo F. Dose–response relationship of autonomic nervous system responses to individualized training impulse in marathon runners. Am J Physiol Heart Circ Physiol 2009: 296: H1733–H1740.

McArdle WD, Katch FI, Katch V.L. Exercise physiology. Energy, nutrition, and human performance. Baltimore: Williams & Wilkins, 1996: 393–415.

Noakes TD, Myburgh KH, Schall R. Peak treadmill running velocity during the VO_{2max} test predicts running performance. J Sports Sci 1990: 8: 35–45.

Nummela A, Hynynen E, Kaikkonen P, Rusko H. Endurance performance and nocturnal HRV indices. Int J Sports Med 2010: 31: 154–159.

Pichot V, Roche F, Gaspoz JM, Enjolras F, Antoniadis A, Minini P, Costes F, Busso T, Lacour JR, Barthelemy J.C. Relation between heart rate variability and training load in middle-distance runners. Med Sci Sports Exerc 2000: 32: 1729–1736.

Portier H, Louisy F, Laude D, Berthelot M, Guezennec CY. Intense endurance training on heart rate and blood pressure variability in runners. Med Sci Sports Exerc 2001: 33: 1120–1125.

Purge P, Jurimae J, Jurimae T. Hormonal and psychological adaptation in elite male rowers during prolonged training. J Sports Sci 2006: 24: 1075–1082.

Saalasti S. Neural networks for heart rate time series analysis. Ph.D thesis. Department of Mathematical Information Technology, University of Jyväskylä, Finland, Jyväskylä Studies in Computing 33, Jyväskylä, 2003

Scharhag-Rosenberger F, Meyer T, Walitzek S, Kindermann W. Time course of changes in endurance capacity: a 1-yr training study. Med Sci Sports Exerc 2009: 41: 1130–1137.

Scharhag-Rosenberger F, Walitzek S, Kindermann W, Meyer T. Differences in adaptations to 1 year of aerobic endurance training: individual patterns of nonresponse. Scand J Med Sci Sports 2010: 22: 113–118.

Shahidi NT. A review of the chemistry, biological action, and clinical applications of anabolic-androgenic steroids. Clin Ther 2001: 23: 1355–1390.

Urhausen A, Gabriel H, Kindermann W. Blood hormones as markers of training stress and overtraining. Sports Med 1995: 20: 251–276.

Uusitalo AL, Huttunen P, Hanin Y, Uusitalo AJ, Rusko HK. Hormonal responses to endurance training and overtraining in female athletes. Clin J Sport Med 1998: 8: 178–186.

Vollaard NB, Constantin-Teodosiu D, Fredriksson K, Rooyackers O, Jansson E, Greenhaff PL, Timmons JA, Sundberg CJ. Systematic analysis of adaptations in aerobic capacity and submaximal energy metabolism provides a unique insight into determinants of human aerobic performance. J Appl Physiol 2009: 106: 1479–1486.

Wheeler GD, Singh M, Pierce WD, Epling WF, Cumming DC. Endurance training decreases serum testosterone levels in men without change in luteinizing hormone pulsatile release. J Clin Endocrinol Metab 1991: 72: 422–425.

II

Predictors of individual adaptation to high-volume or -intensity endurance training in recreational endurance runners

by

V. Vesterinen, K. Häkkinen, T. Laine, E. Hynynen, J. Mikkola &
A. Nummela. 2016

Scandinavian Journal of Medicine and Science in Sports, 26: 885-893.

Scand J Med Sci Sports 2016: 26: 885–893
doi: 10.1111/sms.12530

SCANDINAVIAN JOURNAL OF
MEDICINE & SCIENCE
IN SPORTS

Predictors of individual adaptation to high-volume or high-intensity endurance training in recreational endurance runners

V. Vesterinen[1], **K. Häkkinen**[2], **T. Laine**[1], **E. Hynynen**[1], **J. Mikkola**[1], **A. Nummela**[1]

[1]KIHU – Research Institute for Olympic Sports, Jyväskylä, Finland, [2]Department of Biology of Physical Activity, University of Jyväskylä, Jyväskylä, Finland
Corresponding author: Ville Vesterinen, KIHU – Research Institute for Olympic Sports, Rautpohjankatu 6, 40700 Jyväskylä, Finland. Tel: +35 85 05 45 10 49, Fax: +35 82 07 81 15 01, E-mail: ville.vesterinen@kihu.fi

Accepted for publication 27 June 2015

The aim of this study was to investigate factors that can predict individual adaptation to high-volume or high-intensity endurance training. After the first 8-week preparation period, 37 recreational endurance runners were matched into the high-volume training group (HVT) and high-intensity training group (HIT). During the next 8-week training period, HVT increased their running training volume and HIT increased training intensity. Endurance performance characteristics, heart rate variability (HRV), and serum hormone concentrations were measured before and after the training periods. While HIT improved peak treadmill running speed (RS_{peak}) 3.1 ± 2.8% ($P < 0.001$), no significant changes occurred in HVT (RS_{peak}: 0.5 ± 1.9%). However, large individual variation was found in the changes of RS_{peak} in both groups (HVT: –2.8 to 4.1%; HIT: 0–10.2%). A negative relationship was observed between baseline high-frequency power of HRV (HFP_{night}) and the individual changes of RS_{peak} ($r = -0.74$, $P = 0.006$) in HVT and a positive relationship ($r = 0.63$, $P = 0.039$) in HIT. Individuals with lower HFP showed greater change of RS_{peak} in HVT, while individuals with higher HFP responded well in HIT. It is concluded that nocturnal HRV can be used to individualize endurance training in recreational runners.

It is well known that individuals adapt differently to endurance training. Individual changes in maximal oxygen uptake and endurance performance during training may range from negative (–4%) response to 40% improvements (Bouchard & Rankinen, 2001; Vollaard et al., 2009; Buchheit et al., 2010; Vesterinen et al., 2013). Why some individuals show a great response while others show minor responses to standardized training is still unclear. It has been proposed that age, sex, race, and baseline fitness level collectively accounted for only 11% of the heterogeneity in the adaptation to endurance training (Bouchard & Rankinen, 2001).

Many studies have shown that cardiovascular autonomic regulation, as measured by heart rate variability (HRV), is an important determinant of endurance training adaptation and is related to individual heterogeneity of the adaptation. Increased resting HRV has been associated with the positive adaptation (increased VO_{2max} or maximal aerobic speed) to endurance training (Hautala et al., 2003; Buchheit et al., 2010; Nummela et al., 2010b; Boutcher et al., 2013; Plews et al., 2013; Da Silva et al., 2014). In addition, the positive relationship between vagal mediated resting HRV (high-frequency power, HFP) at baseline and increase in VO_{2max} has been observed in the previous studies of Hautala et al. (2003) and Hedelin et al. (2001), and between change in maximal aerobic speed and nocturnal HFP and total power (TP) at baseline in our previous study (Vesterinen et al., 2013). On the other hand, Buchheit et al. (2010) reported the negative relationship between vagal mediated resting HRV at baseline and change in 10-km running performance after an 8-week training period.

Endurance training in previous studies has mostly been a mixture of low-, moderate-, and high-intensity training which may partly explain contradictory results. Previous studies have not focused on the effects of training intensity and volume to the relation between cardiovascular autonomic regulation and the training adaptation. However, specific physiological adaptations, including cardiovascular, respiratory, metabolic, and neuromuscular adaptations, appear to depend on the training volume, intensity, and frequency (Vollaard et al., 2009; Laursen, 2010). Therefore, it can be assumed that training volume and intensity have different effects on the relationship between cardiovascular autonomic regulation and the training adaptation.

It has also been suggested that basal testosterone and cortisol concentrations can be used in monitoring the adaptation to training. Purge et al. (2006) concluded that the increase in resting testosterone concentration during a 24-week endurance training period represents a positive adaptation to the training load in elite rowers. However, it is well known that endurance training decreases resting testosterone concentration (Wheeler et al., 1991; Urhausen et al., 1995; Hoogeveen & Zonderland, 1996; Uusitalo et al., 1998). It has been documented that decreased resting testosterone concentration is related to energy deficiency (Strauss et al., 1985; Friedl et al., 2000). In addition, because of the findings that testosterone stimulates erythropoiesis (Shahidi, 2001) and enhances lactate transport from the muscle (Enoki et al., 2006), it may be possible that decreased testosterone concentration may reflect limited trainability. However, more research is needed to confirm the utility of serum testosterone and cortisol concentrations as predictors of the individual endurance training adaptation.

The aim of the present study was to assess whether baseline factors, such as age, fitness level, nocturnal HRV, and serum hormone concentrations, are associated with the individual adaptation to high-intensity and high-volume endurance training. In addition, the aim was to investigate whether increased training volume and intensity have different effects on the relationship between nocturnal HRV and individual training adaptation. The results of the previous studies suggest that HRV can be used as a predictor of endurance training adaptation.

Methods

Subjects

Forty recreational endurance runners (20 women, 20 men) were recruited by advertising in the local newspaper and social media to participate in the study. The sample size was determined using the data of Vesterinen et al. (2014) and Stoggl and Sperlich (2014) [expected change in peak treadmill running speed (RS_{peak}) 3 ± 3% and 5 ± 3%]. A priori power analysis suggested that 16 subjects were required for both groups to achieve 80% power and a significance level of 5%. The subjects were healthy, non-obese ($BMI < 30\ kg/m^2$), and they did not have any diseases or use regular medication. They had at least 2 years of regular running training background. After being fully informed about the study design and the possible risks, all subjects completed an informed consent document. The study was approved by the Ethics Committee of the University of Jyväskylä, Finland. A total of 29 subjects (16 women, 13 men) completed the whole 16-week training program. Exclusion of 11 subjects was due to injuries ($n = 6$), sicknesses ($n = 3$), and insufficient compliance with the training program ($n = 2$). Age, pre-training VO_{2max}, and a regular endurance training background of the subjects were for women 35 ± 10 years, 47 ± 5 mL/kg/min, 14 ± 8 years (5.6 ± 1.7 times, 38 ± 19 km running per week during the last 2 months before the study), and for men 35 ± 6 years, 53 ± 5 mL/kg/min, 14 ± 8 years (4.4 ± 2.0 times, 27 ± 15 km running per week).

Experimental design and training

The controlled 16-week training program included two 8-week training periods. All measurements were performed three times: before training (week −9), after the first 8-week training period (week 0), and after the second 8-week training period (week 9). A preparation period (PREP) of 8 weeks was completed first to familiarize the subjects with testing procedures and proper endurance training and to ensure that subjects had a similar background in training before the second 8-week period. The subjects were asked to train once per week at moderate intensity [heart rate (HR) between lactate thresholds 1 and 2] and otherwise at low intensity (HR below lactate threshold 1, LT1). In addition, they were asked to maintain the same training volume as before the study. After PREP, the runners were matched into pairs according to their background (sex, age, training background), endurance performance characteristics (VO_{2max}, RS_{peak}), baseline HRV, and an improvement of endurance performance during PREP. The matching of the pairs was done so that the characteristics were as equal as possible between matched pairs (mean differences in endurance performance variables between matched pairs < 2%), and mean values of the groups were similar. Thereafter, within each pair, the runners were randomly assigned to the high-volume training group (HVT) and high-intensity training group (HIT). For the intense 8-week training period (INT), HVT were instructed to increase their training volume by 30–50% whereas training intensity remained same as during PREP. HIT replaced three low-intensity training sessions during each intense training week with three moderate- or high-intensity (HR above lactate threshold 2, LT2) training sessions: (a) constant speed run 20–40 min at 80–90% HR_{max}; (b) 4 × 4 min at 90–95% HR_{max}, with 3 min of recovery at intensity below LT1; and (c) 6 × 2 min at 100% RS_{peak}, with 2 min of recovery at intensity below LT1, whereas training volume was maintained the same. The training was periodized to cycles of 4 weeks, thus 3 weeks of intense training was followed by an easy training week. Endurance training consisted primarily of running but occasionally included also cycling, Nordic walking, and/or cross-country skiing.

The subjects controlled their training intensity by measuring their HR and speed during all exercises using Garmin FR 610 HR monitors (Garmin Ltd, Schaffhausen, Switzerland). Subjects kept a training diary throughout the study recording training mode, duration of the training session, average HR, and running distance. In addition, the subjects rated their perceived exertion and recovery feelings using the scale from 0 to 10 after each training session (Borg, 1982). HR data were used for determining the times at the three different training intensity zones: low (below LT1), moderate (between lactate thresholds 1 and 2), and high (above LT2) intensities. Weekly main training sessions were supervised by experienced members of the research group.

Blood markers

Venous blood samples (3.5 mL) were collected into serum-gel tubes (Venosafe, Terumo Medical Co., Leuven, Belgium) for the determination of basal serum testosterone and cortisol concentrations after 10 h of fasting in the morning between 07:30 and 08:30 h at each measurement point (weeks −9, 0, and 9). The whole blood was centrifuged at 2700 rpm (Megafuge 1.0R, Heraeus, Germany) for 10 min after which serum was removed and stored at −20 °C until analysis. The concentrations of testosterone and cortisol were determined by using a chemical luminescence technique (Immunlite 1000 Analyzer, DPC Diagnostics Corporation, Los Angeles, California, USA) and hormone specific immunoassay kits (Siemens, New York, New York, USA). The sensitivity of testosterone and cortisol assays was 0.05 and 5.5 nmol/L, respectively. The intra-assay coefficients of variation for testosterone and cortisol were 3.9% and 4.6%, respectively. All the assays were carried out according to instructions of the manufactures. All samples of the test subject were analyzed in the same assay for each variable.

Maximal running test

The subjects were asked not to do any vigorous physical activity 2 days prior to running test. An incremental treadmill test was performed at the same time (±2 h) of each testing day. The subjects performed the test, starting at 7 km/h for women and at 8 km/h for men, and followed by an increase of 1 km/h every third minute until volitional exhaustion. The incline was kept at 0.5° during the whole test. HR was recorded continuously using a HR monitor (Suunto t6, Suunto Ltd, Vantaa, Finland). Oxygen consumption was measured breath by breath throughout the test using a portable spiroergometer (Oxycon Mobile, Viasys Health Care, Würzburg, Germany). After each 3-min stage, the treadmill was stopped for about 15–20 s for fingertip blood samples (20 µL) and blood lactate (La) analysis. Blood lactate was determined using Biosen S_line Lab+ lactate analyzer (EKF Diagnostic, Magdeburg, Germany). The highest 60 s VO_2 value during the treadmill test was considered as maximal oxygen uptake (VO_{2max}). The maximal endurance performance was determined as the peak treadmill running speed (RS_{peak}) when the subject became exhausted. If the subject could not complete the whole 3 min of the last speed, RS_{peak} was calculated as follows: speed of the last completed stage (km/h) + (running time (s) of the speed at exhaustion – 30 s) / (180 – 30 s) * 1 km/h. RS_{peak} has been shown to be closely related to maximal endurance performance (Noakes et al., 1990). Therefore, in the present study, it was used as the main variable for describing the adaptation to endurance training during the training periods. In addition, RS_{peak} has been observed to be highly reliable with intraclass correlation coefficients of 0.99 ± 0.01 and the coefficient of variation of 1.2% measured in the incremental treadmill running test (Dupuy et al., 2012). The determination of lactate thresholds was based on a rise and change in the inclination of the blood lactate curve during the test (Faude et al., 2009). LT1 was set at 0.3 mmoL/L above the lowest lactate value in the test. LT2 was set at the intersection point between: (a) a linear model between LT1 and the next lactate point; and (b) a linear model between the lactate points with La increase of at least 0.8 mmoL/L.

Nocturnal HRV recordings

Nocturnal R-R interval (RRI) recordings were taken during four consecutive nights before an incremental treadmill test before both training periods with Garmin FR 610 HR monitor consisting of a chest belt (two-lead) with a sampling frequency of 1000 Hz (Garmin Ltd). The measuring system has been observed to be reliable for long-term HRV analysis (Weippert et al., 2010). RRI recordings were started just before going to bed to sleep and stopped after awakening in the morning. RRI data were analyzed using the Firstbeat Sports software (version 4.0.0.5, Firstbeat Technologies Ltd, Jyväskylä, Finland). RRIs were checked and edited by an artifact detection filter of the Firstbeat Sports software and subsequently excluded all falsely detected, missed, and premature heartbeats (Saalasti, 2003) caused by movement artifacts or any other artifacts of unknown origin. The consecutive RRI data were then resampled at the rate of 5 Hz by using linear interpolation to obtain equidistantly sampled time series. From the resampled data, the software calculated HRV indices second by second using the short-time Fourier transform method. For a given segment of data, a time window (Hanning) with a length of 256 samples was applied. Fast Fourier transform was calculated and a power spectrum was obtained. The window was then shifted one sample to another and the same process was repeated. The first 30 min after going to bed was excluded and the succeeding 4 h was accepted for nocturnal HRV analysis. The following HRV indices were analyzed: average HR, low-frequency power (LFP; 0.04–0.15 Hz), HFP > 0.15–0.40 Hz, TP = LFP + HFP 0.04–0.40 Hz (Task Force, 1996). Nocturnal HRV indices are subject to a little day-to-day variations with intraclass correlation coefficients between 0.84 and 0.91 in 4 h nocturnal HRV analysis during two consecutive nights after similar training day (Nummela et al., 2010a). The results are provided as averages of two nights for reducing possible day-to-day variation in HRV indices. It was not possible to use averages of the four collected recordings because the recordings with an error percent higher than 33% (of 4 h) were excluded from the analysis in some subjects for ensuring adequate quantity of RRI data for the reliable HRV analysis (Nummela et al., 2010a).

Statistical analysis

The results are expressed as means ± standard deviations (SD) and 95% confidence intervals (CI) for means and correlations. The Gaussian distribution of the data was assessed with the Shapiro–Wilk goodness-of-fit test. Ln transformation was used with the nocturnal HRV variables in order to meet the assumptions of parametric statistical analysis. Group differences (HVT vs HIT, women vs men, high HRV vs low HRV) were analyzed using a one-way analysis of variance (ANOVA) and within-group differences (group by training interaction) were analyzed using repeated measures ANOVA, followed by Bonferroni as a post-hoc test. Pearson's product–moment correlation coefficient was used to determine the relationships between the baseline characteristics and the training adaptation (change in RS_{peak}). Correlations between HRV and the training adaptation were adjusted by age due to effects of age on baseline HRV, and a correlation between baseline testosterone and the training adaptation was adjusted by sex using partial correlation. For an additional analysis of the relationship between baseline HRV and the training adaptation, the subjects were retrospectively divided into high (> 8.1 ln ms^2) (HVT: $n = 8$; HIT: $n = 5$) and low HRV (< 8.1 ln ms^2) (HVT: $n = 5$; HIT: $n = 7$) groups based on baseline HFP (mean of baseline HFP in all subjects was used as the threshold). Statistical significance was accepted as $P < 0.05$. Statistical analyses were carried out using SPSS software (IBM SPSS Statistics 20, IBM, Armonk, New York, USA).

Results

Training

Total training time and distance during PREP remained constant compared with the training before the study (7.0 ± 2.8 vs 6.7 ± 2.7 h/week, $P = 0.59$; 34.0 ± 18.2 vs 36.1 ± 22.0 running km/week, $P = 0.41$). HVT increased running volume by 35% during INT with no change in training intensity. HIT increased proportion of training time at the high-intensity zone from 2.0 ± 2.2% to 7.0 ± 2.4% ($P < 0.001$) while training volume remained similar (Table 1).

Individual training adaptation

RS_{peak} and running speeds at the lactate thresholds (RS_{LT1}, RS_{LT2}) improved by 3.0 ± 2.7% ($P < 0.001$), 2.7 ± 4.8% ($P = 0.02$), and 4.0 ± 4.4% ($P < 0.001$), respectively, during PREP, while VO_{2max} did not change (–0.1 ± 5.1%, $P = 0.293$). VO_{2max} and RS_{peak} improved by 4.3 ± 4.0% ($P = 0.002$) and 3.0 ± 2.8% ($P = 0.003$), respectively, in HIT during INT (Table 2), but no significant changes were observed in HVT (VO_{2max}: 2.6 ± 7.0%; RS_{peak}: 0.5 ± 1.9%) during INT. However, large individual variation was found in the change of

Table 1. Training data of high-volume (HVT, $n = 14$) and high-intensity (HIT, $n = 15$) training groups are means ± SD (95% CI)

	PREP (weeks –9 to 0)		INT (weeks 0–9)	
	HVT	HIT	HVT	HIT
Training volume (h/week)	7.0 ± 1.7 (6.0;8.0)	6.9 ± 3.6 (4.9;8.9)	6.9 ± 1.3 (6.2;7.8)	6.0 ± 2.4 (4.7;7.4)
Training sessions per week	5.6 ± 0.9 (5.1;6.1)	6.3 ± 3.1 (4.6;8,0)	5.8 ± 0.7 (5.4;6.3)	6.5 ± 3.0 (4.9;8.2)
Running volume (km/week)	35 ± 15 (26;44)	33 ± 21 (22;45)	47 ± 13*** (40;54)	39 ± 18 (29;49)
Low intensity (%)	83 ± 10 (78;89)	87 ± 8 (82;92)	81 ± 10 (75;87)	87 ± 5† (85;90)
Moderate intensity (%)	15 ± 9 (10;20)	12 ± 7 (8;16)	17 ± 9 (12;23)	6 ± 3***‡ (4;8)
High intensity (%)	2 ± 2 (1;3)	1 ± 1 (0;2)	2 ± 2 (1;3)	7 ± 2***‡ (6;8)

Significant difference between the periods within the groups, **$P < 0.01$, ***$P < 0.001$ and between the groups within the periods, $^{\dagger}P < 0.05$, $^{\ddagger}P < 0.001$.
PREP, preparation training period; INT, intense training period; HVT, high-volume training group; HIT, high-intensity training group; low-intensity training, heart rate below lactate threshold 1; moderate-intensity training, heart rate between lactate thresholds 1 and 2; high-intensity training, heart rate above lactate threshold 2.

Table 2. Endurance variables, HRV variables, and serum hormone concentrations before and after high-volume (HVT, $n = 14$) and high-intensity (HIT, $n = 15$) endurance training are means ± SD (95% CI)

	HVT		HIT	
	Week 0	Week 9	Week 0	Week 9
VO_{2max} (mL/kg/min)	49.3 ± 3.9 (47.1;51.6)	50.5 ± 4.7 (47.8;53.2)	50.7 ± 6.6 (47.0;54.3)	52.8 ± 6.7**(49.0;56.5)
RS_{peak} (km/h)	15.3 ± 0.9 (14.8;15.8)	15.3 ± 1.1 (14.7;16.0)	15.2 ± 1.3 (14.5;15.9)	15.7 ± 1.4** (14.9;16.5)
RS_{LT2} (km/h)	12.5 ± 0.8 (12.0;12.9)	12.6 ± 1.1 (12.0;13.3)	12.6 ± 1.2 (11.9;13.2)	13.0 ± 1.3* (12.3;13.7)
RS_{LT1} (km/h)	10.2 ± 1.0 (9.6;10.8)	10.3 ± 0.9 (9.8;10.8)	10.3 ± 1.0 (9.7;10.9)	10.7 ± 1.0* (10.2;11.2)
RE_{12} (mL/kg/km)	205 ± 11 (199;212)	210 ± 11 (204;216)	207 ± 11 (201;213)	208 ± 14 (200;215)
RE_{10} (mL/kg/km)	211 ± 14 (203;219)	214 ± 13 (206;221)	215 ± 9 (210;220)	213 ± 12 (206;220)
HR_{night} (bpm)	50.5 ± 4.1 (47.6;53.4)	49.0 ± 4.2 (46.0;52.1)	52.5 ± 7.7 (47.0;58.0)	50.4 ± 7.1 (45.3;55.5)
LFP_{night} (ln ms^2)	8.26 ± 0.44 (7.94;8.58)	8.24 ± 0.36 (7.98;8.50)	8.16 ± 0.51 (7.79;8.53)	8.33 ± 0.66 (7.79;8.53)
HFP_{night} (ln ms^2)	8.23 ± 0.62 (7.79;8.67)	8.24 ± 0.60 (7.81;8.67)	7.75 ± 0.78 (7.19;8.31)	7.93 ± 0.81 (7.35;8.51)
TP_{night} (ln ms^2)	8.98 ± 0.4 (8.66;9.30)	8.95 ± 0.4 (8.66;9.24)	8.71 ± 0.6 (8.32;9.10)	8.87 ± 0.7 (8.39;9.35)
Cortisol (nmol/L)	486 ± 152 (398;573)	522 ± 171 (423;621)	467 ± 102 (408;526)	496 ± 112 (430;563)
Testosterone (nmol/L)	6.8 ± 8.0 (2.1;11.4)	6.9 ± 7.3 (2.7;11.1)	6.8 ± 7.7 (2.4;11.3)	7.6 ± 8.7 (2.6;12.6)

Significant difference from week 0, **$P < 0.01$, ***$P < 0.001$.
HVT, high-volume training group; HIT, high-intensity training group; VO_{2max}, maximal oxygen consumption; RS_{peak}, peak treadmill running speed; RS_{LT2}, running speed at lactate threshold 2; RS_{LT1}, running speed at lactate threshold 1; RE_{12}, running economy at 12 km/h; RE_{10}, running economy at 10 km/h; HR_{night}, nocturnal heart rate; LFP_{night}, nocturnal low-frequency power; HFP_{night}, nocturnal high-frequency power; TP_{night}, nocturnal total power.

RS_{peak} in both groups (HIT: 0–10.2%; HVT: –2.8 to 4.1%) (Fig. 1). No differences were observed between sexes in the changes in any of the endurance variables. In addition, none of the HRV and hormone variables changed in either HVT or HIT during INT. The change of RS_{peak} was greater ($P = 0.015$) in the low HRV group compared with the high HRV group after HVT (Fig. 2). After HIT, the change of RS_{peak} was greater in the high HRV group ($P = 0.031$) compared with the low HRV group. In addition, the change of RS_{peak} was greater ($P = 0.001$) after HIT compared with HVT in the high HRV group, but no difference was found in the change of RS_{peak} between HIT and HVT in the low HRV group ($P = 0.863$).

Predictors of the training adaptation

Age did not correlate with the training adaptation (change in RS_{peak}) in either HVT ($r = –0.14$, $P = 0.66$) or

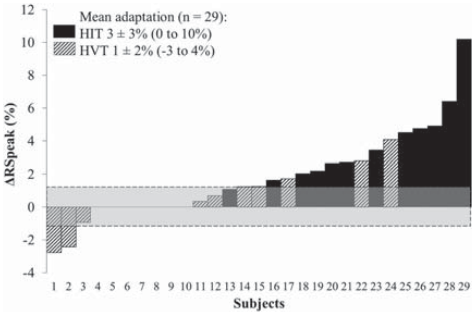


Fig. 1. Individual (bars) and mean (min–max) training adaptation (ΔRS_{peak}) to 8 weeks of high-volume (HVT) and high-intensity (HIT) endurance training. The shaded area represents the typical coefficient of variation (1.2%) in the incremental treadmill test (Dupuy et al., 2012).

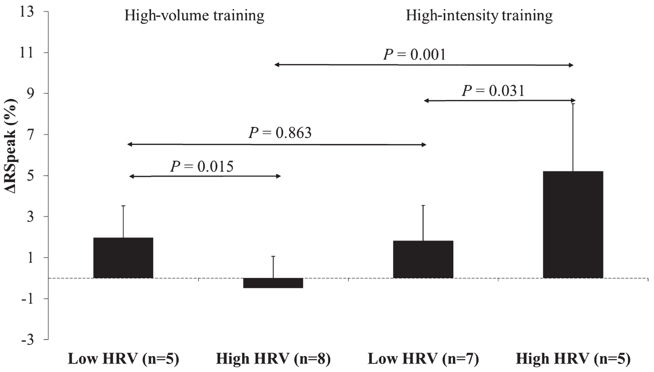


Fig. 2. Training adaptation (ΔRS_{peak}) to 8 weeks of high-volume (HVT) and high-intensity (HIT) endurance training in the low and high heart rate variability (HRV) groups.

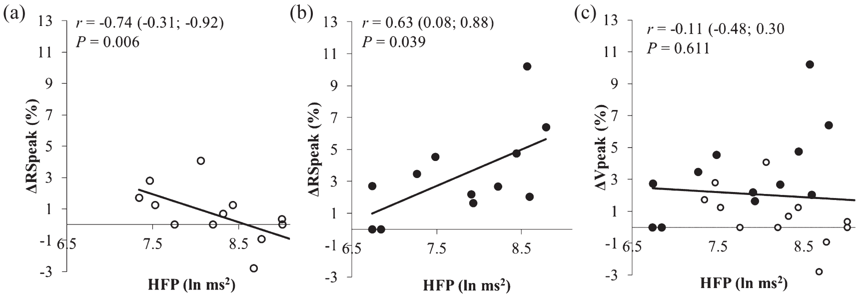


Fig. 3. The relationships between training adaptation (ΔRS_{peak}) and baseline nocturnal heart rate variability (HFP, high-frequency power) in (a) high-volume (HVT, $n = 13$), (b) high-intensity (HIT, $n = 12$), and (c) both training groups ($n = 25$, HVT = open circles, HIT = solid circles). Correlation coefficients (95% confidence intervals) are adjusted by age.

HIT ($r = -0.21$, $P = 0.46$), neither did baseline VO_{2max} (HVT: $r = 0.06$, $P = 0.86$; HIT: $r = 0.12$, $P = 0.68$). Training volume before the study (h/week) correlated to the adaptation in HVT ($r = -0.62$, $P = 0.02$) but not in HIT ($r = 0.01$, $P = 0.97$). In addition, the previous training years tended to be related to the training adaptation in HVT ($r = -0.51$, $P = 0.07$) but not in HIT ($r = 0.36$, $P = 0.46$). A negative correlation was observed between baseline nocturnal HFP and the individual change of RS_{peak} in HVT ($r = -0.74$, $P = 0.006$) and a positive correlation in HIT ($r = 0.63$, $P = 0.039$) (Fig. 3). In addition, TP correlated significantly to the training adaptation in HVT ($r = -0.65$, $P = 0.022$). No significant correlations were observed between baseline basal hormone concentrations and the training adaptations in either HVT (cortisol: $r = 0.40$, $P = 0.180$, testosterone: $r = 0.54$, $P = 0.869$) or HIT ($r = 0.26$, $P = 0.383$, $r = -0.19$, $P = 0.954$, respectively).

Discussion

The main findings of the present study were that nocturnal HFP and TP at baseline were correlated negatively with the adaptation (change in RS_{peak}) to increased volume of low-intensity endurance training (HVT) and nocturnal HFP positively with the adaptation to high-intensity endurance training (HIT). In addition, the results expressed the greater adaptation after HVT in individuals with low HRV compared with individuals with high HRV, and the greater adaptation after HIT in individuals with high HRV compared with individuals with low HRV. To our best knowledge, the present study is the first to show that the relationship between baseline HRV and the endurance training adaptation is dependent on regulation of training volume and intensity.

Adaptations to training

The results of the present study showed that HIT increased VO_{2max} (4.3 ± 4.0%) and RS_{peak} (3.0 ± 2.8%) during the 8-week high-intensity training period. The improvement in endurance performance was slightly smaller compared with the 10% improvement after 8 weeks of low-, moderate-, and high-intensity training in moderately trained runners reported by Buchheit et al. (2010). Esfarjani and Laursen (2007) reported 6–8% improvement in RS_{peak} after 10 weeks of high-intensity training and a nonsignificant change (1%) after low-intensity training in moderately trained men. In the present study, VO_{2max} and RS_{peak} were not improved at the group mean level after the 8-week low-intensity/high-volume training period in HVT. Contrary to the previously mentioned studies, the protocol of this study included the 8-week preparation period before the experimental period. The preparation period led to 3% improvement in RS_{peak} and it is reasonable that prolonged improvement is more challenging thereafter without changing training intensity. The improvement of both 8-week training periods is in line with previous endurance training-induced adaptation (Midgley et al., 2007). It seems that the long-term improved in maximal endurance running characteristics at the mean level is more probable by increasing training intensity rather than training volume in recreational endurance runners.

Large individual differences in the training adaptation have been reported after standardized training (Bouchard & Rankinen, 2001; Mann et al., 2014). Hautala et al. (2003) reported 2–9% range of individual change in VO_{2max} after 8 weeks of moderate endurance training in sedentary subjects. Buchheit et al. (2010) observed 2.5–25% range of change in maximal aerobic speed and −2.1 to 17.5% range of change in 10-km running time after 8 weeks of combined low-, moderate-, and high-intensity training. Large individual variation in the adaptation, described as an individual change in RS_{peak}, was also found in this study in both groups (HIT: 0–10.2%, HVT: −2.8 to 4.1%), despite individualized training volume and frequency according to their previous training history. It seems that the previously mentioned individualization of training according to the previous training background is not enough for diminishing large heterogeneity in the training adaptation.

Individual training adaptation and HRV

Several studies have reported the positive relationship between vagal mediated resting HRV, HFP, at baseline and change in maximal oxygen uptake (higher vagal activity, higher training adaptation) after aerobic endurance training in highly trained endurance athletes (Hedelin et al., 2001), moderately trained men (Hautala et al., 2003; Vesterinen et al., 2013), and previously untrained women (Boutcher et al., 2013). In the present study, we observed the positive relationship ($r = 0.63$) between nocturnal HFP and the change in RS_{peak} after 8 weeks of high-intensity training. In addition, we found that individuals with higher HFP (> 8.1 ln ms^2) showed greater change in RS_{peak} after the high-intensity training compared with individuals with lower HFP (< 8.1 ln ms^2). Only the study of Boutcher et al. (2013) training has included solely high-intensity training. In other previous studies, training has been a mix of low-, moderate-, and high-intensity training. In our previous study (Vesterinen et al., 2013), a positive relationship between baseline nocturnal HFP and change in maximal aerobic speed ($r = 0.71$) was found after 14 weeks of intensive endurance training (increased volume and intensity).

On the other hand, Buchheit et al. (2010) observed that low vagal mediated HRV (RMSSD, the square root of the mean squared differences of successive RRIs) at baseline was related to greater improvement in 10 km running performance after an 8-week training period in moderately trained runners. In the present study, the similar relation ($r = -0.74$) was found after 8 weeks of low-intensity training. In addition, we observed that individuals with lower HFP (< 8.1 ln ms^2) showed greater change in RS_{peak} after the increased volume of low-intensity training compared with individuals with higher HFP (> 8.1 ln ms^2). Buchheit et al. (2010) expressed that the nonresponders had better baseline fitness level than the responders and speculated that training stimuli might not have been enough for the individuals with higher endurance capacities although 8 weeks of training included high-intensity training in addition to training of low and moderate intensities. However, the same observation was not found in terms of the relationship between baseline fitness level and subsequent training adaptation in the present study.

The previously mentioned observations support that individuals with higher vagal activity may have a better capacity to cope with increased training intensity and load for leading greater training adaptation, like that proposed in our previous study (Vesterinen et al., 2013). Greater adaptations of individuals with higher resting vagal activity may also be related to a greater adaptation capacity and an improved post-exercise metabolic recovery (Blasco-Lafarga et al., 2013). Furthermore, low-intensity training may not disturb sufficiently the homeostasis of individuals with higher HRV and thus does not lead to desirable training adaptation. On the other hand, individuals with low vagal activity seem to get sufficient stimulus from low-intensity training for achieving greater adaptation to training. However, precise mechanisms underlying the relation between cardiovascular autonomic regulation and the endurance training adaptation still remain speculative. It has been reported that genetic factors may determine much of the variation in the adaptation to endurance training (Bouchard & Rankinen, 2001; Perusse et al., 2013). It is possible that these factors could partly explain great variation also in autonomic vagal activity. Therefore, there might be a common factor that explains adaptation to endurance training and cardiovascular autonomic regulation (Hautala et al., 2009).

Predictors of training adaptation

Baseline nocturnal vagal activity showed to have the strongest predictor of the change of RS_{peak}, which is in line with the results of Boutcher and Stein (1995), Hautala et al. (2003), and Vesterinen et al. (2013). HFP accounted for 54% of the variation in the training adaptation to low-intensity training and 39% of the variation in the adaptation to high-intensity training. Age, sex, and baseline fitness level have also been reported to be predictors of the endurance training adaptation (Bouchard & Rankinen, 2001; Hautala et al., 2003). However, in the present study, these baseline characteristics were not correlated to the adaptation during training. Age accounted for 2% of the variation in the adaptation in HVT and 4% in HIT, and VO_{2max} 0.4% in HVT and 1% in HIT. This might be explained by the relatively homogenous groups of subjects according to their age and baseline fitness level. Instead, training volume before the study accounted for 38% of the variation in the training adaptation to low-intensity training but not to high-intensity training. In addition, the previous training years tended to be related to the training adaptation (accounted for 26%) in low-intensity training. According to these results, it seems that individuals with lower vagal activity and minor training background achieve greater adaptation to low-intensity training regardless of age and baseline fitness level. Although testosterone and cortisol concentrations have been reported to be related to the positive adaptation to training load (Purge et al., 2006) in the present study, no significant correlations between basal serum hormone concentrations and the training adaptation were found in both groups. Thus, the present results do not support the utility of the baseline basal testosterone and cortisol concentrations as predictors of individual endurance training adaptation. Previously, decreased resting concentration of testosterone has been reported after heavy endurance training (Wheeler et al., 1991; Urhausen et al., 1995; Hoogeveen & Zonderland, 1996; Uusitalo et al., 1998). However, in the present study, serum concentrations of testosterone and cortisol remained statistically unaltered over the whole study. Some fluctuation was found, like in the combined endurance and strength training studies of Taipale et al. (2010; 2014) in recreational endurance runners, but it is possible that training should be more demanding for disturbing homeostasis of the hormonal system. Furthermore, according to these findings, it seems that basal testosterone and cortisol concentrations may not be sensitive enough for monitoring and predicting the adaptation to endurance training in recreational endurance runners.

Limitations of the study and future research

The present study is limited by its relatively small sample size, partly due to dropouts because of sickness, injuries, or lack of training program participation. Moreover, it does not serve adequate statistical power to investigate possible sex differences in the training adaptation. Future research should aim to test larger samples and to clarify individual adaptation among both sexes. In addition, a randomized study, where low and high HRV groups would be randomly divided into high-volume or high-intensity training, with larger sample size would give more statistical power for analyzing differences in training adaptation between the low and high HRV groups and determining the definition threshold for separating individuals with low and high HRV. In the present study, the threshold was the mean value of HFP (8.1 ln ms^2), but more investigation is needed in larger populations with different training backgrounds for confirming the tentative finding. Future research should aim to determine the relation between cardiac autonomic vagal activity and training adaptation especially in high-level endurance athletes. It has been observed that individuals with higher aerobic capacity have greater vagal activity (Hautala et al., 2009), which may have effects of the relation between cardiac autonomic vagal activity and training adaptation compared with recreational endurance runners with lower aerobic capacity.

Perspectives

The results showed that HIT was more productive at mean level compared with HVT in recreational endurance runners. However, individuals showed a wide range of adaptation, like in the previous studies (Bouchard & Rankinen, 2001; Vollaard et al., 2009; Buchheit et al., 2010). For improving outcomes of training and reducing a range of adaptation, more individualized training is needed. Thus, initial identification of low responders is worthwhile. Based on the present findings, nocturnal HRV is a potential tool for identifying a priori an individual's trainability. It seems that individuals with high HFP tended to respond better to HIT compared with HVT. Furthermore, the negative relation between HFP and the adaptation after HVT suggests that individuals with low HRV would respond better to increased volume of low-intensity training compared with individuals with high HRV, but no difference was found between the adaptation to HIT and HVT in individuals with low HRV. Consequently, recreational endurance runners with higher baseline nocturnal HRV are recommended to increase training load primarily by increasing training intensity rather than training volume. In conclusion, HRV may be used to individualize endurance training in recreational endurance runners, especially to adjust training volume and intensity, to achieve greater improvements in endurance performance.

Key words: Running performance, training response, heart rate variability, autonomic nervous system, training programming.

Acknowledgements

This study was financially supported by the Finnish Ministry of Education and Culture. The study was conducted in KIHU – Research Institute for Olympic Sports in cooperation with the Department of Biology of Physical Activity of the University of Jyväskylä. The authors wish to thank Sirpa Vänttinen for her expert assistance during this study, as well as the subjects for their participation.

References

Blasco-Lafarga C, Martinez-Navarro I, Mateo-March M. Is baseline cardiac autonomic modulation related to performance and physiological responses following a supramaximal judo test? PLoS ONE 2013: 8: e78584.

Borg GA. Psychophysical bases of perceived exertion. Med Sci Sports Exerc 1982: 14: 377–381.

Bouchard C, Rankinen T. Individual differences in response to regular physical activity. Med Sci Sports Exerc 2001: 33: S446–S451, discussion S452–3.

Boutcher SH, Park Y, Dunn SL, Boutcher YN. The relationship between cardiac autonomic function and maximal oxygen uptake response to high-intensity intermittent-exercise training. J Sports Sci 2013: 31: 1024–1029.

Boutcher SH, Stein P. Association between heart rate variability and training response in sedentary middle-aged men. Eur J Appl Physiol Occup Physiol 1995: 70: 75–80.

Buchheit M, Chivot A, Parouty J, Mercier D, Al Haddad H, Laursen PB, Ahmaidi S. Monitoring endurance running performance using cardiac parasympathetic function. Eur J Appl Physiol 2010: 108: 1153–1167.

Da Silva DF, Verri SM, Nakamura FY, Machado FA. Longitudinal changes in cardiac autonomic function and aerobic fitness indices in endurance runners: a case study with a high-level team. Eur J Sport Sci 2014: 14: 443–451.

Dupuy O, Mekary S, Berryman N, Bherer L, Audiffren M, Bosquet L. Reliability of heart rate measures used to assess post-exercise parasympathetic reactivation. Clin Physiol Funct Imaging 2012: 32: 296–304.

Enoki T, Yoshida Y, Lally J, Hatta H, Bonen A. Testosterone increases lactate transport, monocarboxylate transporter (MCT) 1 and MCT4 in rat skeletal muscle. J Physiol 2006: 577: 433–443.

Esfarjani F, Laursen PB. Manipulating high-intensity interval training: effects on VO2max, the lactate threshold and 3000 M running performance in moderately trained males. J Sci Med Sport 2007: 10: 27–35.

Faude O, Kindermann W, Meyer T. Lactate threshold concepts: how valid are they? Sports Med 2009: 39: 469–490.

Friedl KE, Moore RJ, Hoyt RW, Marchitelli LJ, Martinez-Lopez LE, Askew EW. Endocrine markers of semistarvation in healthy lean men in a multistressor environment. J Appl Physiol (1985) 2000: 88: 1820–1830.

Hautala AJ, Kiviniemi AM, Tulppo MP. Individual responses to aerobic exercise: the role of the autonomic nervous system. Neurosci Biobehav Rev 2009: 33: 107–115.

Hautala AJ, Makikallio TH, Kiviniemi A, Laukkanen RT, Nissila S, Huikuri HV, Tulppo MP. Cardiovascular autonomic function correlates with the response to aerobic training in healthy sedentary subjects. Am J Physiol Heart Circ Physiol 2003: 285: H1747–H1752.

Hedelin R, Bjerle P, Henriksson-Larsen K. Heart rate variability in athletes: relationship with central and peripheral performance. Med Sci Sports Exerc 2001: 33: 1394–1398.

Hoogeveen AR, Zonderland ML. Relationships between testosterone, cortisol and performance in professional cyclists. Int J Sports Med 1996: 17: 423–428.

Laursen PB. Training for intense exercise performance: high-intensity or high-volume training? Scand J Med Sci Sports 2010: 20 (Suppl. 2): 1–10.

Mann TN, Lambert RP, Lambert MI. High responders and low responders: factors associated with individual variation in response to standardized training. Sports Med 2014: 44: 1113–1124.

Midgley AW, McNaughton LR, Jones AM. Training to enhance the physiological determinants of long-distance running performance: can valid recommendations be given to runners and coaches based on current scientific knowledge? Sports Med 2007: 37: 857–880.

Noakes TD, Myburgh KH, Schall R. Peak treadmill running velocity during the VO2 max test predicts running performance. J Sports Sci 1990: 8: 35–45.

Nummela A, Hynynen E, Kaikkonen P, Rusko H. Endurance performance and nocturnal HRV indices. Int J Sports Med 2010b: 31: 154–159.

Nummela A, Hynynen E, Vesterinen V. Nocturnal heart rate and heart rate variability as a method for monitoring training load. In: Kokusuz F, Ertan H, Tsolakidis E, eds. 15th Annual congress of the European College of Sport Science. Antalya, Turkey: Book of Abstracts, 2010a: p. 516.

Perusse L, Rankinen T, Hagberg JM, Loos RJ, Roth SM, Sarzynski MA, Wolfarth B, Bouchard C. Advances in exercise, fitness, and performance genomics in 2012. Med Sci Sports Exerc 2013: 45: 824–831.

Plews DJ, Laursen PB, Kilding AE, Buchheit M. Evaluating training adaptation with heart-rate measures: a methodological comparison. Int J Sports Physiol Perform 2013: 8: 688–691.

Purge P, Jurimae J, Jurimae T. Hormonal and psychological adaptation in elite male rowers during prolonged training. J Sports Sci 2006: 24: 1075–1082.

Saalasti S. Neural Networks for Heart Rate Time Series Analysis. PhD Thesis. Department of Mathematical Information Technology, University of Jyväskylä, Finland, Jyväskylä Studies in Cumputing 33, Jyväskylä, 2003.

Shahidi NT. A review of the chemistry, biological action, and clinical applications of anabolic-androgenic steroids. Clin Ther 2001: 23: 1355–1390.

Stoggl T, Sperlich B. Polarized training has greater impact on key endurance variables than threshold, high intensity, or high volume training. Front Physiol 2014: 5: 33.

Strauss RH, Lanese RR, Malarkey WB. Weight loss in amateur wrestlers and its effect on serum testosterone levels. JAMA 1985: 254: 3337–3338.

Taipale RS, Mikkola J, Nummela A, Vesterinen V, Capostagno B, Walker S, Gitonga D, Kraemer WJ, Hakkinen K. Strength training in endurance runners. Int J Sports Med 2010: 31: 468–476.

Taipale RS, Mikkola J, Salo T, Hokka L, Vesterinen V, Kraemer WJ, Nummela

A, Hakkinen K. Mixed maximal and explosive strength training in recreational endurance runners. J Strength Cond Res 2014: 28: 689–699.

Urhausen A, Gabriel H, Kindermann W. Blood hormones as markers of training stress and overtraining. Sports Med 1995: 20: 251–276.

Uusitalo AL, Huttunen P, Hanin Y, Uusitalo AJ, Rusko HK. Hormonal responses to endurance training and overtraining in female athletes. Clin J Sport Med 1998: 8: 178–186.

Vesterinen V, Hakkinen K, Hynynen E, Mikkola J, Hokka L, Nummela A. Heart rate variability in prediction of individual adaptation to endurance training in recreational endurance runners. Scand J Med Sci Sports 2013: 23: 171–180.

Vesterinen V, Hokka L, Hynynen E, Mikkola J, Hakkinen K, Nummela A. Heart rate-running speed index may be an efficient method of monitoring endurance training adaptation. J Strength Cond Res 2014: 28: 902–908.

Vollaard NB, Constantin-Teodosiu D, Fredriksson K, Rooyackers O, Jansson E, Greenhaff PL, Timmons JA, Sundberg CJ. Systematic analysis of adaptations in aerobic capacity and submaximal energy metabolism provides a unique insight into determinants of human aerobic performance. J Appl Physiol 2009: 106: 1479–1486.

Weippert M, Kumar M, Kreuzfeld S, Arndt D, Rieger A, Stoll R. Comparison of three mobile devices for measuring R-R intervals and heart rate variability: polar s810i, suunto T6 and an ambulatory ECG system. Eur J Appl Physiol 2010: 109: 779–786.

Wheeler GD, Singh M, Pierce WD, Epling WF, Cumming DC. Endurance training decreases serum testosterone levels in men without change in luteinizing hormone pulsatile release. J Clin Endocrinol Metab 1991: 72: 422–425.

Task force heart rate variability: standards of measurement, physiological interpretation and clinical use. Task force of the European Society of Cardiology and the North American Society of Pacing and Electrophysiology. Circulation 1996: 93: 1043–1065.

III

A Submaximal Running Test with Post-Exercise Cardiac Autonomic and Neuromuscular Function in Monitoring Endurance Training Adaptation

by

V. Vesterinen, A. Nummela, T. Laine, E. Hynynen, J. Mikkola &
K. Häkkinen. 2016

Journal of Strength and Conditioning Research, *In Press*

Reproduced with kind permission from Wolters Kluwer Health, Lippincott Williams & Wilkins.

IV

Monitoring training adaptation with a submaximal running test in field conditions

by

V. Vesterinen, A. Nummela, S. Äyrämö, T. Laine, E. Hynynen, J. Mikkola &
K. Häkkinen. 2016

International Journal of Sports Physiology and Performance, 11: 393-399.

International Journal of Sports Physiology and Performance, 2016, 11, 393-399
http://dx.doi.org/10.1123/ijspp.2015-0366

Human Kinetics
ORIGINAL INVESTIGATION

Monitoring Training Adaptation With a Submaximal Running Test Under Field Conditions

Ville Vesterinen, Ari Nummela, Sami Äyrämö, Tanja Laine, Esa Hynynen, Jussi Mikkola, and Keijo Häkkinen

Regular monitoring of adaptation to training is important for optimizing training load and recovery, which is the main factor in successful training. ***Purpose:*** To investigate the usefulness of a novel submaximal running test (SRT) in field conditions in predicting and tracking changes of endurance performance. ***Methods:*** Thirty-five endurance-trained men and women (age 20–55 y) completed the 18-wk endurance-training program. A maximal incremental running test was performed at weeks 0, 9, and 18 for determination of maximal oxygen consumption (VO_{2max}) and running speed (RS) at exhaustion (RS_{peak}) and lactate thresholds (LTs). In addition, the subjects performed weekly a 3-stage SRT including a postexercise heart-rate-recovery (HRR) measurement. The subjects were retrospectively grouped into 4 clusters according to changes in SRT results. ***Results:*** Large correlations (r = .60–.89) were observed between RS during all stages of SRT and all endurance-performance variables (VO_{2max}, RS_{peak}, RS at LT2, and RS at LT1). HRR correlated only with VO_{2max} (r = .46). Large relationships were also found between changes in RS during 80% and 90% HR_{max} stages of SRT and a change of RS_{peak} (r = .57, r = .79). In addition, the cluster analysis revealed the different trends in RS during 80% and 90% stages during the training between the clusters, which showed different improvements in VO_{2max} and RS_{peak}. ***Conclusions:*** The current SRT showed great potential as a practical tool for regular monitoring of individual adaptation to endurance training without time-consuming and expensive laboratory tests.

Keywords: endurance running, individual adaptation, SRT, predicting performance

The crucial factor in successful training is the optimal balance between training load and recovery. If the training stimulus is too easy or demanding in relation to recovery, training may lead to undesirable adaptations. In addition, it is widely observed that individuals adapt differently to training load.[1–3] Regular (eg, weekly) monitoring of changes in endurance performance during training is important for optimizing training load and recovery. However, regular monitoring is not useful to conduct by maximal laboratory tests due to impracticality, expensiveness, and interfering effects on normal training habits.

Decreased heart rate (HR) at submaximal exercise has been observed to be related to positive training adaptation.[4–6] Thus, submaximal exercise HR may be an efficient method of assessing cardiac autonomic activity and tracking changes in maximal aerobic running speed (RS).[4] Lamberts et al[7] developed a submaximal cycling test for monitoring fatigue and predicting cycling performance. The authors found that cycling power at standardized submaximal HR levels and postexercise HR recovery (HRR) can predict maximal cycling performance,[7–9] but less is known about whether the submaximal test is able to reflect changes in endurance performance during a training period. In our previous study, we observed that HR/RS index—calculated from all constant-speed running exercises—serves as a potential tool for daily monitoring of training adaptation.[10] However, there are many well-established factors (ie, environmental factors, duration and intensity of exercise) that may influence HR response and thus may disturb the relationship between HR and RS.[11,12] The HR–RS relation may provide more valid information about training status if the duration and intensity of exercise are standardized.

In addition to exercise HR, postexercise HRR reflects cardiac autonomic activity, which has been suggested to be an important determinant of endurance-training adaptation.[4,6,8,13] The measurement of postexercise HRR has been proposed to have potential for monitoring fatigue and predicting changes in endurance-performance parameters.[4,8,13] However, previous studies related to submaximal tests and HRR have mainly been conducted in laboratory conditions. Less is known about the applicability of the tests as training-monitoring tools in outdoor conditions. Therefore, the aim of this study was to investigate whether a novel submaximal running test (SRT) in outdoor field conditions could be used in predicting running performance and monitoring changes in endurance performance during training. Based on previous studies,[4,13,14] we hypothesized that RSs at standardized HR levels and postexercise HRR would be able to predict endurance performance and monitor adaptation to endurance training.[4,5]

Methods

Subjects

Forty recreational endurance runners (20 women, 20 men) participated in the study. The subjects were healthy and had been training at least 3 times/wk during the previous 6 months. General characteristics of the subjects are presented in Table 1. After being fully informed about the study design and the possible risks, all subjects completed an informed-consent document. The ethics committee of the University of Jyväskylä, Finland, approved the study.

Vesterinen, Nummela, Laine, Hynynen, and Mikkola are with KIHU—Research Inst for Olympic Sports, Jyväskylä, Finland. Äyrämö is with the Agora Center, and Häkkinen, the Dept of Biology of Physical Activity, University of Jyväskylä, Jyväskylä, Finland. Address author correspondence to Ville Vesterinen at ville.vesterinen@kihu.fi.

Table 1 General Characteristics of the Subjects (Mean ± SD)

	Women (n = 20)	Men (n = 20)
Age (y)	35 ± 10	35 ± 6
Height (m)	166 ± 7	175 ± 6
Weight (kg)	60.3 ± 7.3	77.3 ± 8.0
Body fat %[a]	23.7 ± 4.4	15.2 ± 4.5
VO_{2max} ($mL \cdot kg^{-1} \cdot min^{-1}$)	47 ± 5	53 ± 5
Regular training background (y)	14 ± 8	14 ± 8
Training times/wk[b]	5.6 ± 1.7	4.4 ± 2.0
Running km/wk[b]	38 ± 19	27 ± 15

Abbreviation: VO_{2max}, maximal oxygen uptake.

[a] Based on the sum of 4 skinfolds. [b] During the previous 2 months before the study.

Design and Training

Training consisted of an 8-week low-intensity endurance-training period followed by an 8-week intensive-training period. Maximal incremental treadmill running tests were performed before and after both training periods (at weeks 0, 9, and 18). In addition, the subjects were instructed to perform weekly an SRT on an outside course. All testing was to be performed at about the same time of day (within 2 h).

The subjects were asked to train at low intensity (below lactate threshold [LT] 1) and maintain the same training volume (mean 5.2 ± 1.9 times/wk) as before the study during the first 8 weeks. Thereafter, running training volume and intensity were increased during the following 8 weeks. The training was periodized so that 3 weeks of intense training were followed by an easy training week. The subjects completed 1 to 3 moderate (30–40 min, intensity between LTs 1 and 2) or high-intensity interval (4 × 4-min with 4 min of recovery or 6 × 2 min with 2 min of recovery) or constant-speed (20 min) training sessions with intensity above LT2 per intense week. Endurance training consisted primarily of running but occasionally also included cycling, Nordic walking, and/or cross-country skiing. The subjects were familiarized with the use of a Garmin FR 610 HR monitor (Garmin Ltd, Schaffhausen, Switzerland) and controlled their training intensity by measuring their HR during all exercises. In addition, the moderate- and high-intensity training sessions were supervised.

Maximal Incremental Treadmill Running Test

The subjects were asked not to perform any vigorous physical activity 2 days before the maximal incremental treadmill running test. They performed the running test for determination of maximal oxygen uptake (VO_{2max}), peak treadmill RS (RS_{peak}), LT2, and LT1 as described in the study of Vesterinen et al.[3] The test started at 7 km/h for women and 8 km/h for men, followed by an increase of 1 km/h every 3 minutes until volitional exhaustion. The incline was kept at 0.5° during the whole test. HR was recorded continuously with an HR monitor (Suunto t6, Suunto Ltd, Vantaa, Finland). VO_2 was measured breath by breath throughout the test using a portable gas analyzer (Oxycon Mobile, Viasys Health Care, Würzburg, Germany). Blood samples (20 µL) were taken from the fingertip at the end of each load to analyze blood lactate concentrations (Biosen S_line Laboratory+ lactate analyzer, EKF Diagnostic, Magdeburg, Germany). Maximal endurance performance was determined as RS_{peak} at exhaustion. If the subject could not complete the whole 3 minutes of the last speed, RS_{peak} was calculated as follows: speed of the last completed stage (km/h) + (running time [s] of the speed at exhaustion – 30 s)/(180 – 30 s) × 1 km/h. In the current study RS_{peak} was used as the main variable to describe the adaptation to endurance training during the training period.

Submaximal Running Test

An SRT was modified from the Lamberts and Lambert Submaximal Cycle Test.[7] The SRT was performed as a standardized warm-up protocol for moderate- or high-intensity training sessions taking place after at least 1 easy training day. The subjects were instructed to perform an SRT once per week on the same outdoor course each time. The 16-minute SRT consisted of 3 stages (Figure 1). The subjects were asked to set their RS according to HR corresponding to 70% (RS1), 80% (RS2), and 90% (RS3) of their maximum HR (HR_{max}) for 6, 6, and 3 minutes, by using Garmin FR 610 HR monitors with global positioning systems (GPS) (Garmin Ltd, Schaffhausen, Switzerland). The target HRs were calculated based on HR_{max} in the maximal incremental treadmill test at week 0. A rating of perceived exertion with Borg's 0-to-10 scale[15] was estimated after the last stage. HR and RS were recorded throughout the test, but the data of the first minute of each stage were excluded from analyses due to setting RS to reach the target HR. Therefore, average RS and HR were calculated over a 5-minute period (1:00–6:00 and 7:00–12:00) for stages 1 and 2 and for a 2-minute period (13:00–15:00) for stage 3. After completing the running test, the subjects were asked to stand without moving and talking for 1 minute. They were asked to breathe normally, without controlling their respiratory rate. HRR was calculated by subtracting HR after 60 seconds recovery from HR at the end of the third stage.

Statistical Analysis

The results are expressed as mean ± SD. As the aim of the current study was to investigate usefulness of an SRT in monitoring of individual adaptation to training, the subjects were retrospectively grouped into 4 clusters according to changes in the SRT results. Due to the presence of missing data values (due to sicknesses, mild injuries, or poor HR data) in time series of RS1, RS2, RS3, and HRR, a self-implemented (MATLAB R2013a) variant of the classical K-means method,[16] in which missing values are handled using the available case strategy,[17] was applied in the cluster analysis. The detailed algorithmic description of the K-means method for incomplete data can be found in Äyrämö.[18] To avoid locally optimal cluster models, 1000 clustering models were generated for each set of time series by using random restarts, and the ones with the least sum of squared within-cluster errors were selected for further analysis. Differences of changes in the maximal running test between the clusters were analyzed using a Kruskal Wallis test, followed by the Dunn-Bonferroni post hoc method, due to the small number of subjects in the clusters. Pearson product–moment correlation coefficient was used to determine the relationships between the absolute values of SRT and endurance-performance variables at week 9, as well as between changes in SRT and endurance-training adaptation after 18 weeks of training. In addition to the measures of statistical significance, the following criteria were adopted to interpret the magnitude of correlation between measurement variables: <0.1 (trivial), 0.1 to 0.3 (small), 0.3 to 0.5 (moderate), 0.5 to 0.7 (large), 0.7 to 0.9 (very large), and 0.9 to 1.0 (almost perfect).[19] Statistical significance was accepted at $P < .05$. Statistical analyses were carried out using SPSS software (IBM SPSS Statistics 20, IBM, Armonk, NY, USA).

Results

Training

Five of the 40 subjects did not complete the study due to injuries (n = 4) and lack of motivation (n = 1). Training volume remained similar during both training periods (7.1 ± 2.6 vs 6.4 ± 2.0 h/wk, 5.9 ± 2.1 vs 6.0 ± 2.1 sessions/wk). Running volume increased for the second training period from 33 ± 17 to 41 ± 16 km/wk ($P < .001$). In addition, the percentage amount of high-intensity training increased from 1% ± 2% to 4% ± 3% ($P < .001$), while the amount of low- (86% ± 9% vs 84% ± 9%) and moderate-intensity (13% ± 8% vs 12% ± 9%) training remained unaltered between the training periods.

Submaximal Running Test

The subjects were not able to perform the SRT every week due to sicknesses or mild injuries. In addition, some single-test results were not approved for analysis due to poor HR signal. On average, they repeated SRT the 13 times within the 18 weeks. The presence of missing data values in the time series of RS1, RS2, RS3, and HRR were 23.1%, 23.9%, 24.5%, and 24.9%. The subjects were able to closely regulate their HR for the target HR levels by adjusting their RS according to the GPS of the HR monitor. Mean HRs for the 3 stages were 71% ± 3%, 81% ± 1%, and 90% ± 1% of HR_{max}. Individual mean ranges were 69% to 75% during the first, 77% to 84% during the second, and 87% to 92% of HR_{max} during the third stage of the SRT. Mean rating of perceived exertion (RPE) after the SRT was 5 ± 2 during the training period.

Predictors of Endurance Performance

Correlations between the results of the SRT and endurance-performance variables are presented in Table 2. Correlations between RSs during all stages of the SRT showed very large correlations with VO_{2max}, RS_{peak}, RS at LT2, and RS at LT1, but HRR correlated only with VO_{2max}. No differences were observed between sexes in the correlations, except that HRR correlated with both VO_{2max} and RS_{peak} in women ($r = .66$, $P = .003$; $r = .63$, $P = .005$), but not in men. A similar trend was found between HRR and VO_{2max} ($r = .56$, $P = .073$) in men.

Relationships Between Changes in the SRT and Training Adaptation

All endurance-performance variables improved during the training period. VO_{2max}, RS_{peak}, and RS at LT2 and LT1 improved by 2.2% ± 6.2% ($P = .043$), 3.2% ± 4.0% ($P < .001$), 5.7% ± 4.6% ($P < .001$), and 6.5% ± 5.4% ($P < .001$), respectively. Relationships

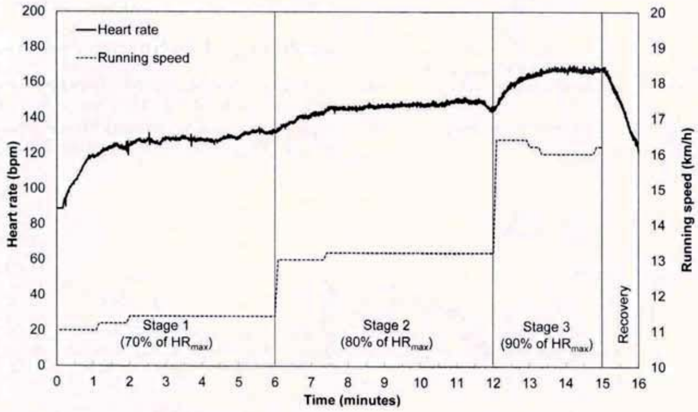


Figure 1 — An example of an arbitrary subject's training-status test including heart rate and running speed during the submaximal running test. Abbreviation: HR_{max}, maximal heart rate.

Table 2 Correlation Between the Results of the Submaximal Running Test and Endurance-Performance Variables (N = 29)

	VO_{2max} (mL · kg^{-1} · min^{-1})	RS_{peak} (km/h)	RS at LT2 (km/h)	RS at LT1 (km/h)
RS stage 1 (km/h)	.60***[b]	.74***[a]	.83***[a]	.87***[a]
RS stage 2 (km/h)	.75***[a]	.83***[a]	.89***[a]	.83***[a]
RS stage 3 (km/h)	.58***[b]	.79***[a]	.78***[a]	.71***[a]
Heart-rate recovery (beats/min)	.46*[c]	.22	.31	.22

Abbreviations: VO_{2max}, maximal oxygen consumption; RS, running speed; RS_{peak}, peak RS in the maximal treadmill test; LT2, lactate threshold 2; LT1, lactate threshold 1.

[a] Very large correlation. [b] Large correlation. [c] Moderate correlation.

Pearson's correlation: *$P < .05$, ***$P < .001$.

between the changes of variables in the SRT and the changes in endurance-performance variables after 18 weeks of training are shown in Table 3 and Figure 2. The changes in RS 2 and RS 3 of the SRT correlated significantly with the change in VO_{2max}, RS_{peak}, and RS at LTs. No sex differences were observed in the correlations.

Time series of the changes in RS of the SRT for the clusters are presented in Figure 3. The clusters based on the change in RS 2 showed differences between the clusters in the change of VO_{2max} ($P = .038$) and RS_{peak} ($P = .008$). Cluster 1, which showed the greatest improvement in RS 2, improved more in RS_{peak} than clusters 2 and 3 ($P = .004$). The clusters grouped by the change in RS 3 also showed differences in the change of VO_{2max} ($P = .009$) and RS_{peak} ($P = .004$) and RS at LT2 ($P = .042$). Clusters 1 and 2 showed significantly greater improvements in RS_{peak} than clusters 3 and 4. The clusters grouped by the changes in RS 1, HRR, and RPE showed no differences in the change of any endurance-performance variables.

Table 3 Correlations Between the Changes in Endurance-Performance Variables and the Changes in the Submaximal Running Test (N = 26) After 18 Weeks of Training

	VO_{2max} (%)	RS_{peak} (%)	RS at LT2 (%)	RS at LT1 (%)
RS stage 1 (%)	.34	.24	.27	.34
RS stage 2 (%)	.60**[b]	.57**[b]	.43*	.48*
RS stage 3 (%)	.62***[b]	.79***[a]	.74***[a]	.52**[b]
Heart-rate recovery (%)	.13	−.01	.21	.37

Abbreviations: VO_{2max}, maximal oxygen consumption; RS, running speed; RS_{peak}, peak RS in the maximal treadmill test; LT2, lactate threshold 2; LT1, lactate threshold 1.

[a] Very large correlation. [b] Large correlation. [c] Moderate correlation.

Pearson's correlation: *$P < .05$, **$P < .01$, ***$P < .001$.

Discussion

The main finding of the current study describes the relationships between the changes in RS during the second and third stages of the SRT and change in the endurance-performance variables after the training period. In addition, the cluster analysis revealed different trends in RS in the second and third stages between the clusters, which also showed differences in the improvement of VO_{2max} and RS_{peak} after the 18-week training period.

The subjects successfully regulated RS themselves for the target HR levels in outdoor conditions during the SRT. The intensity of the third stage (90% of HR_{max}) seems to be the most reasonable for exact regulation of HR according to the small individual range of HRs. These findings are in accordance with previous studies related to SRTs.[20,21] The SRT was designed to be the standardized warm-up protocol for main training sessions, without interfering with normal training. Although all subjects were not able to do the SRT every week during the training period, due to sicknesses or mild injuries, they were able to repeat it regularly (mean: 13 times within 17 wk). HR levels and RPE of the stages showed that the SRT protocol was truly submaximal, did not cause remarkable training load, and thus is a suitable warm-up protocol for high-intensity exercise.

Predictors of Endurance Performance

Very large correlations were found between the variables of the SRT, especially RS 2, RS 3, and RS_{peak} (Table 2). This finding suggests that running intensity should achieve the level of 80% to 90% of HR_{max} to predict maximal endurance-performance variables

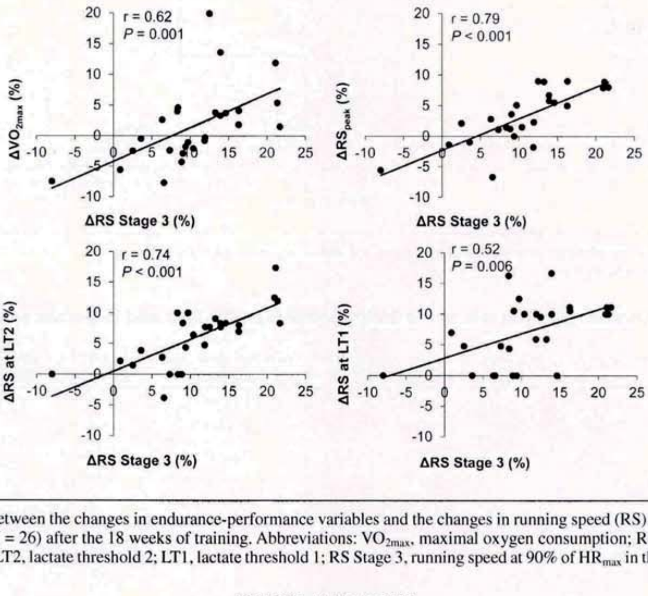


Figure 2 — Correlations between the changes in endurance-performance variables and the changes in running speed (RS) during the third stage in the submaximal running test (N = 26) after the 18 weeks of training. Abbreviations: VO_{2max}, maximal oxygen consumption; RS_{peak}, peak running speed in the maximal treadmill test; LT2, lactate threshold 2; LT1, lactate threshold 1; RS Stage 3, running speed at 90% of HR_{max} in the submaximal running test.

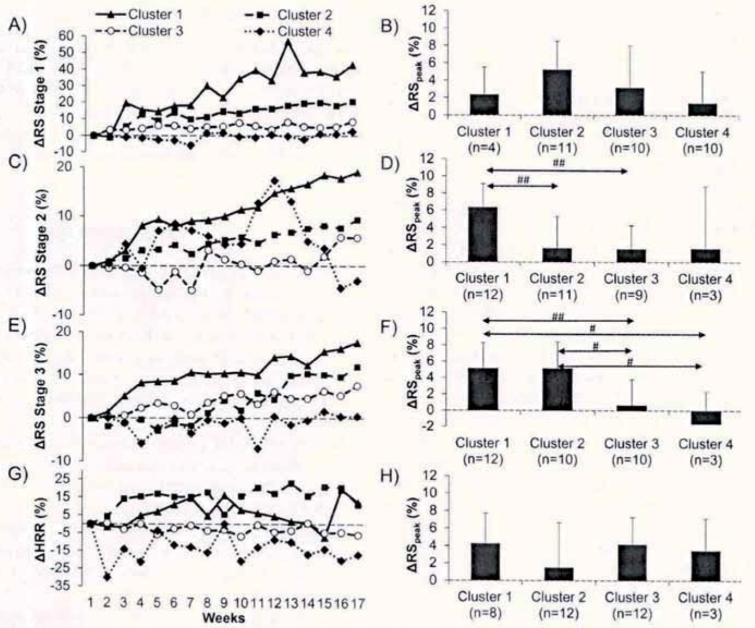


Figure 3 — Representative time series for the clusters based on the changes of running speed (RS) in the (A) first, (C) second, and (E) third stage; (G) change in heart-rate recovery (HRR); and changes in peak running speed in the maximal treadmill test (RS_{peak}) for the clusters based on changes of (B) RS 1, (D) RS 2, (F) RS 3, and (H) HRR. Between-clusters differences in change of RS_{peak}: #$P < .05$, ##$P < .01$ (revealed by Kruskal-Wallis test).

(VO_{2max}, RS_{peak}), which supports the findings of Lamberts et al[7] and Otter et al.[14] Previously, slightly higher correlations were found between cycling power corresponding the intensity of 80% ($r = .88$) and 90% ($r = .94$) of HR_{max} and peak cycling performance[7] and between rowing power at 90% of HR_{max} and 2000-m maximal rowing time ($r = -.93$),[14] which may be explained by more standardized testing conditions (laboratory) than in the current study (outdoor conditions). In addition, we observed that the best predictor for RS at LT2 was RS at 80% of HR_{max} in the SRT and for RS at LT1 RS at 70% of HR_{max}. This is reasonable because RSs of those stages are close to RSs of the LTs. Postexercise HRR has been shown to reflect cardiac autonomic activity and training adaptation.[4,8,13] In the current study, HRR after the SRT correlated moderately with VO_{2max} but not with endurance performance. The current finding indicates that faster cardiorespiratory recovery after exercise is related to a greater aerobic capacity as reported by Daanen et al.[22]

Monitoring of Training Adaptation

The main finding of the current study was that the changes of RS 2 and RS 3 in the SRT were able to reflect changes in the endurance-performance variables (VO_{2max}, RS_{peak}, RS at LT2, RS at LT1). In addition, the cluster analysis revealed that it is possible to identify the lowest and highest responders during training based on the changes in RS at 80% and 90% of HR_{max}. Furthermore, the trends of the changes in RS at 90% of HR_{max} allow more exact identification of the amount of improvement in maximal endurance performance in the 4 clusters. Previously, Buchheit et al[4] observed that the change in exercise HR during an SRT at 60% intensity of maximal aerobic speed were not different between responders and nonresponders during an 8-week training program. According to the current findings, intensity of 80% to 90% of HR_{max} is needed to monitor the changes in endurance-performance variables during training. Previously, we observed that the change of HR-RS index measured from every continuous-type running exercise correlated moderately ($r = .43–.61$) with the change of maximal RS during 28 weeks of endurance training.[10] However, many external (such as duration and intensity of exercise) and internal factors (eg, level of hydration, body temperature, cardiac drift) may disturb the use of the relation between RS and HR[11,12,23] as a tool to monitor training adaptation. The standardized duration and intensity of the protocol in the current study decreased possible disturbing factors and thus may explain larger correlations between the changes in RS of the SRT and the change in the endurance-performance variables in the current study compared with our previous findings.[10]

The novel current finding that RS in an SRT can be used to monitor training adaptation is based on the observations about the relation between decreased exercise HR and positive improvements in endurance performance.[4–6,10] However, it has to be kept in mind that negative training adaptation, in the case of short-term overreaching or overtraining, may be related to decreased exercise and HR_{max}.[24,25] On the other hand, RPE may increase at submaximal levels in overreaching or overtraining states because one should work harder to achieve the same HR level due to higher intensity if HR_{max} is reduced.[24] Therefore, RPE together with the data of RS give reasonable information about training adaptation. In the current study, RPE remained stable in the clusters, which does not express any signs of overreaching.

Previously, Lamberts et al[13] observed relationships between a change in HRR after a 40-km cycling time trial and changes in maximal cycling performance ($r = .73–.95$) after 4 weeks of high-intensity training. Furthermore, HRR has been associated with the change in training load and endurance performance.[8,26] In contrast to the previous studies, we did not observe any relationships between the change in HRR and the changes in endurance variables. Instead, our finding is in line with the studies of Buchheit et al[27,28] and Otter et al.[14] The absence of the relationship can be explained by the relatively homogeneous group of subjects in the current study. It seems that the relation is weaker in homogeneous groups.[14] The contradicting findings between the studies can also be explained with different protocols in the measurements, such as durations and intensities of exercises, as well as time frames, when HRR is measured. On the other hand, intensity during the third stage was exactly the same (87–92% of HR_{max}) as the recommendation of Lamberts et al[29] that exercise intensity should be 86% to 93% of HR_{max} to achieve the highest level of sensitivity in detecting meaningful changes in HRR. Future studies should focus more on the effects of methodological issues in measuring postexercise HRR.

A limitation of the current study was a relatively small number of subjects, which did not allow systematic comparison between sexes. In addition, missing values due to sicknesses, injuries, or incorrect HR or GPS data in weekly SRTs may cause some fluctuation in the trends because of large variation between individuals. Therefore, repeated ANOVA was not suitable as a statistical method. Instead, cluster analysis can be used in the presence of missing values.

Practical Applications

RSs at 80% and 90% of HR_{max}, which were previously observed to predict endurance performance in cycling[13] and rowing,[14] were the most competent variables to reflect changes in maximal running performance during training. Furthermore, monitoring the change in RS at 90% of HR_{max} makes it possible to identify individuals who fail positive adaptation during training. This is essential information for coaches and athletes and enables them to adjust training programs to achieve better outcomes. Regardless of the absence of a relation between the change in HRR and training adaptation in the current study, HRR has been proposed to reflect the change in training load[13] and describe aerobic fitness,[22] as in the current study. Therefore, we recommended that an SRT include measurements of RS (at 80–90% of HR_{max} intensities), postexercise HRR, and RPE to monitor the status of cardiorespiratory and cardiac autonomic regulation. The submaximal test shows great potential as a practical tool for regular monitoring of individual adaptation to endurance training in field conditions.

Conclusions

RS during the SRT was able to predict maximal endurance performance. This study also showed that RS at 80% to 90% HR_{max} during an SRT was able to monitor endurance-training adaptation in recreational endurance runners. Future studies should assess whether individualizing training programs on the basis of an SRT would be more productive than a traditional, predetermined training program.

Acknowledgments

The results of the current study do not constitute endorsement of the product by the authors or the journal. Funding of this study was provided by the Finnish Ministry of Education and Culture. The study was conducted in KIHU—Research Institute for Olympic Sports in collaboration with the University of Jyväskylä, Department of Biology of Physical Activity. The authors wish to thank Sirpa Vänttinen for her expert assistance during this study, as well as the subjects for their participation.

References

1. Bouchard C, Rankinen T. Individual differences in response to regular physical activity. *Med Sci Sports Exerc*. 2001;33(6 Suppl):S446–S451; disc S452–S453. doi:10.1097/00005768-200106001-00013
2. Vollaard NB, Constantin-Teodosiu D, Fredriksson K, et al. Systematic analysis of adaptations in aerobic capacity and submaximal energy metabolism provides a unique insight into determinants of human aerobic performance. *J Appl Physiol*. 2009;106(5):1479–1486. PubMed doi:10.1152/japplphysiol.91453.2008
3. Vesterinen V, Hakkinen K, Hynynen E, Mikkola J, Hokka L, Nummela A. Heart rate variability in prediction of individual adaptation to endurance training in recreational endurance runners. *Scand J Med Sci Sports*. 2013;23(2):171–180. PubMed doi:10.1111/j.1600-0838.2011.01365.x
4. Buchheit M, Chivot A, Parouty J, et al. Monitoring endurance running performance using cardiac parasympathetic function. *Eur J Appl Physiol*. 2010;108(6):1153–1167. PubMed doi:10.1007/s00421-009-1317-x
5. Scharhag-Rosenberger F, Meyer T, Walitzek S, Kindermann W. Time course of changes in endurance capacity: a 1-yr training study. *Med Sci Sports Exerc*. 2009;41(5):1130–1137. PubMed doi:10.1249/MSS.0b013e3181935a11
6. Borresen J, Lambert MI. Autonomic control of heart rate during and after exercise: measurements and implications for monitoring training status. *Sports Med*. 2008;38(8):633–646. PubMed doi:10.2165/00007256-200838080-00002
7. Lamberts RP, Swart J, Noakes TD, Lambert MI. A novel submaximal cycle test to monitor fatigue and predict cycling performance. *Br J Sports Med*. 2011;45:797–804. PubMed doi:10.1136/bjsm.2009.061325
8. Lamberts RP, Swart J, Capostagno B, Noakes TD, Lambert MI. Heart rate recovery as a guide to monitor fatigue and predict changes in performance parameters. *Scand J Med Sci Sports*. 2010;20(3):449–457. PubMed doi:10.1111/j.1600-0838.2009.00977.x
9. Lamberts RP. Predicting cycling performance in trained to elite male and female cyclists. *Int J Sports Physiol Perform*. 2014;9(4):610–614. PubMed doi:10.1123/IJSPP.2013-0040a
10. Vesterinen V, Hokka L, Hynynen E, Mikkola J, Hakkinen K, Nummela A. Heart rate-running speed index may be an efficient method of monitoring endurance training adaptation. *J Strength Cond Res*. 2014;28(4):902–908. PubMed doi:10.1519/JSC.0000000000000349
11. Lambert MI, Mbambo ZH, St Clair Gibson A. Heart rate during training and competition for long-distance running. *J Sports Sci*. 1998;16(Suppl):S85–S90. PubMed doi:10.1080/026404198366713
12. Achten J, Jeukendrup AE. Heart rate monitoring: applications and limitations. *Sports Med*. 2003;33(7):517–538. PubMed doi:10.2165/00007256-200333070-00004
13. Lamberts RP, Swart J, Noakes TD, Lambert MI. Changes in heart rate recovery after high-intensity training in well-trained cyclists. *Eur J Appl Physiol*. 2009;105(5):705–713. PubMed doi:10.1007/s00421-008-0952-y

14. Otter RT, Brink MS, Lamberts RP, Lemmink KA. A new submaximal rowing test to predict 2000 meter rowing ergometer performance. *J Strength Cond Res*. 2015;29(9):2426–2433. PubMed doi:10.1519/JSC.0000000000000902
15. Borg GA. Psychophysical bases of perceived exertion. *Med Sci Sports Exerc*. 1982;14(5):377–381. PubMed doi:10.1249/00005768-198205000-00012
16. MacQueen J. Some methods for classification and analysis of multivariate observations. In: Le Cam LM, Neyman J, eds. *Proceedings of the Fifth Berkeley Symposium on Mathematical Statistics and Probability*. 1st ed. Berkeley: University of California Press; 1967:281–297.
17. Little RJ, Rubin DB. *Statistical Analysis With Missing Data*. New York: John Wiley & Sons; 1987.
18. Äyrämö S. *Knowledge mining using robust clustering* [doctoral dissertation]. Department of Mathematical Information Technology, University of Jyväskylä; Jyväskylä, Finland; 2006.
19. Hopkins WG, Marshall SW, Batterham AM, Hanin J. Progressive statistics for studies in sports medicine and exercise science. *Med Sci Sports Exerc*. 2009;41(1):3–13. PubMed doi:10.1249/MSS.0b013e31818cb278
20. Lamberts RP, Lambert MI. Day-to-day variation in heart rate at different levels of submaximal exertion: implications for monitoring training. *J Strength Cond Res*. 2009;23(3):1005–1010. PubMed doi:10.1519/JSC.0b013e3181a2dcdc
21. Lamberts RP, Lemmink KA, Durandt JJ, Lambert MI. Variation in heart rate during submaximal exercise: implications for monitoring training. *J Strength Cond Res*. 2004;18(3):641–645. PubMed
22. Daanen HA, Lamberts RP, Kallen VL, Jin A, Van Meeteren NL. A systematic review on heart-rate recovery to monitor changes in training status in athletes. *Int J Sports Physiol Perform*. 2012;7(3):251–260. PubMed
23. Boudet G, Albuisson E, Bedu M, Chamoux A. Heart rate running speed relationships-during exhaustive bouts in the laboratory. *Can J Appl Physiol*. 2004;29(6):731–742. PubMed doi:10.1139/h04-047
24. Le Meur Y, Hausswirth C, Natta F, Couturier A, Bignet F, Vidal PP. A multidisciplinary approach to overreaching detection in endurance trained athletes. *J Appl Physiol (1985)*. 2013;114(3):411–420.
25. Uusitalo AL, Uusitalo AJ, Rusko HK. Endurance training, overtraining and baroreflex sensitivity in female athletes. *Clin Physiol*. 1998;18(6):510–520. PubMed doi:10.1046/j.1365-2281.1998.00121.x
26. Borresen J, Lambert MI. Changes in heart rate recovery in response to acute changes in training load. *Eur J Appl Physiol*. 2007;101(4):503–511. PubMed doi:10.1007/s00421-007-0516-6
27. Buchheit M, Simpson MB, Al Haddad H, Bourdon PC, Mendez-Villanueva A. Monitoring changes in physical performance with heart rate measures in young soccer players. *Eur J Appl Physiol*. 2012;112(2):711–723. PubMed doi:10.1007/s00421-011-2014-0
28. Buchheit M, Racinais S, Bilsborough JC, et al. Monitoring fitness, fatigue and running performance during a pre-season training camp in elite football players. *J Sci Med Sport*. 2013;16(6):550–555. PubMed doi:10.1016/j.jsams.2012.12.003
29. Lamberts RP, Maskell S, Borresen J, Lambert MI. Adapting workload improves the measurement of heart rate recovery. *Int J Sports Med*. 2011;32(9):698–702. PubMed doi:10.1055/s-0031-1275357

V

Individual Endurance Training Prescription with Heart Rate Variability

by

V. Vesterinen, A. Nummela, I. Heikura, T. Laine, E. Hynynen, J. Botella &
K. Häkkinen. 2016

Medicine and Science in Sports & Exercise, 48: 1347-1354.

Individual Endurance Training Prescription with Heart Rate Variability

VILLE VESTERINEN[1], ARI NUMMELA[1], IDA HEIKURA[2], TANJA LAINE[1], ESA HYNYNEN[1],
JAVIER BOTELLA[2], and KEIJO HÄKKINEN[2]

[1]KIHU—Research Institute for Olympic Sports, Jyväskylä, FINLAND; and [2]Department of Biology of Physical Activity, University of Jyväskylä, Jyväskylä, FINLAND

ABSTRACT

VESTERINEN, V., A. NUMMELA, I. HEIKURA, T. LAINE, E. HYNYNEN, J. BOTELLA, and K. HÄKKINEN. Individual Endurance Training Prescription with Heart Rate Variability. *Med. Sci. Sports Exerc.*, Vol. 48, No. 7, pp. 1347–1354, 2016. **Introduction**: Measures of HR variability (HRV) have shown potential to be of use in training prescription. **Purpose**: The aim of this study was to investigate the effectiveness of using HRV in endurance training prescription. **Methods**: Forty recreational endurance runners were divided into the HRV-guided experimental training group (EXP) and traditional predefined training group (TRAD). After a 4-wk preparation training period, TRAD trained according to a predefined training program including two to three moderate- (MOD) and high-intensity training (HIT) sessions per week during an 8-wk intensive training period. The timing of MOD and HIT sessions in EXP was based on HRV, measured every morning. The MOD/HIT session was programmed if HRV was within an individually determined smallest worthwhile change. Otherwise, low-intensity training was performed. Maximal oxygen consumption ($\dot{V}O_{2max}$) and 3000-m running performance (RS_{3000m}) were measured before and after both training periods. **Results**: The number of MOD and HIT sessions was significantly lower ($P = 0.021$, effect size = 0.98) in EXP (13.2 ± 6.0 sessions) compared with TRAD (17.7 ± 2.5 sessions). No other differences in training were found between the groups. RS_{3000m} improved in EXP (2.1% ± 2.0%, $P = 0.004$) but not in TRAD (1.1% ± 2.7%, $P = 0.118$) during the intensive training period. A small between-group difference (effect size = 0.42) was found in the change in RS_{3000m}. $\dot{V}O_{2max}$ improved in both groups (EXP: 3.7% ± 4.6%, $P = 0.027$; TRAD: 5.0% ± 5.2%, $P = 0.002$). **Conclusion**: The results of the present study suggest the potential of resting HRV to prescribe endurance training by individualizing the timing of vigorous training sessions.

Key Words: RUNNING TRAINING, TRAINING ADAPTATION, AUTONOMIC NERVOUS SYSTEM, VAGAL ACTIVITY, TRAINING PROGRAMMING

Large individual variation in training adaptation has been observed after standardized endurance training. It is typical that some individuals show great improvements (even to 40%) in maximal oxygen uptake ($\dot{V}O_{2max}$) or endurance performance after standardized endurance training, whereas some individuals show no changes or sometimes even a decrement in endurance performance (5,7,36). In our previous study (34), a slightly smaller variation in improvement of endurance performance was observed after 8 wk of both high-intensity training (HIT) (0% to 10.2%) and low-intensity training (LIT) (−2.8% to 4.1%) when training volume and frequency were individualized according to individuals' previous training history. However, some nonresponders (change in endurance performance ≤0%) were observed, which proposes that a more precisely and comprehensively individualized training program would be beneficial for achieving greater improvements and smaller variation in the adaptation to training.

Cardiac autonomic regulation is an important determinant of endurance training adaptation. Baseline vagal-mediated resting HR variability (HRV) has been shown to be related to greater improvements in $\dot{V}O_{2max}$ and endurance performance after endurance training in different populations (2,12,13,33,34). In addition, increased resting HRV during a training period has been related to improvements of endurance performance or $\dot{V}O_{2max}$ (6,7,10,12,22).

It has been proposed that training prescription according to the status of cardiac vagal activity may be a beneficial method to improve endurance training adaptation. Kiviniemi et al. (18,19) expressed promising results while using HRV

Address for correspondence: Ville Vesterinen, M.Sc., KIHU—Research Institute for Olympic Sports, Rautpohjankatu 6, 40700 Jyväskylä, Finland;
E-mail: ville.vesterinen@kihu.fi.

Submitted for publication November 2015.
Accepted for publication February 2016.

0195-9131/16/4807-1347/0
MEDICINE & SCIENCE IN SPORTS & EXERCISE®

DOI: 10.1249/MSS.0000000000000910

in daily training prescription. Individuals who were prescribed HIT sessions according to HRV showed greater improvements in $\dot{V}O_{2max}$ among moderately fit men (19) and in endurance performance among healthy individuals (18,19) compared with individuals who trained according to a traditional predefined training program. Women benefitted from HRV guidance by achieving the same significant improvement in endurance performance with a lower amount of HIT compared with predefined training (18,19). In the studies by Kiviniemi et al. (18,19), training prescription was based on daily single-HRV measurements. However, Plews et al. (24) suggested that it is more valuable to use longer trends of HRV, e.g., a week rolling average, compared with assessing its value on a single day. In addition, Plews et al. (25) proposed to use the individual's own HRV profile, the individually determined smallest worthwhile change (SWC), which reflects normal values of HRV, in interpreting HRV values and training prescription.

Although determinants of endurance performance are widely accepted, the optimal training volume and intensity distribution is still indefinite (31). The majority of endurance training studies present a high proportion of high-volume LIT among endurance athletes, and also a polarized training model with a higher amount of HIT has been proposed to be an effective training model especially in high-level athletes (21,30). Furthermore, increasing training intensity also in sedentary adults would be more effective compared with increasing training volume (28). Recent studies have shown that changing the periodization of LIT and HIT without changing the training intensity distribution may have a positive effect on performance improvement (26,27). Traditionally, periodized endurance training includes usually single-HIT sessions, e.g., two times per week, simultaneous with LIT and moderate-intensity training (MOD) trying to develop many fitness components at the same time. On the contrary, block training includes shorter training periods (1–4 wk), when the aim is to develop a few selected fitness components (17). Recently, it has been suggested that block periodization of HIT may provide superior training adaptation compared with traditionally organized HIT (26,27). However, the timing of HIT blocks has been typically determined subjectively without objective information about the athlete's training status. A good recovery status may be needed before an intense training block to avoid imbalance between training load and recovery.

Endurance training programs are typically predetermined based on the literature, general recommendations, and experience of coaches regardless of objective information about the athlete's training and recovery status. In addition, adaptation to endurance training is individualized, and the same training program would not be optimal for everyone in spite of similar training background. Furthermore, more individualized, objective training prescription may improve training adaptation. The aim of this study was to investigate the effectiveness of using HRV averaged over 7 d in endurance training prescription for endurance training adaptation compared with traditional predefined endurance training in recreational endurance runners. It was hypothesized that HRV-guided training would result in greater adaptations to training (18,19).

METHODS

Subjects. Forty recreational endurance runners (20 women and 20 men) were recruited to participate in the study through advertisement in the local newspaper and social media. The minimal sample size was determined based on the data of Vesterinen et al. (35) and Stöggl and Sperlich (30) (expected changes in maximal running speed, 3% ± 3% and 5% ± 3%). *A priori* power analysis suggested that 16 subjects were required for both groups to achieve 80% power and a significance level of 5%. The subjects did not have any diseases or use regular (e.g., daily) medication for any kind of chronic or long-term diseases. They had at least 2 yr of regular endurance running training background. Age, $\dot{V}O_{2max}$, regular training background, and weekly running kilometers during the previous 2 months were 34 ± 8 yr, 49 ± 4 $mL \cdot kg^{-1} \cdot min^{-1}$, 13 ± 8 yr, and 34 ± 22 km, respectively, for women and 35 ± 7 yr, 56 ± 5 $mL \cdot kg^{-1} \cdot min^{-1}$, 15 ± 8 yr, and 39 ± 19 km, respectively, for men. After being fully informed about the study design and the possible risks, all subjects provided a written informed consent document. The study was approved by the ethics committee of the local university.

Study design. The study protocol included two training periods: a 4-wk preparation period (PREP) and an 8-wk intensive training period (INT). All measurements were performed before and after both training periods on weeks 0, 5, and 14. For INT, the subjects were matched into pairs according their baseline background (sex, age, and training background), endurance performance characteristics ($\dot{V}O_{2max}$, 3000-m running time), and HRV. Thereafter, within each pair, the runners were randomized into the HRV-guided experimental training group (EXP) and traditional predefined training group (TRAD).

Maximal running tests. The subjects were asked not to do any vigorous physical activity 2 d before the running tests. The subjects performed an incremental treadmill test, starting at 7 $km \cdot h^{-1}$ for women and at 8 $km \cdot h^{-1}$ for men, and were followed by an increase of 1 $km \cdot h^{-1}$ every third minute until volitional exhaustion. The incline was kept at 0.5° during the whole test. HR was recorded continuously using an HR monitor (Suunto t6; Suunto Ltd., Vantaa, Finland). Oxygen consumption was measured breath by breath throughout the test using a portable spiroergometer (Oxycon mobile; Viasys Health Care, Würzburg, Germany). After each 3-min stage, the treadmill was stopped for about 15–20 s for fingertip blood samples (20 μL) and blood lactate analysis. Blood lactate was determined using a Biosen S_line Lab + lactate analyzer (EKF Diagnostic, Magdeburg, Germany). The highest 60-s $\dot{V}O_2$ value during the treadmill test was considered as the maximal oxygen uptake ($\dot{V}O_{2max}$). The determination of lactate thresholds was based on a rise and change in the inclination of the blood lactate curve during the test (11). Lactate threshold 1 (LT1) was set at 0.3 $\text{mmol}\cdot\text{L}^{-1}$ above the lowest lactate value. Lactate threshold 2 (LT2) was set 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 with a lactate increase of at least 0.8 $\text{mmol}\cdot\text{L}^{-1}$.

For the determination of maximal endurance performance, the subjects performed the 3000-m running test on a 200-m indoor track before and after both training periods. Time and a mean running speed of 3000 m (RS_{3000m}) were calculated. At least two easy training days were prescribed between the treadmill test and the 3000-m running test.

Training. During PREP, all subjects were asked to maintain the same training volume as that before the study. The period followed a periodization model of three hard training weeks followed by an easy training week with progressively increasing intensity throughout the period (Table 1). Endurance training was mainly running, but the subjects were encouraged to do at least one easy session per week in some other training mode than running (i.e., cycling or cross-country skiing). In addition, muscle endurance circuit training was instructed to be performed once a week.

Predefined training. For INT, all subjects were instructed to maintain the same training volume as that during PREP. TRAD trained according to a predefined training program, which included approximately 50% of weekly training sessions performed at LIT (below LT1) and the other 50% at MOD/HIT, with the week periodization 3/1 as that during PREP (Table 1). The main training sessions at moderate and high intensities were similar to the training sessions during PREP in both groups.

HRV-guided training. All subjects in EXP were instructed to measure their R–R interval data at home every morning after awakening and emptying their urinary bladder. Omegawave Pro Mobile System, with a two-lead chest belt (Omegawave Ltd., Helsinki, Finland), was used to record R–R intervals. Four minutes of recording was performed in supine position, and the subjects were allowed to breathe spontaneously. R–R interval data were analyzed using the Omegawave cloud service, and the vagal-mediated square root of the mean squared differences of successive R–R intervals (RMSSD) was selected to be used in training prescription because of its greater reliability than other HRV spectral indices (1). Furthermore, a 7-d rolling average of RMSSD ($RMSSD_{7d}$) was calculated because it has been proposed to be more sensitive to track changes in the training status compared with single-day values (24).

The basic idea of using HRV in endurance training prescription was to decrease training intensity when cardiac vagal activity differed meaningfully from the regular level based on the findings of Plews et al. (24,25). Thus, the SWC of $RMSSD_{7d}$ for each subject in EXP was determined, as mean ± 0.5 SD, from RMSSD values of 4 wk over PREP based on observations by Plews et al. (24,25) and Kiviniemi et al. (18,19) (Fig. 1). When $RMSSD_{7d}$ was within the SWC, only MOD and HIT sessions were performed. If $RMSSD_{7d}$ fell outside the SWC, the subjects trained only at low intensities or rested. When $RMSSD_{7d}$ returned to the mean level of the SWC, the subjects started to perform MOD and HIT sessions and continued until $RMSSD_{7d}$ fell outside the SWC. The subjects maintained the same number of training sessions and rest days every week compared with PREP regardless of HRV. The SWC was updated after the first 4 wk of INT based on the values over the previous 4 wk because of previous findings about a relationship between an increment of resting cardiac autonomic activity and improved endurance performance (6,7,22).

Training monitoring. The subjects controlled their training intensity by measuring their HR and RS during all exercises using the Garmin FR 610 HR monitor with GPS (Garmin Ltd., Schaffhausen, Switzerland). In addition, the subjects rated their perceived exertion (RPE) and recovery feelings using the scale of 0–10 after each training session (3) and reported possible other stress factors, e.g., sicknesses, injuries, and work/school stress, in their training diary via a cloud service. HR data were used to determine the times at the three different training intensity zones: low

TABLE 1. Week template of the predefined training program for both groups over weeks 0 to 5 and for predefined group (TRAD) over weeks 6 to 14.

Weeks	Week Periodization	Test Runs	HIT Constant Run	Intervals	Moderate Run	Low-Intensity Run (Intensity < LT1)
0	Test	3000-m run, $\dot{V}O_{2max}$ test				
1	Int				30′ at 80%–85%	3–6 km × 6–12 km
2	Int			4′ × 4′ at 90%–95%/rec 3′	40′ at 80%–85%	2–5 km × 6–12 km
3	Int		30′ at 85%–90%	4′ × 4′ at 90%–95%/rec 3′	40′ at 80%–85%	2–5 km × 6–12 km
4	Rec					3–5 km × 6–12 km
5	Test	$\dot{V}O_{2max}$ test				3–5 km × 6–12 km
6	Int	3000-m run	30′ at 85%–90%		40′ at 80%–85%	2–4 km × 6–12 km
7	Int		30′ at 85%–90%	4′ × 4′ at 90%–95%/rec 3′	40′ at 80%–85%	2–4 km × 6–12 km
8	Int		30′ at 85%–90%	4′ × 4′ at 90%–95%/rec 3′	40′ at 80%–85%	2–4 km × 6–12 km
9	Rec					3–5 km × 6–12 km
10	Int		30′ at 85%–90%	4′ × 4′ at 90%–95%/rec 3′	40′ at 80%–85%	2–4 km × 6–12 km
11	Int		30′ at 85%–90%	4′ × 4′ at 90%–95%/rec 3′	40′ at 80%–85%	2–4 km × 6–12 km
12	Int		30′ at 85%–90%	4′ × 4′ at 90%–95%/rec 3′	40′ at 8%–85%	2–4 km × 6–12 km
13	Rec			4′ × 4′ at 90%–95%/rec 3′		3–4 km × 6–12 km
14	Test	3000-m run, $\dot{V}O_{2max}$ test				2–4 km × 6–12 km

Training intensities are expressed as a percentage of maximal HR.

All moderate- and high-intensity sessions started with a 15- to 20-min warm-up and were followed by a 15-min cool down. Moderate- and high-intensity runs were instructed to be performed after rest or easy training day. If the number of all training sessions per week was ≤4, only two moderate-/high-intensity runs were instructed to be performed per week.

Int, intensive training week; Rec, recovery week; Test, testing week; rec, recovery between intervals (intensity < LT1).

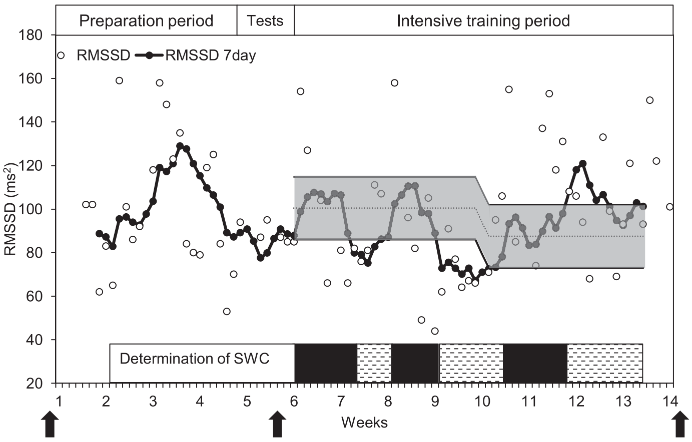


FIGURE 1—Example of programming moderate- and high-intensity sessions in the HRV-guided EXP. The *gray area* indicates the SWC of RMSSD. The black area indicates timing of MOD and HIT. The *dashed line area* indicates timing of LIT. The *arrows* represent timing of the running tests.

(below LT1), moderate (between LT1 and LT2), and high (above LT2) intensities. Weekly main training sessions were supervised by experienced members of the research group.

Statistical analysis. The results are expressed as means ± SD. The Gaussian distribution of the data was assessed using the Shapiro–Wilk goodness-of-fit test. The adaptation to training was analyzed using repeated measures of ANOVA followed by Bonferroni as a *post hoc* test. Differences in the training adaptation between EXP and TRAD were analyzed using Student's *t*-test for independent samples and between sexes using the Kruskal–Wallis test. In addition, the magnitudes of changes after training and differences between groups were expressed as standardized effect sizes (ES), calculated from pooled means and SD (15). The threshold values for Cohen's ES statistics were <0.2 (trivial), 0.2–0.5 (small), 0.5–0.8 (moderate), and >0.8 (large) (8). Pearson's product–moment correlation coefficient was used to determine the relationships between the amount of MOD/HIT sessions and the training adaptation (change in RS_{3000m} and $\dot{V}O_{2max}$). Statistical significance was accepted as $P \leq 0.05$. Statistical analyses were carried out using SPSS Statistics 20 software (IBM, Armonk, NY).

TABLE 2. Training characteristics of HRV-guided experimental (EXP) and predefined (TRAD) training groups over the preparation (PREP, weeks 1–4) and intensive (INT, weeks 6–13) training periods presented as means ± SD.

	EXP (*n* = 13)		TRAD (*n* = 18)	
	PREP	**INT**	**PREP**	**INT**
Training ($h \cdot wk^{-1}$)	7.1 ± 3.0	6.5 ± 2.8	7.0 ± 2.7	6.3 ± 2.5
Running ($km \cdot wk^{-1}$)	43 ± 18	42 ± 22	40 ± 23	41 ± 20
Training (times per week)	6.0 ± 1.7	6.1 ± 1.8	5.9 ± 1.8	5.6 ± 1.6
Low intensity (%)	89 ± 8	83 ± 27	88 ± 9	84 ± 12
Moderate intensity (%)	10 ± 7	14 ± 25	10 ± 8	13 ± 10
High intensity (%)	2 ± 3	3 ± 5	1 ± 2	3 ± 4

Low intensity, intensity below LT1; moderate intensity, intensity between LT1 and LT2; high intensity, intensity above LT2.

RESULTS

A total of 31 subjects (13 in EXP and 18 in TRAD) completed the whole study. Nine subjects dropped out because of injuries (*n* = 2), sicknesses (*n* = 2), and insufficient compliance with the training program (i.e., <90% of all training sessions in EXP and more than two main training sessions missing in TRAD during INT, *n* = 5).

No differences were observed between the groups in training during PREP (Table 2). Training volume remained similar between PREP and INT. In addition, proportions of times in different training zones remained similar. The number of MOD and HIT sessions over INT was significantly lower (*P* = 0.021, ES = 0.98) in EXP (13.2 ± 6.0 sessions) compared with TRAD (17.7 ± 2.5 sessions). Individual ranges in the number of MOD/HIT sessions were from 5 to 24 sessions in EXP and from 11 to 21 sessions in TRAD.

TABLE 3. Endurance performance variables in EXP and TRAD before (week 5) and after (week 14) the 8-wk INT.

	$\dot{V}O_{2max}$ ($mL \cdot kg^{-1} \cdot min^{-1}$)	RS_{3000m} ($km \cdot h^{-1}$)	RS_{LT2} ($km \cdot h^{-1}$)	RS_{LT1} ($km \cdot h^{-1}$)
EXP (*n* = 13)				
Week 5	54.4 ± 6.2	15.4 ± 1.6	13.4 ± 1.4	11.0 ± 1.2
Week 14	56.4 ± 7.0	15.7 ± 1.5	13.8 ± 1.3	11.3 ± 1.2
% change	3.7 ± 4.6*	2.1 ± 2.0**	2.6 ± 3.3*	2.8 ± 3.7*
ES (rating)	0.40 (small)	0.54 (mod)	0.38 (small)	0.37 (small)
TRAD (*n* = 18)				
Week 5	53.0 ± 5.8	15.0 ± 1.6	12.8 ± 1.6	10.6 ± 1.4
Week 14	55.5 ± 5.8	15.2 ± 1.5	13.1 ± 1.5	10.7 ± 1.5
% change	5.0 ± 5.2**	1.1 ± 2.7 (NS)	1.9 ± 2.2**	1.0 ± 2.9 (NS)
ES (rating)	0.49 (small)	0.14 (trivial)	0.46 (small)	0.17 (trivial)
Between-group differences in responses to training				
	0.26 (small)	0.42 (small)	0.25 (small)	0.54 (mod)

Values are presented as means ± SD.

$^*P < 0.05$, $^{**}P < 0.01$, $^{***}P < 0.001$ (significant difference from mid).

$\dot{V}O_{2max}$, maximal oxygen consumption; RS_{LT2}, running speed at LT2; RS_{LT1}, running speed at LT1; NS, not statistically significant.

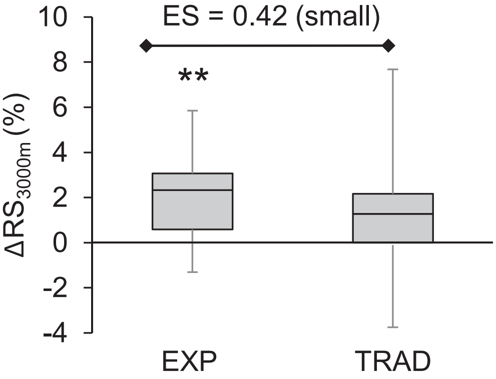


FIGURE 2—Changes (%) in running performance of 3000 m after the 8-wk HRV-guided training (EXP) and predefined training (TRAD). The box plots represent the median values (*solid line*), 50th percentile values (box outline), and minimal/maximal values (whiskers). **P < 0.01, significant difference from week 5.

RS_{3000m} improved by 2.7% ± 2.5% ($P < 0.001$) and $\dot{V}O_{2max}$ by 2.9% ± 4.4% ($P = 0.003$) over PREP. Time in the 3000-m running test improved in EXP (−14.3 ± 14.1 s, $P = 0.005$) but not in TRAD (−7.8 ± 19.8 s, $P = 0.111$) during INT. A small between-group difference was observed in the change in RS_{3000m} (Table 3 and Fig. 2). $\dot{V}O_{2max}$ and RS_{LT2} improved in both groups (a small between-group difference), whereas RS_{LT1} improved only in EXP (a moderate between-group difference). No differences were observed in the changes of the endurance performance variables between sexes.

Individual ranges in the change in RS_{3000m} were from −1% to 6% in EXP and from −4% to 8% in TRAD. One subject in EXP and five subjects in TRAD showed decrements in RS_{3000m}, whereas other subjects improved or maintained their running performance over INT. Figure 3 presents three examples of HRV-based individualization in training prescription. Subject A responded well to a high amount of MOD/HIT. The training program included three MOD/HIT blocks (a total of 34 d) during INT. Subject B performed also three MOD/HIT periods, but those were much shorter (a total of 15 d). However, the response to the high amount of LIT was good. Subject C performed two 7-d periods of MOD/HIT at the beginning of INT. After that, HRV was below the SWC because of work stress and the training was solely LIT. Subject C was the only subject who showed a decrement in the 3000-m running performance in EXP during INT. No significant correlations were found between the number of MOD/HIT sessions and the change in RS_{3000m} ($r = 0.42$, $P = 0.17$) or $\dot{V}O_{2max}$ ($r = 0.26$, $P = 0.43$).

DISCUSSION

The aim of the present study was to compare training adaptation induced by HRV-guided and predefined endurance training. The main finding was that 3000-m running performance improved only in the HRV-guided training group over the 8-wk INT by performing less MOD and HIT sessions compared with predefined training.

Changes in endurance performance. Vagal activity of the autonomic nervous system has widely been observed to be related to individual adaptation to endurance training, for example (6,7,10,12,22). To our best knowledge, only a few previous studies have examined the use of HRV in endurance training prescription (4,18,19). In the study by Kiviniemi et al. (19), the HIT session was programmed if high frequency power (HFP), measured every morning, was increased or remained the same compared with the reference value of HFP (an average of 10 d − SD). Otherwise, LIT or rest was programmed. The HRV-guided group showed 7% improvement in $\dot{V}O_{2max}$ and 6% improvement in maximal running performance, whereas the predefined group improved by 4% in running performance and maintained $\dot{V}O_{2max}$ after 4 wk of training. The change in running performance was greater in the HRV group (19). The present study expressed similar findings. Maximal running performance and RS_{LT1} improved in EXP but not in TRAD, whereas $\dot{V}O_{2max}$ and RS_{LT2} improved in both groups. The group difference in the change in running maximal performance (2.1% in EXP vs 1.1% in TRAD) was rated as small in qualitative and as nonsignificant in the *t*-test analyses. However, in practice, a difference of 1% in sport performance can make the difference between winning and losing (9). The finding may suggest that it may be possible to identify more optimal timing to receive vigorous training stimulus according to HRV compared with subjectively predefined training.

It is worth considering that a slightly greater improvement in 3000-m running performance was achieved with a lower frequency of MOD and HIT sessions in EXP compared with TRAD. Furthermore, training focused more on LIT in EXP, which may explain the greater improvement in RS_{LT1} compared with TRAD. The previous finding is in line with the results of Kiviniemi et al. (18) among moderately trained women. The authors did not observe any differences in the training adaptation between the HRV-guided and the predefined groups, but the HRV group performed less HIT sessions (1.8 vs 2.8 sessions per week) during 8 wk of training. In addition, they proposed that a different HRV-guided program is needed for women because they are more susceptible to longer recovery of HRV (18). In the present study, no differences were observed between sexes in the training adaptation. Kiviniemi et al. (18) proposed that the gender differences in HRV responses to HIT could be explained by a lower relative fitness level in women compared with men. In the present study, the relative fitness level was even a bit higher in women (29), which can explain the contradictory findings in gender differences between the present study and the study by Kiviniemi et al. (18). However, clarification of possible sex differences needs more investigations with larger sample sizes.

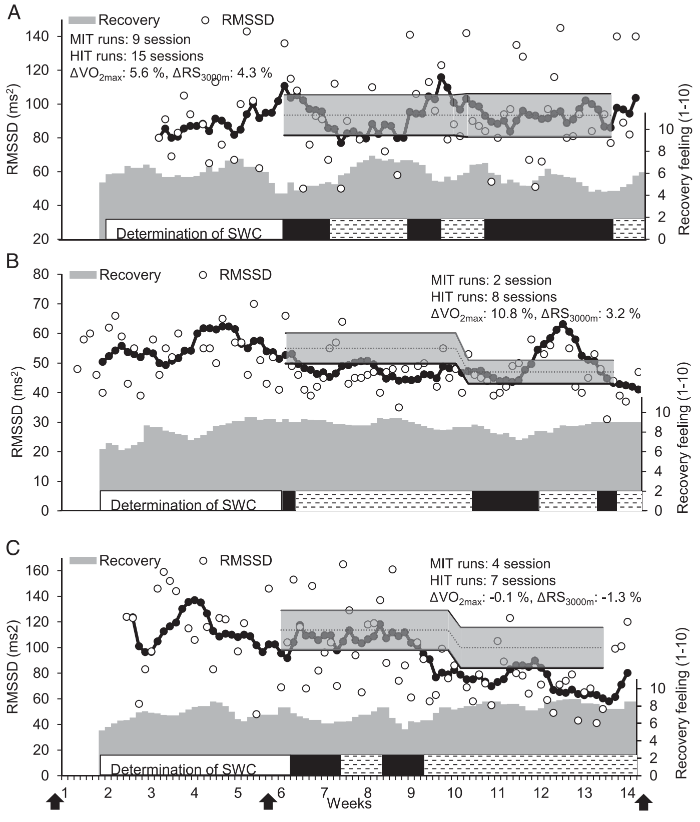


FIGURE 3—Daily changes in RMSSD, RMSSD_{7d}, and recovery feeling for subject A (good response to the high amount of HIT), subject B (good response to the high amount of LIT), and subject C (poor response to the high amount of LIT). The *gray area* indicates the SWC of RMSSD. The *black area* indicates timing of MOD and HIT. The *dashed line area* indicates timing of LIT. The *arrows* represent timing of the running tests.

Individual variation in the adaptation. Large individual differences in training adaptation after standardized endurance training are common (5,7,36). In the present study, EXP showed a slightly smaller range (−1% to 6%) in the change in $\text{RS}_{3000\text{m}}$ compared with the predefined training group (−4% to 8%), whereas the individual range in the amount of HIT sessions was larger in EXP (5 to 24 sessions) compared with TRAD (11 to 21 sessions). This finding suggests that HRV-based timing of HIT may be beneficial for diminishing variation in the adaptation. However, one subject in EXP failed to improve running performance during INT (Fig. 3C). The subject trained only at low intensities during the last 5 wk of INT because his RMSSD values were below the SWC. Reduced HRV was mainly induced by work stress, and it caused challenges to the function of the HRV-based training prescription method. Regardless, it might be assumed that the predefined HIT in that kind of stress state would not result in optimal training outcomes; thus, LIT is recommended to enhance the recovery process. On the other hand, the insignificant correlation between the training adaptation and the number of MOD/HIT sessions showed that the adaptation to training was independent of the amount of vigorous sessions. Some individuals responded well to the high amount of MOD and HIT (Fig. 3A), whereas other individuals (Fig. 3B) achieved good responses to the smaller dose of MOD/HIT sessions. This can be partly explained by our previous finding (34), which showed that some individuals respond better to LIT and some individuals to HIT. It seems also that individuals' recovery of HRV and further capacity to cope vigorous training are different. Subject A (Fig. 3) performed three HIT blocks during INT. The longest one continued 21 d and included 15 MOD/HIT sessions. During the blocks, recovery feeling decreased and HRV changed relatively slowly from the regular level, whereas some individuals' HIT blocks were remarkably shorter. Thus, individualized training program is needed for diminishing variation in the adaptation and increasing effectiveness of training.

Methodological issues to use HRV in training prescription. In the present study, the HRV-based method to prescribe training was different compared with the method by Kiviniemi et al. (18,19). We used the vagal-mediated, time-domain index, RMSSD instead of the HFP spectral density because it has been proposed that RMSSD has greater reliability compared with HRV spectral indices (1). Furthermore, in the present study, a 7-d rolling average was used because it provides a better representation of training adaptation by diminishing the large day-to-day variation in HRV compared with single-day values (24), which were used in the studies by Kiviniemi et al. (18,19). The averaged value of HRV and SWC together shows that one single-training session does not typically change HRV more than SWC. Thus, the present method prescribes the timing of MOD/HIT blocks rather than the single-MOD/HIT sessions. It is closer to practical endurance athletes' training, which includes vigorous training periods, such as training camps, and not only single-training sessions. In addition, block periodization of HIT has been proposed to provide superior training adaptation compared with traditionally organized HIT (26,27). However, exhaustive HIT block training has mainly been used among high-level athletes. Individually determined duration and timing of HIT block according to HRV may be a more approachable training model also for untrained individuals. It may be easier to avoid the imbalance between training load and recovery when training prescription is based on the status of cardiac vagal activity. However, further studies are needed in different populations.

Instead of using a strict limit for the HRV value to determine the intensity of training, which was used in the studies by Kiviniemi et al. (18,19), we used the individually determined SWC, which reflects the regular values of HRV (24,25). When the HRV value falls either below or above the SWC, it is reflecting a sign of an abnormal situation. When HRV is below the SWC, it is indicating increased sympathetic activity, which has been observed to occur after vigorous training periods reflecting an insufficient recovery state (16,23). When HRV is above the SWC, it is indicating increased vagal activity called parasympathetic hyperactivity, which could also be a sign of functional overreaching (20) or overtraining (14,32). The imbalance of cardiac autonomic regulation may indicate an unfavorable situation to adapt to HIT sessions. It is also worth considering that HRV response to training is individualized, and it can vary in different situations. For example, it is shown in Figure 3A that HRV decreased during the first and third MOD/HIT blocks, but during the second block, it oppositely increased above the SWC. As it is unknown, whether HRV should be expected to increase or decrease in the case of overreaching and overtraining, it is recommended that the HRV-based training prescription method includes upper and lower limits for normal area of HRV.

Regardless of the encouraging results to use the present HRV method for training prescription, there are some uncertain issues to solve in future studies. First, baseline HRV recordings for determining the SWC should not be performed under extensive stress factors, like work stress, sicknesses, etc. Otherwise, the SWC does not represent a normal situation. The second issue is related to the magnitude of the SWC. In the present study, it was determined as mean ± 0.5 SD based on the previous findings by Plews et al. (25) and Hopkins et al. (15). The SWC should be wide enough for allowing an individual to train enough at high intensities to achieve adequate disturbances in homeostasis so that further training adaptation can be attained. On the other hand, it should give enough recovery time after HRV falls outside the SWC. That is the reason why LIT was performed until HRV returned to the mean level of the SWC, not only to the area of SWC. Performance changes and recovery feelings during INT did not reveal any signs of overtraining in the present study. Future studies should examine whether a shorter recovery time results in greater adaptations. In that case, LIT should continue until HRV is close to the mean level (e.g., within the area of mean ± 0.1 SD). In addition, an uncertain issue is the updating of SWC. Previous studies have expressed that resting HRV can increase as a positive result of training, especially in previously untrained and moderately trained subjects (6,7,10,12,22). Therefore, the SWC was decided to be updated after the first 4 wk of INT. Although the change in the SWC was relatively small in most subjects in the present study, it is recommended to update the SWC after certain time spans, especially during longitudinal training periods.

Limitations. HRV measurements performed at home may not be as highly standardized as those performed in laboratory conditions. However, it is impractical to perform the measurements in the laboratory every morning during the training period. In addition, it is possible to avoid psychophysiological effects of laboratory conditions on HRV by performing the measurements at home. In addition, the present study is limited by its relatively small number of subjects. Unfortunately, the relatively big number of dropouts due to sickness and injuries reduced statistical power, especially in comparisons between sexes. It does not allow adequate statistical power to investigate possible sex differences with parametric analyses. Furthermore, future studies should aim to examine the usefulness of HRV in endurance training prescription among different populations from sedentary individuals to high-level endurance athletes.

CONCLUSIONS

The present study expressed that the 3000-m running performance improved only in the HRV-guided training group over the 8-wk INT by performing less MOD and HIT sessions compared with the predefined training. In addition, individual range in the training adaptation was smaller in the HRV-guided group compared with the TRAD. The findings may suggest that the timing of MOD and HIT sessions according to HRV is more optimal compared with the subjectively predefined training. Therefore, HRV shows a potential tool in endurance training prescription by optimizing the timing of vigorous training sessions, although there is a need to solve some methodological issues related to the use of HRV in training prescription in future studies.

The authors wish to thank Sirpa Vänttinen and David Leith for their expert assistance during this study, as well as the subjects for their participation.

This study was financially supported by the Finnish Ministry of Education and Culture. The study was conducted in KIHU—Research Institute for Olympic Sports in collaboration with the Department of Biology of Physical Activity of the University of Jyväskylä.

The authors have no conflict of interest to disclose. The results of the present study do not constitute endorsement by the American College of Sports Medicine.

REFERENCES

1. Al Haddad H, Laursen PB, Chollet D, Ahmaidi S, Buchheit M. Reliability of resting and postexercise heart rate measures. *Int J Sports Med*. 2011;32(8):598–605.
2. Baynard T, Goulopoulou S, Sosnoff RF, Fernhall B, Kanaley JA. Cardiovagal modulation and efficacy of aerobic exercise training in obese individuals. *Med Sci Sports Exerc*. 2014;46(2):369–75.
3. Borg GA. Psychophysical bases of perceived exertion. *Med Sci Sports Exerc*. 1982;14(5):377–81.
4. Botek M, McKune AJ, Krejci J, Stejskal P, Gaba A. Change in performance in response to training load adjustment based on autonomic activity. *Int J Sports Med*. 2014;35(6):482–8.
5. Bouchard C, Rankinen T. Individual differences in response to regular physical activity. *Med Sci Sports Exerc*. 2001;33(6 Suppl): S446–51; discussion S452–3.
6. Boutcher SH, Park Y, Dunn SL, Boutcher YN. The relationship between cardiac autonomic function and maximal oxygen uptake response to high-intensity intermittent-exercise training. *J Sports Sci*. 2013;31(9):1024–9.
7. Buchheit M, Chivot A, Parouty J, et al. Monitoring endurance running performance using cardiac parasympathetic function. *Eur J Appl Physiol*. 2010;108(6):1153–67.
8. Cohen J. *Statistical Power Analysis for the Behavioral Sciences*. New Jersey: Lawrence Erlbaum; 1988.
9. Currell K, Jeukendrup AE. Validity, reliability and sensitivity of measures of sporting performance. *Sports Med*. 2008;38(4):297–316.
10. Da Silva DF, Verri SM, Nakamura FY, Machado FA. Longitudinal changes in cardiac autonomic function and aerobic fitness indices in endurance runners: a case study with a high-level team. *Eur J Sport Sci*. 2014;14(5):443–51.
11. Faude O, Kindermann W, Meyer T. Lactate threshold concepts: how valid are they? *Sports Med*. 2009;39(6):469–90.
12. Hautala AJ, Makikallio TH, Kiviniemi A, et al. Cardiovascular autonomic function correlates with the response to aerobic training in healthy sedentary subjects. *Am J Physiol Heart Circ Physiol*. 2003;285(4):H1747–52.
13. Hedelin R, Bjerle P, Henriksson-Larsen K. Heart rate variability in athletes: relationship with central and peripheral performance. *Med Sci Sports Exerc*. 2001;33(8):1394–8.
14. Hedelin R, Wiklund U, Bjerle P, Henriksson-Larsen K. Cardiac autonomic imbalance in an overtrained athlete. *Med Sci Sports Exerc*. 2000;32(9):1531–3.
15. Hopkins WG, Marshall SW, Batterham AM, Hanin J. Progressive statistics for studies in sports medicine and exercise science. *Med Sci Sports Exerc*. 2009;41(1):3–13.
16. Iellamo F, Legramante JM, Pigozzi F, et al. Conversion from vagal to sympathetic predominance with strenuous training in high-performance world class athletes. *Circulation*. 2002;105(23): 2719–24.
17. Issurin V. Block periodization versus traditional training theory: a review. *J Sports Med Phys Fitness*. 2008;48(1):65–75.
18. Kiviniemi AM, Hautala AJ, Kinnunen H, et al. Daily exercise prescription on the basis of HR variability among men and women. *Med Sci Sports Exerc*. 2010;42(7):1355–63.
19. Kiviniemi AM, Hautala AJ, Kinnunen H, Tulppo MP. Endurance training guided individually by daily heart rate variability measurements. *Eur J Appl Physiol*. 2007;101(6):743–51.
20. Le Meur Y, Pichon A, Schaal K, et al. Evidence of parasympathetic hyperactivity in functionally overreached athletes. *Med Sci Sports Exerc*. 2013;45(11):2061–71.
21. Munoz I, Seiler S, Bautista J, Espana J, Larumbe E, Esteve-Lanao J. Does polarized training improve performance in recreational runners? *Int J Sports Physiol Perform*. 2014;9(2):265–72.
22. Nummela A, Hynynen E, Kaikkonen P, Rusko H. Endurance performance and nocturnal HRV indices. *Int J Sports Med*. 2010; 31(3):154–9.
23. Pichot V, Busso T, Roche F, et al. Autonomic adaptations to intensive and overload training periods: a laboratory study. *Med Sci Sports Exerc*. 2002;34(10):1660–6.
24. Plews DJ, Laursen PB, Kilding AE, Buchheit M. Evaluating training adaptation with heart-rate measures: a methodological comparison. *Int J Sports Physiol Perform*. 2013;8(6):688–91.
25. Plews DJ, Laursen PB, Kilding AE, Buchheit M. Heart rate variability in elite triathletes, is variation in variability the key to effective training? A case comparison. *Eur J Appl Physiol*. 2012; 112:3729–41.
26. Rønnestad BR, Hansen J, Ellefsen S. Block periodization of high-intensity aerobic intervals provides superior training effects in trained cyclists. *Scand J Med Sci Sports*. 2014;24(1):34–42.
27. Ronnestad BR, Hansen J, Thyli V, Bakken TA, Sandbakk O. 5-week block periodization increases aerobic power in elite cross-country skiers. *Scand J Med Sci Sports*. 2016;26(2):140–6.
28. Ross R, de Lannoy L, Stotz PJ. Separate effects of intensity and amount of exercise on interindividual cardiorespiratory fitness response. *Mayo Clin Proc*. 2015;90(11):1506–14.
29. Shvartz E, Reibold RC. Aerobic fitness norms for males and females aged 6 to 75 years: a review. *Aviat Space Environ Med*. 1990;61(1):3–11.
30. Stöggl T, Sperlich B. Polarized training has greater impact on key endurance variables than threshold, high intensity, or high volume training. *Front Physiol*. 2014;5:33.
31. Stöggl TL, Sperlich B. The training intensity distribution among well-trained and elite endurance athletes. *Front Physiol*. 2015;6:295.
32. Uusitalo AL, Uusitalo AJ, Rusko HK. Heart rate and blood pressure variability during heavy training and overtraining in the female athlete. *Int J Sports Med*. 2000;21(1):45–53.
33. Vesterinen V, Hakkinen K, Hynynen E, Mikkola J, Hokka L, Nummela A. Heart rate variability in prediction of individual adaptation to endurance training in recreational endurance runners. *Scand J Med Sci Sports*. 2013;23(2):171–80.
34. Vesterinen V, Häkkinen K, Laine T, Hynynen E, Mikkola J, Nummela A. Predictors of individual adaptation to high-volume or high-intensity endurance training in recreational endurance runners. *Scand J Med Sci Sports*. 2015. Epub ahead of print. doi: 10.1111/ sms.12530.
35. Vesterinen V, Hokka L, Hynynen E, Mikkola J, Hakkinen K, Nummela A. Heart rate-running speed index may be an efficient method of monitoring endurance training adaptation. *J Strength Cond Res*. 2014;28(4):902–8.
36. Vollaard NB, Constantin-Teodosiu D, Fredriksson K, et al. Systematic analysis of adaptations in aerobic capacity and submaximal energy metabolism provides a unique insight into determinants of human aerobic performance. *J Appl Physiol (1985)*. 2009;106(5): 1479–86.