INDIVIDUAL ADAPTATION TO ENDURANCE TRAINING GUIDED BY HEART RATE VARIABILITY

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ABSTRACT

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Heart rate variability (HRV) reflects the function of the cardiac autonomic system. Therefore, planning daily endurance training based on HRV has been suggested to be a potential training method compared to preprogrammed training. The purpose of this study was to examine the effects of an individualized training program based on 7-day rolling averaged HRV on endurance training adaptation.

Methods. A total of 40 recreational endurance runners, 20 women (age 34.0 ± 7.8 yr, VO_{2max} 48.6 ± 4.4 ml/kg/min) and 20 men (age 35.4 ± 6.6 yr, VO_{2max} 55.5 ± 5.3 ml/kg/min) volunteered for the study. For the final analysis, 31 subjects were included. All subjects trained similarly during the first 4-week training period, after which they were matched for age, sex, endurance performance and HRV into two training groups (HRV and TRAD) for the eight-week long second training period. HRV group trained according to a 7-day rolling averaged morning RMSSD ($RMSSD_{rollavg}$), whereas TRAD trained based on a predetermined training program. HRV trained at high intensity on days when the $RMSSD_{rollavg}$ was within the individually determined smallest worthwhile change (SWC) and when the RMSSD was outside this area subjects did low intensity training. TRAD did 50 % of the training at high intensity during the second period. Individual training frequency was kept unchanged throughout the study in all groups. Endurance performance was measured with a maximal incremental running test on a treadmill and a field 3000 m running test. HRV group measured real-time morning RMSSD with Omegawave. Nightly HRV was measured with Garmin HR monitor and analyzed with Firstbeat SPORTS software.

Results. The velocity in the 3000 m run improved in HRV (2.1 %, p = 0.004) but not in TRAD. In contrast, VO_{2max} increased in both HRV (3.7 %, p = 0.027) and TRAD (5.0 %, p = 0.002). Maximum velocity (2.6 %, p = 0.005; 2.1 %, p < 0.001) and velocities at LT2 (2.6 %, p = 0.025; 1.9 %, p = 0.004) and LT1 (2.8 %, p = 0.028) on a treadmill increased significantly in HRV and all but V_{LT1} in TRAD, respectively. $RMSSD_{day}$ (-25.3 %) and $RMSSD_{rollavg}$ (-8.3 %) decreased from pre to post. The CV for the mean $RMSSD_{day}$ was 14.5 %, whereas for the $RMSSD_{rollavg}$ it was 6.7 %.

Conclusion. The change in the 3000m run velocity improved in HRV but not in TRAD even though HRV did less HIT. $RMSSD_{rollavg}$ provides a more reliable method to assess the response to training compared to $RMSSD_{day}$ which has more day-to-day variability. Future studies should further investigate HRV guided training and aim to find a reliable protocol for field practice. Based on the results of the current study, the use of HRV in planning daily endurance training to optimize training adaptation is highly recommended.

Keywords: endurance training, autonomic nervous system, heart rate variability, recovery, training monitoring, HRV-guided training

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Sykevaihtelu kuvastaa autonomisen hermoston toimintaa, minkä vuoksi sen on ajateltu kertovan luotettavasti urheilijan palautumistilasta. Viime vuosina onkin herännyt ajatus, voisiko sykevaihtelun avulla ohjelmoida kestävyysharjoittelua ja sitä kautta optimoida harjoitusvaste. Tämän tutkimuksen tavoitteena oli selvittää, johtaako sykevaihteluun perustuva harjoittelun ohjelmointi parempaan lopputulokseen kuin perinteinen, ennalta suunniteltu ohjelma.

Menetelmät. Tutkimukseen valittiin 40 koehenkilöä, 20 naista (ikä 34.0 ± 7.8 v, VO_{2max} 48.6 ± 4.3 ml/kg/min) ja 20 miestä (ikä 35.4 ± 6.6 v, VO_{2max} 55.5 ± 5.3 ml/kg/min), lopulliseen analyysiin otettiin 31 henkilöä. Koehenkilöt harjoittelivat samalla tavalla ensimmäisen neljän viikon jakson ajan, jonka jälkeen heidät jaettiin iän, sukupuolen, kestävyyssuorituskyvyn ja sykevaihtelun perusteella kahteen ryhmään (HRV ja TRAD) kahdeksan viikkoa kestävää toista jaksoa varten. HRV harjoitteli 7 päivän liukuvasti keskiarvostetun sykevaihtelun ($RMSSD_{rollavg}$) perusteella, kun taas TRAD noudatti ennalta määrättyä harjoitusohjelmaa. HRV harjoitteli kovaa aina kun $RMSSD_{rollavg}$ pysyi yksilöllisesti määritellyn alueen (SWC) sisällä, ja vastaavasti kevyttä harjoittelua oli ohjelmassa jos $RMSSD_{rollavg}$ oli alueen ulkopuolella. TRAD-ryhmän harjoituksista 50 % oli kovatehoisia. Yksilökohtainen harjoituskertojen lukumäärä pysyi muuttumattomana kaikilla henkilöillä koko tutkimuksen ajan. Kestävyyssuorituskykyä mitattiin maksimaalisella nousujohteisella juoksumattotestillä sekä 3000 m kenttätestillä. HRV-ryhmä mittasi reaaliaikaisesti RMSSD:n joka aamu Omegawaven avulla, ja kaikilla koehenkilöillä yösykevaihtelua mitattiin Garmin sykemittarilla ja analysoitiin Firstbeat SPORTS ohjelmistolla.

Tulokset. HRV-ryhmä paransi 3000 m vauhtia (2.1 % p = 0.004) mutta näin ei käynyt TRAD-ryhmällä. Sen sijaan sekä HRV:n (3.7 %, p = 0.027) että TRAD:n (5.2 %, p = 0.002) VO_{2max} parani merkitsevästi. Juoksumattotestissä maksiminopeus (2.6 %, p = 0.005; 2.1 %, p < 0.001) ja nopeus anaerobisella (2.6 %, p = 0.025; 1.9 %, p = 0.004) sekä aerobisella kynnyksellä (2.8 %, p = 0.028) kasvoivat selkeästi HRV-ryhmässä ja kaikki paitsi nopeus aerobisella kynnyksellä TRAD-ryhmässä. $RMSSD_{day}$ (-25.3 %) ja $RMSSD_{rollavg}$ (-8.3 %) laskivat tutkimuksen aikana. Yhden päivän RMSSD:n CV (14.5 %) oli suurempi kuin 7 päivän liukuvan keskiarvon lukema (6.7 %).

Johtopäätökset. HRV-ryhmä paransi 3000 m juoksun vauhtia tilastollisesti merkitsevästi, mutta TRAD-ryhmä ei, vaikka HRV teki vähemmän tehoharjoittelua. $RMSSD_{day}$ vaihteli enemmän kuin $RMSSD_{rollavg}$, joten sykevaihtelu kannattaa keskiarvoistaa kuormitustilaa analysoidessa. Tulosten perusteella sykevaihtelun avulla ohjelmoitu kestävyysharjoittelu saattaa johtaa parempaan harjoitusvasteeseen kuin ennalta määrätyn ohjelman noudattaminen.

Avainsanat: kestävyysharjoittelu, autonominen hermosto, sykevaihtelu, palautuminen, harjoittelun seuranta, harjoittelun ohjelmointi

ABBREVIATIONS

ANS	autonomic nervous system
BP	block periodization
CO	cardiac output
ECG	electrocardiography
HFP	high frequency power
HR	heart rate
HR_{supine}	supine heart rate
HR_{stand}	standing heart rate
HR_{max}	maximal heart rate
HRV	heart rate variability
LFP	low frequency power
LT_1	first lactate threshold
LT_2	second lactate threshold
N-FOR	non-functional overreaching
NN50	number of interval differences of successive NN intervals greater than 50ms
OR	overreaching
OT	overtraining
pNN50	proportion derived by dividing NN50 by the total number of NN intervals
PNS	parasympathetic nervous system
rMSSD	square root of the mean squared differences between successive RR intervals
RRI	RR interval
SDANN	standard deviation of the average NN interval calculated over short periods
SDNN	standard deviation of the NN interval
SNS	sympathetic nervous system
SV	stroke volume
SWC	smallest worthwhile change
TP	total power
VO_{2max}	maximal oxygen uptake
V_{max}	maximal velocity
V_{LT2}	velocity at the second lactate threshold
V_{LT1}	velocity at the first lactate threshold

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1 INTRODUCTION

Endurance athletes face on a daily basis a challenge of balancing high training loads with a sufficient amount of rest and recovery. At the highest level, the improvements in aerobic capacity are subtle and require an optimal amount of training-induced stress just enough to disturb the body's homeostasis without being too much to trigger an undesired state of fatigue called non-functional overreaching (Issurin 2010; Plews et al. 2012; Stanley et al. 2013). Indeed, the fine art of planning daily athletic training to maximize training adaptation is a continuous battle of trial and error. Sometimes we succeed in it, while other times something might go wrong, causing the athlete to fail to perform well in his discipline. Knowing when the athlete is ready to train again and when, on the other hand, his body needs rest is something that could truly help him and his coach in structuring training programs in a meaningful way to increase the athlete's level of performance and at the same time avoid the dreaded decrement in his performance and health.

The cardiovascular system plays a key role in controlling the body's homeostasis (Stanley et al. 2013). Autonomic nervous system (ANS) is extremely sensitive to the stress the body encounters, whether it is due to intense exercise (Carter et al. 2003; Mourot et al. 2004; Tulppo et al. 2011; Myllymäki et al. 2012; Stanley et al. 2013; Buchheit 2014) or mental pressures (Tharion et al. 2009; Clays et al. 2011; Hynynen et al. 2011). Parasympathetic activity decreases under stress, while it returns to normal levels after a period of recovery. The function and the changes in the activity of the ANS seem to reflect quite well the overall recovery state of the body (Stanley et al. 2013).

Heart rate variability (HRV) is closely related to the function of the ANS, especially to the parasympathetic nervous system (PNS) (Malik 1998, 161 - 172; Pumprla et al. 2002; Martinmäki et al. 2006), and could serve as a valuable tool in monitoring ANS recovery from (Uusitalo et al. 2000; Plews et al. 2012; Le Meur et al. 2013) and adaptation to (Plews et al. 2013a, 2013b) endurance training. Monitoring night-time or morning heart rate (HR) and HRV is an easy, low-cost and time-saving method (Buchheit 2014) which athletes and coaches can use by themselves to monitor the athlete's cardiac autonomic system recovery from exercise and design training based on individually determined HRV patterns (Kiviniemi et al. 2007;

2010; Stanley et al. 2013). Two of the most common applications of HRV include preventing fatigue and overtraining in athletes (Uusitalo et al. 2000; Plews et al. 2012), and optimizing endurance training adaptation with the use of HRV-guided training programs (Kiviniemi et al. 2007, 2010). The use of HRV in monitoring the athlete's state of fatigue and possible signs of overreaching-overtraining continuum has been studied more, and indeed this has been proven to be quite good a method to assess recovery from training (Plews et al. 2012; 2013a, 2013b, 2014b; Stanley et al. 2013; Buchheit 2014).

The use of HRV in planning daily training has been investigated in only a handful of studies. According to some experts, doing higher intensity training sessions on days when parasympathetic activity has rebounded back to normal level or higher than that has a potential to increase training adaptation (Kiviniemi et al. 2007, 2010; Stanley et al. 2013). The idea in these studies has been to decrease the training stimulus when morning averaged HRV is decreased and train hard on days when HRV is normal or above normal. Kiviniemi et al. (2010) studied the effects of HRV-guided training on the adaptation to endurance training in recreational men and women. The subjects trained according to daily morning HRV values but had at highest two hard training days in a row, followed by either low intensity training or rest, regardless of the HRV of that day. The results showed that HRV-guided training improved the subjects' endurance performance more than traditional training plan, despite or because of doing less high intensity exercise and more moderate intensity training sessions than the control group. Also, they showed that the women might do better with even less frequent high intensity exercise compared to men, which lead the authors to the conclusion that women might need more time to recover from high intensity training.

Although HRV has been an increasingly popular research topic in recent years, there still seem to be many unanswered questions related to the use of HRV in planning daily endurance training in athletes. Factors such as saturation (Plews et al. 2012; Plews et al. 2013b; Buchheit 2014) and a high day-to-day variability of HRV (Buchheit 2014) as well as individual differences in HRV patterns (Plews et al. 2012; Plews et al. 2013b; Buchheit 2014) all influence the interpretation of the data obtained. Thus, knowing which values to look at and how to interpret the data acquired is of great importance. Also, by monitoring each athlete longitudinally and determining their optimal zone of HRV values known as the smallest worthwhile change (SWC) (Plews et al. 2013a, 2013b; Buchheit 2014) the practitioner can help the athlete in the continuous challenge of balancing between stress and recovery. Finally, averaging daily HRV values over multiple days instead of looking at single day isolated values can give a more reliable picture of the actual ANS recovery state as the high daily variation of HRV is smoothened (Plews et al. 2013b; Plews et al. 2014b).

Guiding daily training based on HRV values is a relatively new idea in the field of sports science research. Thus, this study investigated the effect of planning daily endurance training based on morning HRV measures. In contrast to previous studies, our study was based on the following approach. On days when 7-day moving average of morning HRV values were within the SWC, the athletes did high intensity training on training days and continued as long as the average HRV moved off the SWC, whereafter they did low intensity training on training days as long as the SWC moved back inside the SWC and to the mean level. The novelty of this approach, which hasn't been used before in any study protocol, is that it is much closer to the real life training of elite athletes, where special high intensity training blocks are used and high intensity training is emphasized on several days of the training week. No study before has studied the use of HRV in monitoring recovery from and adaptation to endurance training carried out in a block periodized fashion.

The aim of this study was to find out whether this novel, individualized endurance training program based on 7-day rolling averaged HRV indices, improves endurance performance and cardiac autonomic function of recreationally active runners to a greater extent than a traditional, pre-determined training program. The second aim was to compare HRV indices obtained from single isolated days to 7-day averaged ones and find out if these differ in any way. The third aim was to investigate gender differences and see whether men and women differ in cardiac autonomic response to endurance training.

2 ENDURANCE TRAINING

Endurance training is usually characterized by high volumes of training, interspersed with some quality work at higher intensities. To improve aerobic capacity, an athlete needs to train hard enough but not too much, which would impede recovery and adaptation to training. Simple as that. Or is it? Although the physiological background of endurance training is well known, there still isn't any consensus on what kinds of training regimes are best for improving key physiological variables in endurance sports (Jones & Carter 2000). This chapter takes a closer look at the physiological adaptation processes related to chronic endurance training as well as different training regimens and how they can be used to increase endurance performance. Finally, the importance of a high enough work load with a sufficient amount of recovery, and the idea of periodization in endurance sports, are discussed.

2.1 Physiological basis of endurance training adaptation

Endurance can be determined as the capacity to sustain a given velocity as long as possible. Success in endurance sports depends on the body's ability to resynthesize ATP aerobically, which requires an adequate delivery of oxygen from ambient air to the mitochondria, the small organism inside muscle cells responsible for aerobic metabolism. (Jones & Carter 2000; Hawley 2002; Jones 2006; Hawley & Spargo 2007.) The main physiological determinants for endurance performance are the maximal oxygen uptake (VO_{2max}), work economy and second lactate threshold (LT_2). VO_{2max} is considered as the maximal rate at which oxygen can be taken from the ambient air, transported to active working muscles and used by muscle cells for cellular respiration during exercise. Although work economy and the velocity at the second lactate threshold (V_{LT2}) also have some influence on endurance exercise performance, VO_{2max} is often considered the most important factor as it sets the upper limit for how much oxygen can be used at the LT_2. (Jones 2006; Midgley et al. 2006; Jones & Carter 2000.) To be able to improve endurance performance it is of paramount importance that the athlete or coach knows how the body adapts to different endurance training concepts and therefore can decide which kind of training is most appropriate for improving the athlete's level of performance (Jones & Carter 2000; Midgley et al. 2006; Hatle et al. 2014; Rønnestad et al. 2014a, 2014b; Stöggl & Sperlich 2014).

Physiological adaptations. Endurance training affects pulmonary, cardiovascular and neuromuscular systems in the body by inducing adaptations which enhance endurance performance by improving the delivery of oxygen to the working muscles (figure 1). One of the most relevant factors for success in endurance sports is a high stroke volume (SV) of the heart. (Jones & Carter 2000; Joyner & Coyle 2008.) Chronic endurance training increases SV by inducing a mechanical overload which increases ventricular diastolic stretch and resistance to ventricular emptying due to increased afterload. This, in turn, increases cardiac output (CO) and $VO_{2max,}$ and lowers HR at submaximal work rates. (Midgley et al. 2006; Jones & Carter 2000.) Also, neuroendocrine factors such as thyroxine, testosterone, angiotensin II, and the catecholamines stimulate myocardial adaptations (Midgley et al. 2006). Plasma volume (PV) and erythrocyte mass are increased after chronic endurance training. Skeletal muscle capillarisation, caused by shear stress and capillary pressure, is considered one of the major physiological adaptations to endurance training, as this facilitates the transportation of oxygen and other metabolic byproducts between muscle cells and the blood. (Jones & Carter 2000; Midgley et al. 2006; Joyner & Coyle 2008.) Also, skeletal muscle myoglobin content has been found to be increased with training. Myoglobin transports oxygen from the sarcolemma to the mitochondria, thus facilitating cellular respiration. The oxidative capacity of skeletal muscle fibers is increased after training due to increases in the number and activity of oxidative enzymes and mitochondria. (Jones & Carter 2000; Hawley 2002; Midgley et al. 2006; Hawley & Spargo 2007.) Endurance training increases the size of type I oxidative, slow-twitch fibers, and possibly causes a transformation of type IIb fibers to IIa and even type IIa to Ia eventually (Jones & Carter 2000). Also, it has been shown that trained endurance athletes are able to use more fat as a fuel during exercise, which decreases the reliance on carbohydrates and thus slows down the depletion of glycogen stores in the muscle. This has a major role in the improved endurance capacity that follows years of training. (Hawley 2002.)

High volume low intensity training. Endurance training includes four different training concepts which athletes usually use to maximize their performance. These concepts are high-volume low-intensity (HVT), lactate threshold (THR), high intensity interval (HIIT) and polarized (POL) training. (Stöggl & Sperlich 2014.) HVT (<80% HR_{max}, < 2 mmol/l blood lactate) is generally considered the bread-and-butter of endurance training, and it is known to improve endurance performance by increasing SV and PV, thereby increasing VO_{2max} (Jones & Carter 2000; Midgley et al. 2006; Midgley et al. 2007; Rønnestad et al. 2014a, 2014b; Stöggl &

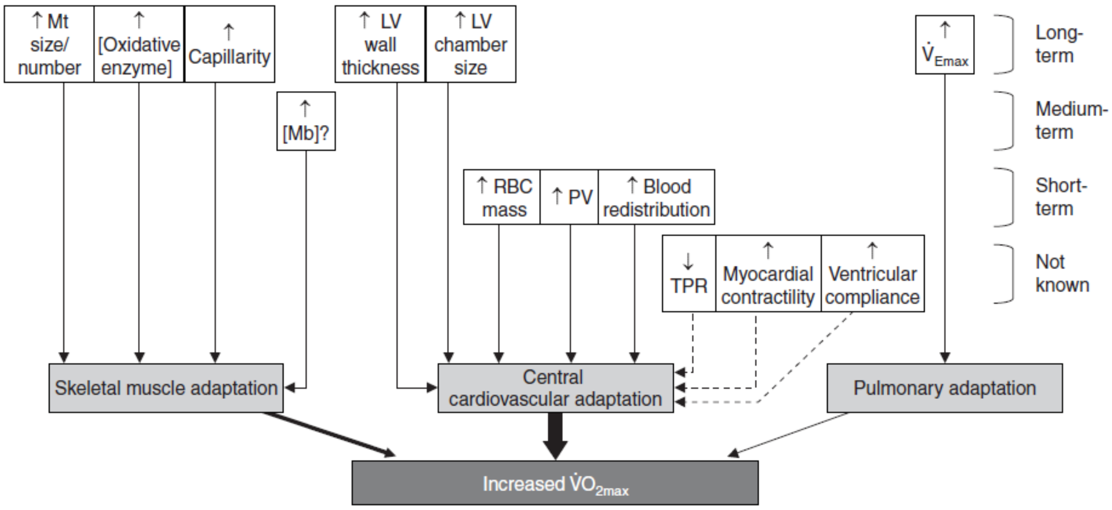

FIGURE 1. Physiological adaptations following endurance training lead to the improvement of maximal oxygen uptake (VO_{2max}). The arrows with broken lines indicate that the time course of those adaptations is currently unknown. The width of the three shaded arrows at the bottom of the figure broadly represents the total contribution of each of those adaptations in the long-term improvement of VO_{2max}. Maximum period of adaptability for myoglobin concentration is based on rat studies. *LV* = left ventricular; *Mb* = Myoglobin concentration; *Mt* = mitochondrial; *Oxidative enzyme* = oxidative enzyme concentration; *PV* = plasma volume; *RBC* = red blood cell; *TPR* = total peripheral resistance; VE_{max} = maximal minute ventilation; ↑ indicates increase; ↓ indicates decrease; ? indicates presently unknown in humans. (Midgley et al. 2006.)

Sperlich 2014). Exercise at around 75% VO_{2max} is suggested optimal since at this level the stimulus for myocardial adaptation is probably at its highest (Midgley et al. 2006). Also, HVT has been suggested to improve running economy, thereby improving performance in endurance events. Endurance athletes have traditionally used this type of a high mileage training with only little time advocated to training at higher intensities. (Midgley et al. 2007; Rønnestad et al. 2014a, 2014b; Stöggl & Sperlich 2014.) HVT induces molecular adaptations at the cellular level including mitochondrial biogenesis, and all these changes improve the metabolic efficiency of movement (Jones & Carter 2000; Stöggl & Sperlich 2014).

High intensity interval training. HIIT has been shown to improve aerobic capacity of both untrained and trained individuals by increasing availability, extraction and utilization of oxygen, thereby improving some of the key variables in endurance performance such as time to exhaustion, time trial performance, running economy and VO_{2max} (Stöggl & Sperlich 2014). Training at or near VO_{2max} stresses maximally the physiological structures such as the myocardium and related physiological processes which are considered limiting factors for an improvement in VO_{2max}. The mechanical overload resulting from intense endurance exercise increases the maximal SV of the heart, which has been considered one of the limiting factors of VO_{2max} in trained population. (Jones & Carter 2000; Midgley et al. 2006, 2007.) Also, mitochondrial biogenesis has been shown to be increased after intense endurance training. Research has shown that training at 90 - 95% of HR_{max} twice or three times a week is superior to continuous low to moderate intensity (60 - 70% HR_{max}) exercise in improving VO_{2max}. (Helgerud et al. 2007; Midgley et al. 2007; Hatle et al. 2014; Rønnestad et al. 2014a, 2014b; Stöggl & Sperlich 2014.) Thus, the optimal stimulus for adaptation might be obtained by using high intensity interval endurance training.

Threshold and polarized training. Training at or close to the LT_2 (also known as anaerobic threshold, AnT), as is the case in THR training, is a more controversial subject. Some say this type of training only improves aerobic capacity in untrained population, while others have shown that also world-class level athletes use this type of training regularly. (Jones & Carter 2000; Midgley et al. 2007; Stöggl & Sperlich 2014.) Finally, there is what is called polarized training, which means that low and high intensity are emphasized more while training between the first (also known as the aerobic threshold) and second lactate thresholds or around LT_2, is scanted (Stöggl & Sperlich 2014). This is how many elite endurance athletes have been reported to train (Plews et al. 2014a), doing most of their training (~75% of total training volume) at low intensities and the rest (~15 - 20%) well above the LT_2. When the efficacy of the four aforementioned training concepts was compared in a group of Austrian national team level endurance athletes during nine weeks of training, POL resulted in by far the most greatest improvements in VO_{2max} (+11.7%). Indeed, HIIT was the next best option quite far behind (+4.8%), with only a small change in HVT (+2.6%) and even a decrease in THR (-4.1%). Also, time to exhaustion (TTE) and velocity at peak power output were increased in POL. (Stöggl & Sperlich 2014.)

2.2 Stress and recovery – finding the balance to optimal adaptation

Although physical training is highly recommended for people of all ages, exercise is actually a stress situation from which the body has to recover to be able to function optimally. The word "stress" usually refers to external or internal forces that can alter the body's homeostasis. To adapt to various stressors it encounters, the body must be able to react to these changes to restore homeostasis and prevent further damage caused by excessive stress. The hypothalamic-pituitary-adrenal (HPA) axis and the autonomic nervous system (see chapter 3) play a key role in regulating the adaptive response to stressful situations, the most important factors in this process being the corticotropin-releasing hormone (CRH) and vasopressin (AVP) neurons in the hypothalamus, as well as the locus ceruleus (LC)/norepinephrine (NE) and central autonomic sympathetic system in the brainstem (figure 2). (Mastorakos et al. 2005.)

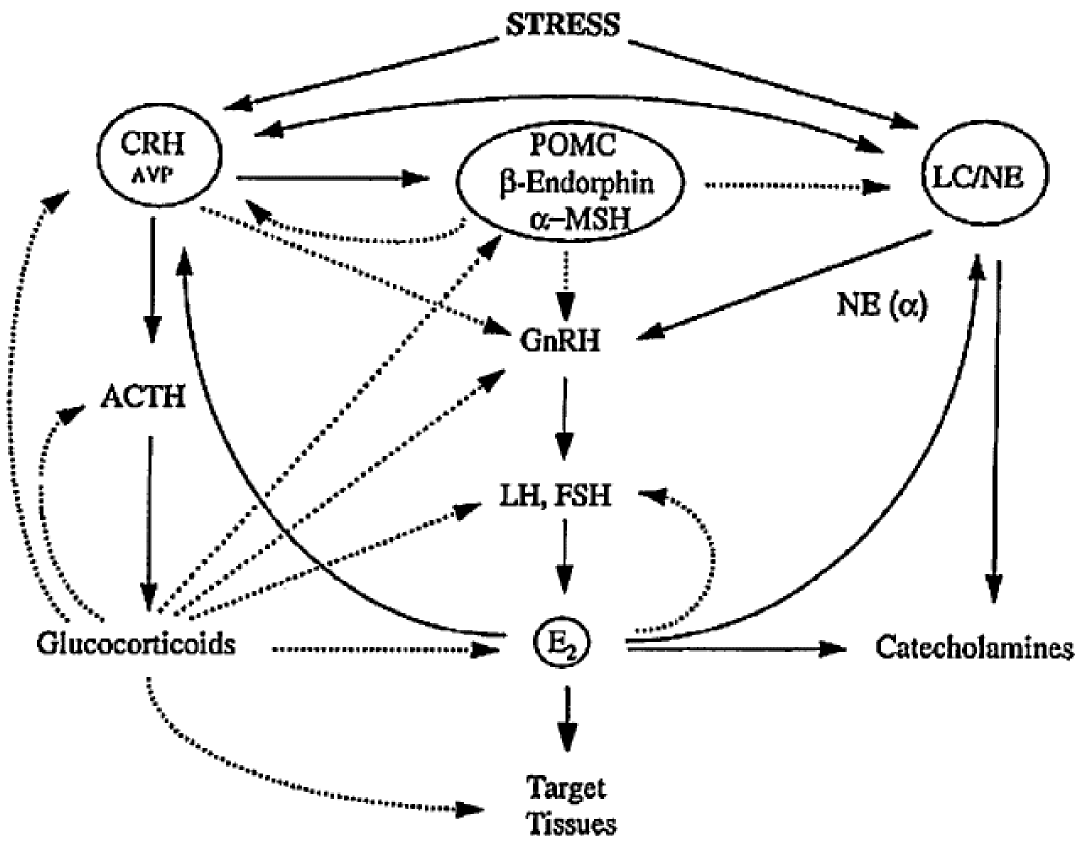

FIGURE 2. The interplay among the hypothalamic-pituitary-adrenal axis, the locus ceruleus/norepinephrine (LC/NE) sympathetic system and the hypothalamic-pituitary-gonadal axis. *Dotted lines* = inhibition, *solid lines* = stimulation. (Mastorakos et al. 2005.)

During exercise, the HPA axis is activated and the secretion of hormones such as the CRH from the hypothalamus is increased, stimulating in turn the release of the adrenocorticotropin hormone (ACTH) from the pituitary and cortisol from the adrenal medulla. This response is usually attenuated in highly trained athletes compared to sedentary population. However, at baseline, highly trained subjects are actually under mild hypercortisolism, as daily strenuous exercise has been shown to lead to chronic ACTH hypersecretion and adrenal hyperfunction. Thus, exercise training has a beneficial effect in improving the individual’s capacity to tolerate high workloads with less pituitary-adrenal activation. Plasma AVP levels are increased after exercise in an intensity-dependent fashion, and AVP may also be involved in the ACTH response to exercise. Stress and catecholamines also stimulate the secretion of endogenous IL-6, which in turn leads to the release of growth hormone (GH) and prolactin (PRL), the response of which is, again, influenced by previous training, with higher release in untrained compared to trained athletes. The different components of the HPA axis inhibit the hypothalamic-pituitary-gonadal axis at all levels. CRH suppresses gonadotropin-releasing hormone (GnRH), while glucocorticoids suppress the secretion of luteinizing hormone (LH) as well as the hormone secretion of the gonads. Suppression of gonadal function caused by chronic activation of the HPA axis has been shown in athletes under strenuous stress such as runners and ballet dancers, as well as in individuals suffering from anorexia nervosa or starvation. This causes in males low LH and testosterone levels, while females are prone to health issues such as amenorrhea, possibly leading to more severe problems like the so-called female athlete triad. Also, glucocorticoids released during exercise are known to suppress the thyroid axis function, which in the long-term can possibly lead to euthyroid sick syndrome due to abnormal thyroid function caused by extreme stress situations. (Mastorakos et al. 2005.)

Perhaps the most challenging thing in athletic training is finding the optimal balance between training stimulus and recovery. As discussed earlier, exercise disturbs the body’s homeostasis, which provides a stimulus for physiological adaptation processes. Recovery, on the other hand, is a process of restoration, involving the integrated response of many systems that help to return the body back to homeostasis or even higher than that. During the recovery process, metabolites such as hydrogen ions are removed from the muscles, body temperature and fluid balance return to baseline levels, and neuroendocrine-immune responses are activated. The cardiovascular system has an important role in this process as it regulates many of the physiological changes in the body. (Stanley et al. 2013.) A more detailed discussion of the importance of cardiovascular system in assessing recovery from endurance training is found in chapters 3 and 4.

The phenomenon of supercompensation is of crucial importance in athletic training, and the interaction between stress and recovery forms the basis behind this phenomenon. The supercompensation cycle starts with a physical overload, which causes fatigue and acutely reduces the athlete’s work capacity (figure 3). During the following phases, the athlete starts to recover and exercise capacity increases first to pre-load levels and, in the ideal case, continues to increase further, above the previous baseline, achieving the climax at the supercompensation phase. Usually, a number of workouts can be performed in a fatigued state as supercompensation happens only after accumulation of stress from several training sessions instead of only one session. (Issurin 2010; Stanley et al. 2013.)

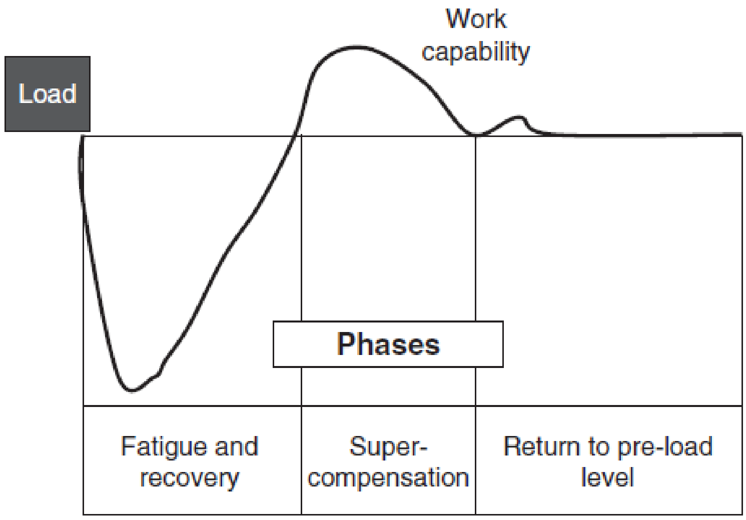

FIGURE 3. The well-known model of supercompensation. Intense training leads to fatigue, which is reversed following sufficient recovery and thereafter the level of work capability reaches a new, higher level. (Issurin 2010.)

The danger with high training loads combined with limited periods of recovery usually seen in elite or highly trained athletes is drifting into a state of too much fatigue, known as a continuum consisting of overreaching (OR), non-functional overreaching (N-FOR), and, in the worst case, overtraining (OT). These conditions refer to a stress-regeneration imbalance, which impairs the athlete’s health status and performance in multiple, yet to some degree unknown ways, by for instance disturbing the athlete’s hormonal system function, sleep and readiness to perform. Although short-term OR is often a desired outcome of a training program, eventually leading to an improved performance, going too hard too long can push the athlete over the line to a state of N-FOR, or even OT, from which recovery can take months or even years. (Plews et al. 2012.) Because of the risks of training too hard, planning short- and long-term training (known as periodization) is recommended to avoid cessation of training adaptation.

Periodization refers to the manipulation of training load, intensity and volume during a specific time-frame to optimize athletic performance. The traditional periodization (TP) model stems from the 1950s and is based on simultaneous development of many fitness components (aerobic capacity, strength, power). The relatively new approach, called block periodization (BP), is characterized by the use of highly concentrated loads focused on the development of few key variables. Blocks typically last between two to six weeks, and the sequencing of different blocks is reasoned to be superior to the traditional model due to the fact that the focus is only on few selected abilities, which optimizes the training adaptation and leads to increased level of performance. (Garciá-Pallarés et al. 2010; Issurin 2010; Rønnestad et al. 2014a, 2014b.)

Many studies looking at BP have shown enhanced endurance performance, usually in a short amount of time. For example, twelve and even four (figure 4) weeks of BP in a group of trained male cyclists improved VO_{2max}, peak power output at 2 mmol/l lactate level compared to a TP model (Rønnestad et al. 2014a, 2014b). Also, in elite world-class male kayak paddlers BP training was shown to be more effective than TP for improving the performance level, and the time required to elicit these improvements was much shorter in BP compared to TP, which means that BP is a time-efficient way to train for improvements in aerobic capacity. (Garciá-Pallarés et al. 2010.)

However, more is not always better, as was indeed the case in a study of Hatle et al. (2014), in which the efficacy of two different block training concepts was evaluated. Subjects were divided into either a moderate (MF) or high (HF) frequency training groups, doing HIIT three or eight times a week, for a period of eight or three weeks, respectively. VO_{2max} increased in the MF group throughout eight weeks and was highest (+10.7%) at the end of the training period, whereas in the HF group, the adaptation was significantly delayed and the highest VO_{2max} (+6.1%) value was observed after a detraining period of two weeks after cessation of the training intervention (figure 5). In MF, SV was increased by 14.5% and the activity of citrate synthase (CS), a mitochondrial enzyme, was increased by 39%, while in HF there was no change in SV and a smaller, 25% increase in CS activity. Higher frequency of high intensity intervals may induce significant fatigue which may be a limiting factor for the function of the cardiopulmonary system. Therefore, a more progressive approach with three interval sessions per week seems to be a better option.

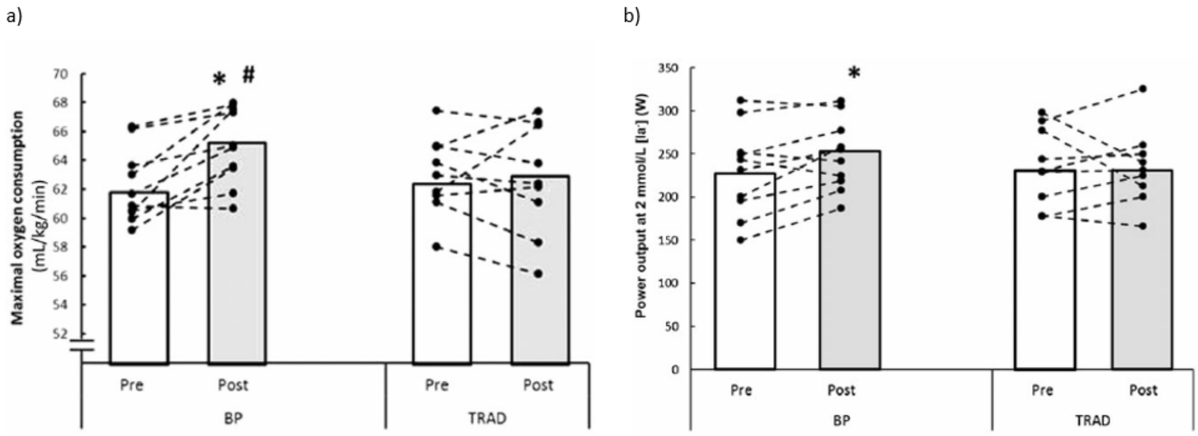

FIGURE 4.Maximal oxygen consumption (a) and power output (W) at 2 mmol/l $[la^-]$ (b) before (Pre) and after (Post) the intervention period for the block periodization (BP) and the traditional (TRAD) group. * Larger than at Pre ($p < 0.05$); # The relative change from Pre is larger than in TRAD ($p < 0.05$). (Rønnestad et al. 2014b.)

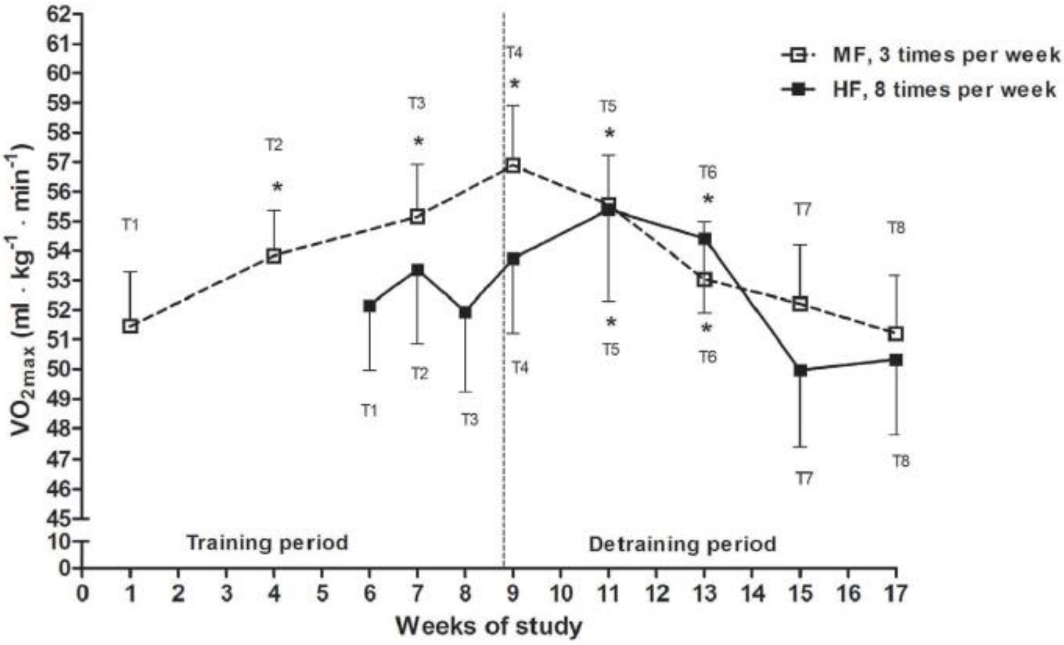

FIGURE 5. Means and standard errors of the mean of VO_{2max} for the MF and HF groups during training and detraining period. Note how MF improved VO_{2max} throughout the 8-week training period, whereas in the HF, no improvement was seen until two weeks of detraining. *Vertical dotted line* = last day of training. (Hatle et al. 2014.)

3 AUTONOMIC NERVOUS SYSTEM AND HEART RATE VARIABILITY

In order to understand the connections between the ANS and HRV, one must first understand how the heart and the ANS are related to each other. In the following sections, the functions of the heart and the ANS are briefly discussed, followed by a more detailed analysis of the physiological background of HRV. Finally, the reader is provided with some examples on how HRV is related to different factors such as age, gender, and psychological stress.

3.1 The heart and the autonomic nervous system

The heart is a muscular organ that pumps blood to various parts of the body in a continuous, rhythmic fashion. In fact, the heart is composed of two separate pumps: the right side of the heart pumps deoxygenated blood into the lungs (pulmonary circulation), while the left part pumps blood out to the rest of the body (systemic circulation). Both sides of the heart are further divided into atria and ventricles. The atria are responsible for pumping the blood to the ventricles, from which blood is further carried into either the lungs or other parts of the body. (Guyton & Hall 2011, 101 - 120.)

The function of the heart is influenced by the spontaneous action of the sinus (SA) node, or pacemaker cells, which, in turn are influenced by the activity of the two branches of the ANS. The SA node sets the timing and rate at which cardiac cells contract, and usually this rate is around 70 - 80 beats per minute. Parasympathetic, or vagal, nerves dominate the SA and atrioventricular (AV) nodes of the heart, while sympathetic nerves are found mainly in the atria (figure 6). Vagal stimulation decreases HR, causes vasodilation and increases the movement of the bowel, for example, whereas sympathetic activation has the opposite actions. Increased activity of parasympathetic nerves decreases CO to almost half the normal, while sympathetic activation can increase it to almost twofold (figure 6). Due to stimulation of parasympathetic nerves, acetylcholine is released from the vagus nerve, which increases cell membrane K+ conductance. This hyperpolarizes the cell membrane. Sympathetic nerve stimulation, in turn, causes epinephrine and norepinephrine to be released, which then activates beta-adrenergic receptors. The permeability of the cell membrane to Na+ and K+ ions is increased, which changes the resting membrane potential into a more positive direction. (Task Force 1996; Guyton & Hall 2011, 101 - 120, 229 - 230, 729 - 741.)

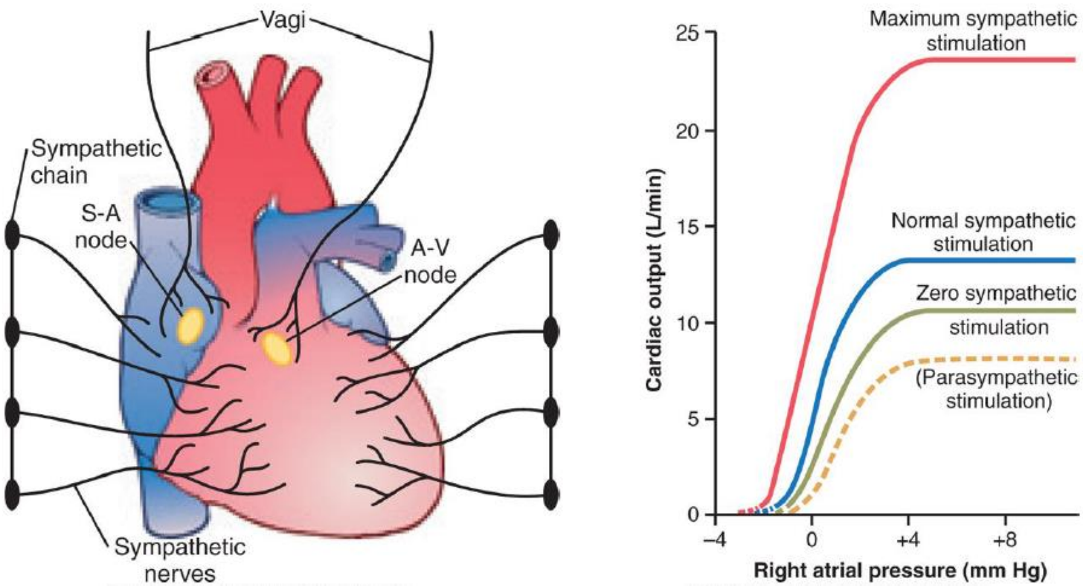

FIGURE 6. The heart is innervated by the nerves from PNS and SNS (left). Parasympathetic stimulation decreases and sympathetic stimulation increases cardiac output (right). (Guyton & Hall 2011, 111.)

Changes in blood volume affect ANS activity, with increased blood volume increasing and decreased blood volume decreasing parasympathetic activity. An increase in PV after exercise reflects a simultaneous increase in parasympathetic activity over baseline. This parasympathetic reactivation after endurance exercise has been suggested to reflect the recovery of an individual and a possible phase of supercompensation. (Stanley et al. 2013.)

As the cardiovascular system is involved in, for example, thermoregulation and delivery/removal of nutrients and waste products, it can be said that both the heart and the cardiovascular system are in a key position in regulating recovery from exercise. Thus, by monitoring the changes in cardiac autonomic activity caused by a disturbance in homeostasis and the time it takes for cardiac function to return to baseline, one could possibly gain information on how exercise affects cardiac function as well as haemodynamics in an effort to restore homeostasis. (Stanley et al. 2013.)

3.2 Heart rate variability

HRV is a noninvasive, easy-to-use method for assessing changes in the ANS function (Buchheit 2014). The HR is not stable, but instead there is naturally some amount of variability due to variations in the activities of the sympathetic (SNS) and parasympathetic (PNS) nervous systems (Carter et al. 2003). HRV refers to variations of both instantaneous HR and RR intervals (RRI). The former describes the oscillations between successive instantaneous heart rates, and the latter the oscillation in the interval between two consecutive heart beats (see figure 7 later). It is important to understand that, although the term generally used in the literature is “heart rate variability”, it is actually the interval between consecutive heart beats being analyzed, rather than the HR per se. (Task Force 1996.)

The SA node is innervated by both parasympathetic and sympathetic nerves, and whichever branch is dominating will also have an effect on the intrinsic firing rate of the pacemaker cells. The influence of parasympathetic stimulation is mediated by synaptic release of acetylcholine, which has a short latency time and thus enables modification of cardiac function on a beat-to-beat basis. Sympathetic activation, on the other hand, is mediated via synaptic release of norepinephrine, which is metabolized more slowly, and therefore influences cardiac function with a delay. (Malik 1998, 149; Pumprla et al. 2002.)

Because of the differences in operating frequencies between the two branches, HRV (low- or high frequency) is thought to reflect the function of either of the two (sympathetic and parasympathetic, respectively). This has been confirmed in studies using different pharmacological blockades, which has been justified as follows. There is naturally some variation in cardiac function during different cycles of respiration, called respiratory sinus arrythmia. Because this respiration-induced variation is usually seen at higher frequencies (0.25 Hz or 15 times per minute) and can be abolished by vagal blockade (eg. atropine) but is not significantly influenced by sympathetic blockade (β-blockade, propranolol), it is thought that this high frequency component of HRV is of parasympathetic origin. Since time-domain indices of HRV reflect mainly vagal activity, blockade of parasympathetic nerves can be seen in these variables. (Malik 1998, 161 - 172; Pumprla et al. 2002; Martinmäki et al. 2006.)

There is also some variation due to baroreflex activity at lower frequencies (0.10 Hz or six times per minute), which can be modified by sympathetic blockade and thus, could be reflecting the activity of that part of the ANS. However, since vagal blockade has also been shown to influence low frequency component of HRV, it is now suggested that LF reflects the activity of both branches of the ANS. Measurement of the activity of both high and low frequency power is recommended, since this can give information concerning sympathovagal balance. (Malik 1998, 161 - 172; Pumprla et al. 2002; Martinmäki et al. 2006.)

The advantage of HRV as a method for assessing ANS function lies in the fact that it is a simple and noninvasive method which can be used both at laboratory and field conditions (Task Force 1996). HRV measurements can nowadays be conducted with commercial heart rate monitors and smart phone applications and so on, which makes this method appealing to both athletes and researchers who are seeking for a practical but at the same time a valid method to use. However, despite it being an increasingly popular method among athletic training and a popular focus in current research, the unfortunate fact is that HR and HRV monitoring still hasn't been accepted as a gold standard, likely due to the controversy in the literature. (Buchheit 2014.)

3.3 Effect of age, gender, and psychological stress on HRV

A low HRV is known to reflect a higher risk of mortality, and thus increasing or maintaining HRV can be an important tool in preventing various diseases. Studies have shown that HRV decreases with aging. Physical activity has been shown to slow the decrement in HRV and could, therefore, have a beneficial impact on cardiac health. (Uusitalo et al 2002; Achten & Jeukendrup 2003; Aubert et al. 2003; Carter et al. 2003; McNarry & Lewis 2012.) Sex differences in HRV are still quite controversial, but it may be so that women have slightly lower HRV values compared to males (Achten & Jeukendrup 2003).

Many people think that it is only the physical activity that influences HRV. In reality, however, the psychological side of stress is as important as is the physiological one. Whether it is work pressures or problems with social relationships, the stress we encounter every day has a huge impact on our well-being and also on the function of the ANS. (Tharion et al. 2009; Clays et al. 2011; Hynynen et al. 2011.) Tharion et al. (2009) showed in their study that students had lower morning HRV values during exam period, while later, during the holidays, HRV was increased probably due to lack of psychological stress. In a study of Hynynen et al. (2011), on the other hand, it was shown that mental stress affected negatively the level of HRV in an orthostatic test in the morning but this effect was not shown during the night measurement.

3.4 Measurement of HRV

In measuring HRV one has to keep in mind that there are numerous factors that need to be considered. It has been said that there are as many methods for assessing HRV as there are researchers, and because of this measurement situation should be carefully standardized so that future studies can be compared with each other and some real conclusions can be made. In the following section, the two main HRV methods for measuring HRV, that is time-domain and frequency-domain, are discussed.

3.4.1 Time domain

There are numerous methods for assessing variations in HR. Time-domain measures, which usually determine either the HR itself at any time point or the interval between two consecutive normal complexes, are perhaps the simplest method to perform. The limitation of this method is the lack of discrimination between the activities of the two autonomic branches. The measurement starts with a continuous electrocardiographic (ECG) record, from where each QRS complex is detected (figure 7). Thereafter, the so-called normal-to-normal (NN) intervals (intervals between adjacent QRS complexes resulting from sinus node depolarizations), or the instantaneous HR is determined. Some of the simple time-domain variables that can easily be calculated from the measurements include the mean NN interval, the mean HR, the difference between the shortest and longest NN interval, and so on. Also, time-domain measurements can be used to evaluate variations in instantaneous HR secondary to respiration, tilt, Valsalva manoeuvre, etc. Differences can be expressed as either differences in HR or cycle length. (Task Force 1996; Malik 1998, 101 - 107; Aubert et al. 2003.)

From a series of recorded heart rates or cycle lengths, more complex statistical time-domain measures can be calculated. These are usually divided into a) those derived from direct measurements of the NN intervals or instantaneous HR, and b) those derived from the differences between NN intervals. It is possible to either derive the before-mentioned variables from analysis of the total ECG recording or calculate them using smaller segments of the recording period. The shorter sample allows comparison of HRV between various activities, for example rest, sleep and so forth. The more commonly used statistical variables to describe HRV with time-domain method include the standard deviation of the NN interval (SDNN), the standard deviation of the average NN interval calculated over short periods (SDANN), and the mean of the 5-min standard deviation of the NN interval calculated over 24h (SDNN index). SDNN is the simplest variable to calculate, reflecting all the cyclic components responsible for variability in the period of recording. Quite often, SDNN is calculated over a 24-hour period and thus encompasses both short-term high frequency variations as well as the lowest frequency components seen during 24 hours. (Task Force 1996; Malik 1998, 101 - 107; Aubert et al. 2003.)

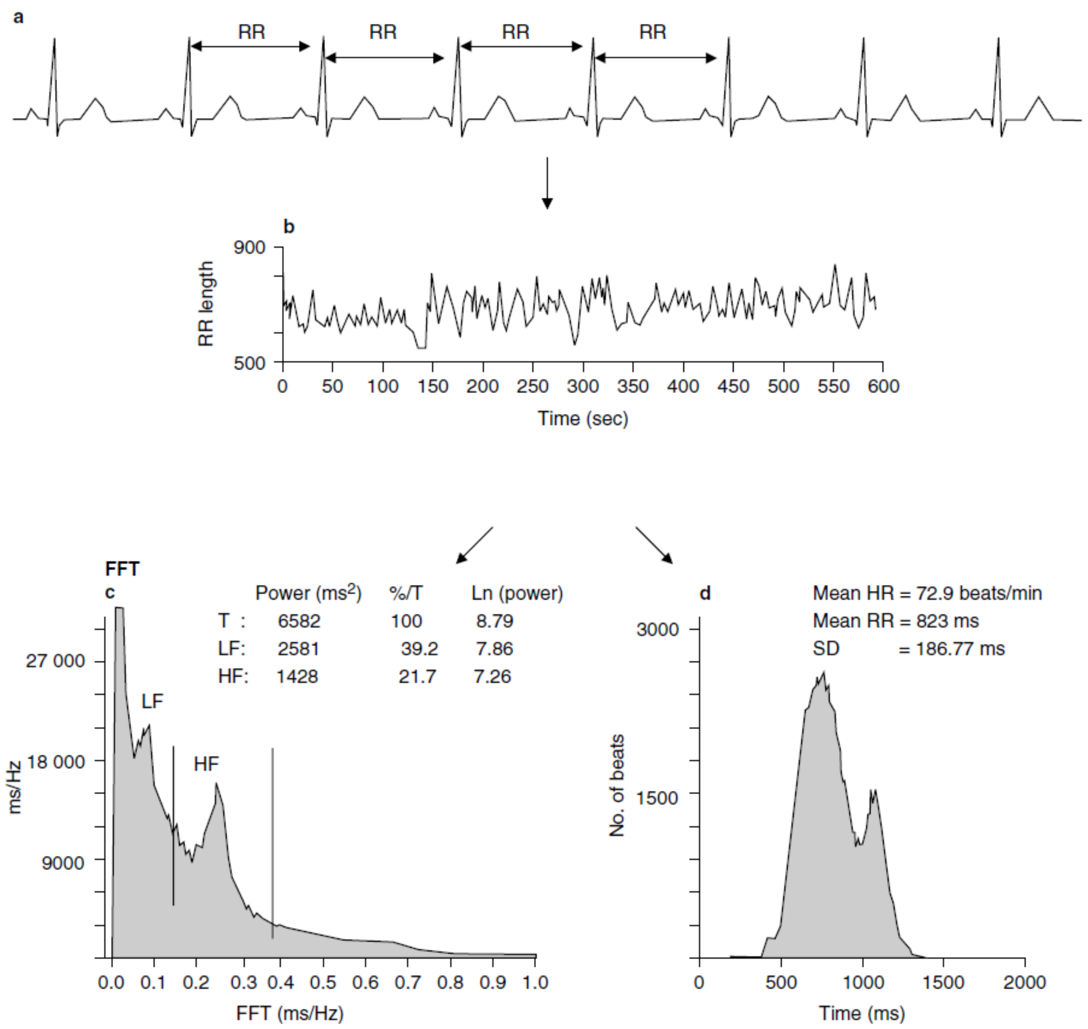

FIGURE 7. Analysis of HRV from ECG. Consecutive RR intervals are calculated from the ECG (a), resulting in a tachogram (b), which can be analyzed with both time-domain (d) and frequency-domain (c) methods. FFT = fast Fourier transform; HF = high frequency power; HR = heart rate; LF = low frequency power; Ln = natural logarithm; T = total power. (Aubert et al. 2003.)

As the total variance of HRV increases with the length of the recording, it is impossible and inconvenient to compare SDNN measures obtained from recordings of different length. SDANN estimates the changes in HR due to cycles longer than 5 min, while the SDNN index measures variability due to cycles shorter than 5 min. When it comes to the measures derived from interval differences, the most common ones are the square root of the mean squared differences of successive NN intervals (rMSSD), the number of interval differences of successive NN intervals greater than 50ms (NN50), and the proportion derived by dividing NN50 by the total number of NN intervals (pNN50). (Task Force 1996; Malik 1998, 101 - 107; Aubert et al. 2003.) A summary of common time-domain indices is shown in table 1.

TABLE 1. Variables used in time-domain analysis (Sztajzel 2004).

Variable	**Units**	**Description**
SDNN	ms	standard deviation of all NN intervals
SDANN	ms	standard deviation of the averages of NN intervals in all 5-minute segments of the entire recording
SD	ms	standard deviation of differences between adjacent NN intervals
rMSSD	ms	square root of the mean of the sum of the squares of differences between adjacent NN intervals
pnn50	%	percent of difference between adjacent NN intervals that are greater than 50ms

Due to a high correlation between many of the time-domain measures, it is recommended to use SDNN, HRV triangular index (estimate of overall HRV), SDANN and rMSSD for time-domain HRV assessment. The reason why rMSSD is preferred over NN50 and pNN50 is that it has better statistical properties. Further, the methods used for short- and long-term analysis cannot replace each other, and the method selected should be in line with the aim of the study. Also, distinction should be made between measures derived from direct NN interval or instantaneous HR recordings and from the differences between NN intervals. Comparison of time-domain measures should be made with caution, as the duration of the recording affects the interpretation of the data. (Task Force 1996.)

3.4.2 Frequency domain

In addition to time-domain method, another method, called frequency-domain, can be used to assess HRV. In this technique, a HR time series is reduced to its constituent frequency components, and the relative power of these is calculated (see figure 7 in the previous section). This spectral analysis provides practitioner with information on how power is distributed as a function of frequency. There are parametric and non-parametric methods of power spectral density, with the Fast Fourier transform analysis being the best known non-parametric method. (Carter et al. 2003.)

Spectral analysis divides variation in HR into three components: high frequency power (HFP, 0.15 - 0.40 Hz), low frequency power (LFP, 0.04 - 0.15 Hz), and very low frequency power (VLFP, <0.04 Hz) (table 2). In addition, the total power (TP = LFP + HFP) is usually calculated, reflecting variability in all spectral areas. The activity of PNS is reflected by the HFP component, while the LF probably includes the activity of both branches of the ANS. The values of spectral components can be converted into normalized units (nu) to minimize the influence of LFP and HFP on TP. However, the best way would be to report both nu and absolute values to avoid misinterpretation of results. (Task Force 1996.)

TABLE 2. Frequency-domain measures of HRV (Sztajzel 2004).

Variable	**Units**	**Description**	**Frecuency range**
Total power	ms^2	variance of all NN intervals	<0.4 Hz
ULFP	ms^2	ultra low frequency	<0.003 Hz
VLFP	ms^2	very low frequency	<0.003-0.04 Hz
LFP	ms^2	low frequency power	0.04-0.15 Hz
HFP	ms^2	high frecuency power	0.15-0.4 Hz
LFP/HFP ratio		ratio of low-high frequency power	

When the two methods of assessing HRV are compared, it can be said that although there exists more experience and theoretical knowledge on the physiological background of the frequency-domain measures, many time-domain and frequency-domain variables measured over the entire 24-h period are strongly correlated with each other (table 3). (Task Force 1996.) On the other hand, time-domain measures typically have a lower typical error of measurement when expressed as a CV compared to frequency-domain (Plews et al. 2013b).

It is highly recommended that researchers choose only one vagally-derived HRV variable for assessment of ANS function, as comparison of distinct methods is difficult. The use of Ln rMSSD (Plews et al. 2013b; Buchheit 2014) and SD1 (standard deviation of instantaneous beat-to-beat interval variability measured from Poincaré plots) (Buchheit 2014) is recommended for three reasons. First, these are not influenced by breathing frequency. Second, they can be used to evaluate levels of parasympathetic activity over short periods of time, which is more practical for athletes who do not have the entire day time to measure their cardiac autonomic function. Finally, Ln rMSSD and SD1 values can be calculated on excel using RR intervals, which makes this method easy to use for practically anyone. As Buchheit (2014) concludes, although previously recommended, the use of spectral methods in the field work is no longer encouraged.

TABLE 3. Approximate correspondence of time- and frequency-domain methods applied to 24h ECG recordings (Task Force 1996).

Time domain variable	Approximate frequency domain correlate
SDNN	TP
HRV triangular index	TP
SDANN	ULF
SDNN index	Mean of 5 min TP
rMSSD	HF
SDSD	HF
NN50 count	HF
pNN50	HF

4 HRV AND ENDURANCE TRAINING ADAPTATION

In the following section, the relationship between HRV and acute as well as chronic endurance training is briefly reviewed, after which the application of HRV in monitoring recovery from and adaptation to endurance training is discussed. Finally, an overview of endurance training guided by HRV measures is given as this is the main focus of the study.

4.1 Acute changes in HRV with endurance training

Cardiac parasympathetic activity has been shown to be decreased during the first few hours after endurance exercise. This suppression of vagal activity is caused by a drop in blood pressure, which reduces afferent input from baroreceptors. Meanwhile, the accumulated metabolites such as hydrogen ions in the muscles stimulate chemoreceptors in the carotid body, increasing sympathetic nerve activity. Also, catecholamines, especially epinephrine, released during exercise may give rise to further sympathetic excitation. All these exercise-induced physiological processes slow down the return of HRV to baseline levels. (Stanley et al. 2013.) The longer the duration (Myllymäki et al. 2012) or the higher the intensity (Carter et al. 2003; Mourot et al. 2004; Tulppo et al. 2011; Buchheit 2014) of the training session, the longer it usually takes for the HR and HRV to return to the resting levels. The decrease in vagal-related HRV indices after intense exercise can last up to 72 h (Buchheit 2014).

Heavy training combined with additional stressors such as heat can actually have the opposite influence by increasing HRV despite an acute decrease in perceived wellness of an individual. Indeed, this has been the case in some studies looking at intense multi-day endurance races, where the false increase in HRV is thought to be due to increased plasma volume, which usually increases HRV despite of an individual's state of fitness or level of fatigue. This is why interpretation of changes in HRV should always be done within the context of other factors involved. (Buchheit 2014.)

4.2 Chronic changes in HRV with endurance training

Chronic endurance training increases parasympathetic activity and decreases sympathetic activity at rest. This, in turn, decreases HR both at rest and during submaximal exercise. (Al-

Ani et al. 1996; Hedelin et al. 2001; Uusitalo et al. 2002; Achten & Jeukendrup 2003; Aubert et al. 2003; Carter et al. 2003; Lee et al. 2003; Martinmäki et al. 2008; Nummela et al. 2010; Boullosa et al. 2009; Hynynen et al. 2010.) However, due to controversy in the literature, currently it seems that a better aerobic capacity does not directly translate into a higher level of HRV (Uusitalo et al. 2002; Achten & Jeukendrup 2003; Bosquet et al. 2007; Hynynen et al. 2010). The inconsistency of results between different studies may be due to methodological differences, as HRV can vary greatly depending on the measurement type, how the data are analyzed, and study design, such as the duration and time of the intervention (Achten & Jeukendrup 2003). For example, as Buchheit (2014) explains, nowadays it is a well-known fact that HRV changes throughout a training season with high values usually seen during moderate training loads and decreased HRV values over higher loads.

Saturation of HRV. The common misconception is that the relationship between fitness and HRV is linear, although there is actually a bell-shaped relationship between HRV and fitness in highly trained athletes (figure 8). This means that at both low and high levels of vagal tone indices of HRV are reduced. For example, in the lead up to competition, an athlete's HRV can decrease despite achievement of optimal performance level. This reduction in HRV may be due to saturation at lower HR levels typically seen in athletes. The reason for this is likely the saturation of acetylcholine receptors at the myocyte level, which then eliminates respiratory heart modulation and thus decreases HRV. This makes it much more challenging to use HRV in monitoring recovery from and adaptation to training in this population. Because vagal-related indices of HRV reflect the magnitude of change in the parasympathetic modulation rather than an overall parasympathetic tone per se, HRV may decrease at low resting HR levels usually seen in elite athletes. (Plews et al. 2013b; Buchheit 2014.)

To avoid misconceptions related to interpreting the results of the measurements and see whether there is saturation or not, the HRV values obtained should always be looked at in light of the retrospective changes in resting HR and in the context of training. This can be done by using the Ln rMSSD to RR interval ratio, which simultaneously considers changes in both vagal tone (RRI) and modulation (HRV). The use of both Ln rMSSD and Ln rMSSD to RR interval ratio is recommended to decide whether the athlete is fatigued or ready to perform (figure 9). (Plews et al. 2012; Plews et al. 2013b; Buchheit 2014.) Reduced Ln rMSSD with an increase in Ln rMSSD to RR interval ratio is indicating of fatigue, while reductions in both indicate an optimal state of performance. The optimal relationship between these values is likely individual, and therefore, longitudinal screening is needed to find each athlete's zone of optimal state (figure 10). (Plews et al. 2012; Plews et al. 2013b; Buchheit 2014.)

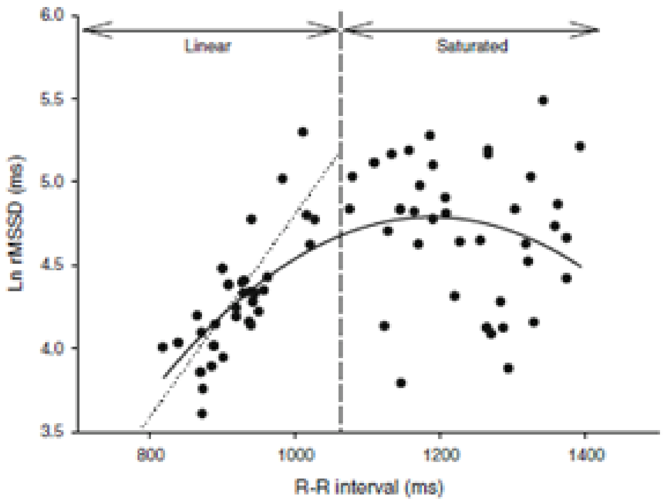

FIGURE 8. The relationship between the RRI and Ln rMSSD is usually bell-shaped. As the duration of the RRI increases, HRV becomes saturated, which makes it difficult to tell whether the athlete is fatigued or not. (Plews et al. 2013b.)

4.3 Monitoring training adaptation and recovery with HRV

Monitoring recovery from training is of great importance in endurance sports such as running and cross-country skiing, where the volume and intensity of training is high and the athlete is pushing his body towards its limits. There is a thin line between optimal training and overreaching, and the biggest challenge for the athlete is to find the right balance in training hard and recovering from workouts to reach a higher level of fitness. HRV has been studied intensively to find out if it could be used to manage training loads and avoid fatigue and possible overreaching or overtraining.

Plews et al. (2012) monitored the recovery state of two elite triathletes by assessing morning HRV daily during a 77-day competitive period. The relationship between Ln rMSSD and RRI length was identified as either "linear", "low-correlated", or "saturated" (see figure 8 earlier). According to Plews et al. (2012), a detailed depiction of this method has been described earlier by Kiviniemi et al. (2004). During the observation period, Plews et al. (2012) noted that one of the athletes performed well while the other became non-functionally overreached (NFOR) and could not finish a key triathlon event. The NFOR athlete had a declining trend in both weekly and 7-day rolling average of HRV, and moved from "saturated" when training well to "linear" on becoming NFOR. Also, there was less variance in the NFOR athlete's day-to-day Ln rMSSD values, which could possibly be an early warning sign of fatigue (figure 11). However, this is on contrast with the findings of Schmitt et al. (2013) on elite endurance athletes, where larger intraindividual changes in HRV were related to fatigue compared with "no fatigue" state. Nevertheless, regarding HRV and NFOR, Plews et al. (2012) conclude that (1) HRV seems to be a more sensitive indicator of NFOR compared to resting HR, (2) the 7-day rolling averaged HRV correlates well with the possible development of NFOR, and (3) a decrease in day-to-day variability HRV values and a transfer from "saturated" to "linear" HRV profile may be another indicator of NFOR.

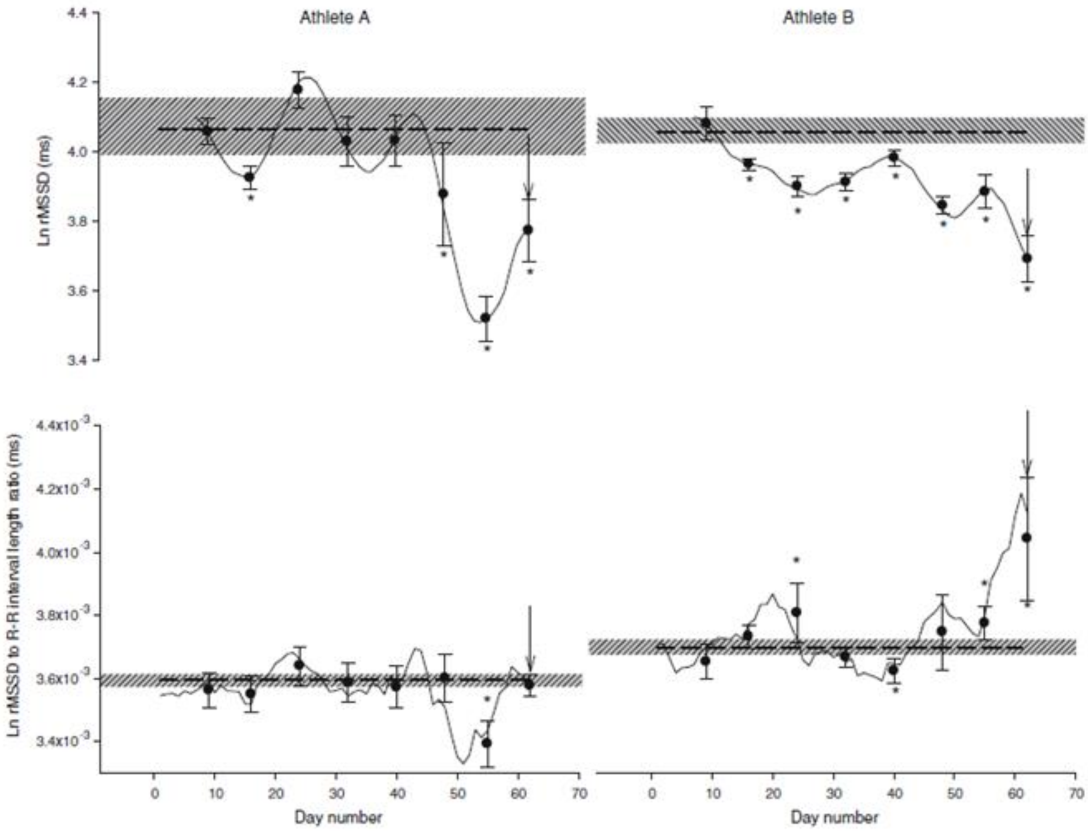

FIGURE 9. Changes in the Ln rMSSD and Ln rMSSD to R - R interval ratio with 90 % CI for Athlete A (performing well) and Athlete B (performing poorly, NFOR) over a 62-day build-up period to a key rowing event. *Black circular symbols* = the weekly average values for Ln rMSSD and Ln rMSSD to R - R interval ratio; while *the black line* = the 7-day rolling average. *The arrows* = the day of the final race. *The grey shaded area* = the individual smallest worthwhile change, SWC; *the black dashed line* = the zero line of the SWC to indicate clear/unclear changes when the 90 % CI overlaps. (Plews et al. 2013b.)

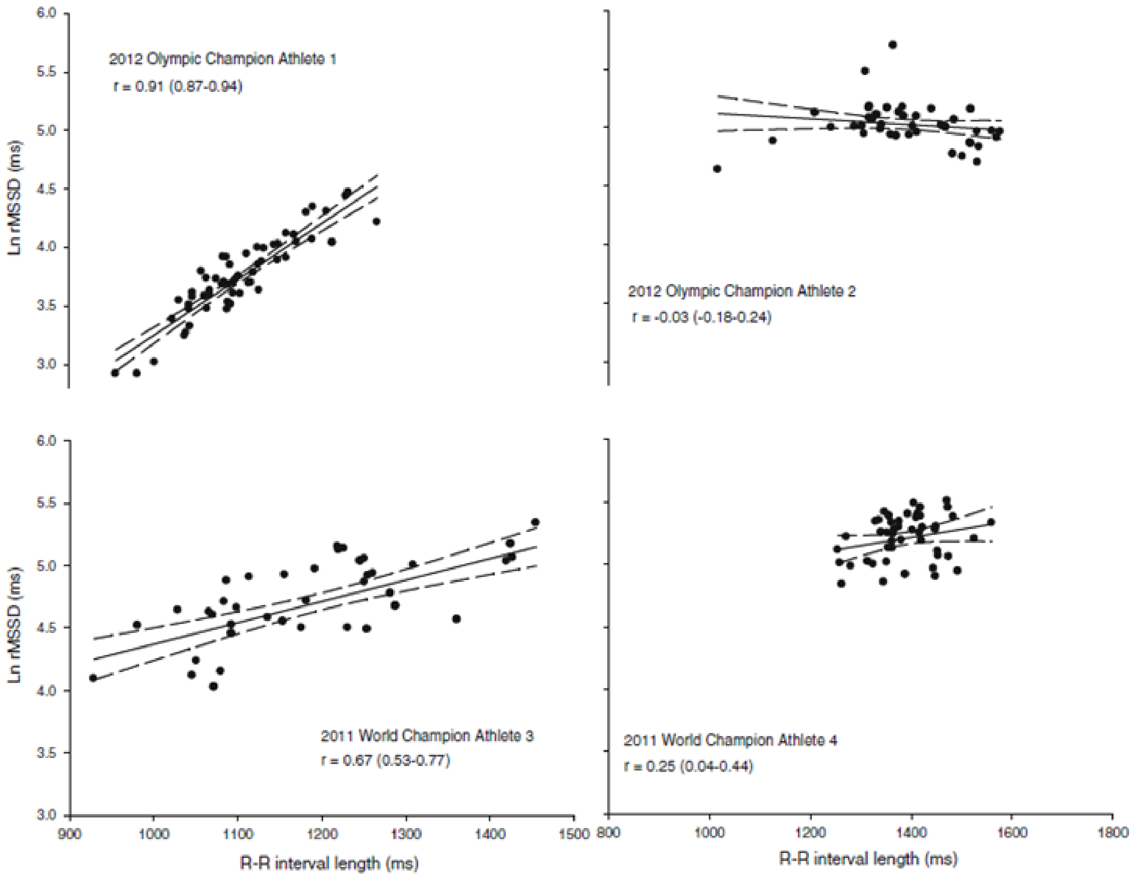

FIGURE 10. Correlation and 90 % confidence intervals between Ln rMSSD and R - R interval length in two 2012 Olympic Champion rowers and two 2011 World Champion rowers taken every morning upon awakening in the 62-day build-up to each event. Correlation coefficients were almost perfect (r = 0.91) and trivial (r = -0.03) for athletes 1 and 2, respectively. Instead, the values were large (r = 0.67) small (r = 0.25) for the athletes 3 and 4, respectively. (Plews et al. 2013b.)

As already discussed in the previous chapter, interpreting HRV and its relationship with fatigue in well-trained athletes requires caution. For example, Le Meur et al. (2013) showed how intensified training leading into functional overreaching induced parasympathetic hyperactivity as assessed with weekly averaged HRV, although running performance was greatly reduced. This was in contrast with a common assumption and previous studies showing reduced vagal-related HRV indices after an overload training period (Uusitalo et al. 2000). The reason behind the decrease in performance despite an increase in HRV may be that vagal control during exercise acted as a limiting factor at the end of the overload period, whereas after a week-long taper, this reduction in maximal HR was no longer enough to limit oxygen transport to the working muscles at maximal effort (Le Meur et al. 2013).

The difficulty in interpreting the results from HRV measurements is that each athlete is an individual and has his own optimal zone (SWC). If this zone is not detected longitudinally, then interpretation of the HRV data may be inaccurate and possibly lead to wrong conclusions. Therefore, it is important that each athlete is monitored long enough during both light and heavy training to find out how his body normally reacts to different training stimuli and what are the signs of going over the line. The other challenge is the phenomenon of saturation, and how to know whether the athlete is fatigued or ready to perform. Because of this, monitoring should always include multiple other factors such as resting HR, and the results from HRV recordings should always be interpreted in the context of everything else. (Plews et al. 2013a,b; Buchheit 2014.)

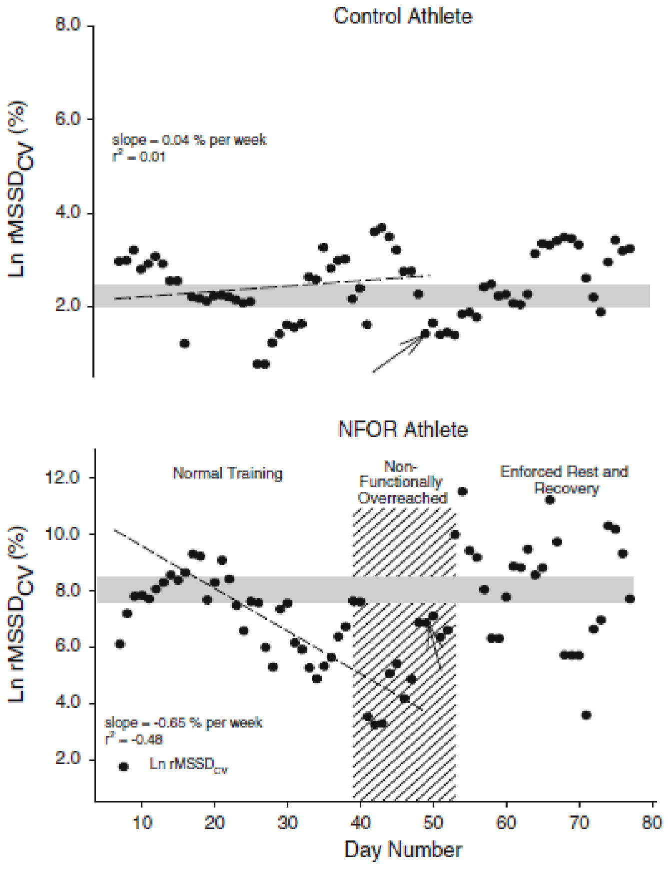

FIGURE 11. CV of the 7-day rolling Ln rMSSD average (Ln $rMSSD_{CV}$) for non-functionally overreached (NFOR) and control triathletes. *The dashed line* represents the linear regression between day number and Ln $rMSSD_{CV}$ towards the day of the final race on day 48 (indicated by *the arrow*). The lack of day-to-day variance in Ln rMSSD may be an early sign of NFOR. The SWC is indicated by *the horizontal shaded area*. (Plews et al. 2012.)

4.4 Endurance training guided individually by daily HRV measures

In recent years, studies focusing on how recovery from endurance exercise can be monitored with HRV have become increasingly popular. Individualizing training for each athlete to get optimal results is important, since, after all, we all are individuals and what works for one does not necessarily work for someone else. As HRV reflects the state of the ANS, it is theorized that based on daily HRV values the athlete could plan his training, and therefore, possibly avoid overtraining and reach an optimal level of performance.

This has been studied by measuring daily HRV of athletes and then averaging these values over a 7- or 10-day period with a rolling fashion, or by weekly average, as these have been proven to be more reliable than single isolated values. The idea has been to decrease the training stimulus if the morning HRV is decreased below a certain predefined level (the SWC), which is thought to be a sign of overreaching. On the other hand, if the HRV value is within or above the SWC, this is thought to act as a “green light”, indicating that the athlete is well recovered and ready for the next (hard) training session. (Kiviniemi et al. 2007, 2010.) As research has shown, low intensity training usually accelerates recovery and induces parasympathetic supercompensation within 24 hours, which is why this type of training should be emphasized in between hard threshold and high intensity sessions. Doing high intensity or threshold training at the time of peak HRV supercompensation response is theorized to be a superior tool for improving endurance capacity. (Stanley et al. 2013.)

This kind of a HRV-guided training has been proven to be quite efficient. Kiviniemi et al. (2010) studied the effects of HRV-guided training on the adaptation to endurance training in recreational men and women. They found out that HRV-guided groups improved more than the control group, and thus, encourage individual planning in daily training to get the best results (figure 12). The interesting finding was that HRV-guided groups did less high intensity exercise and more moderate intensity exercise than the control group, and that the women might do better with even less high intensity exercise compared to men. According to these results, assessing cardiac ANS function with HRV may be a good indicator of an individual’s state of recovery and therefore, lead to better outcome in performance gains.

Also, Botek et al. (2013) studied HRV based endurance training in 10 national level athletes. Over a 17-week period, training intensity was manipulated individually based on daily HRV measures to maintain vagal activity at a relatively high and stable level. The results indicate that daily training load adjustment was associated with a change in performance that ranged from -8.8 to +8.5%. Training load had to be changed on approximately half the number of training days during the study, which means that without knowledge of their ANS state these athletes could have under- or overtrained. The authors conclude that a daily assessment of ANS function with HRV may be a promising biofeedback mechanism to objectively monitor individual training response and the level of trainability.

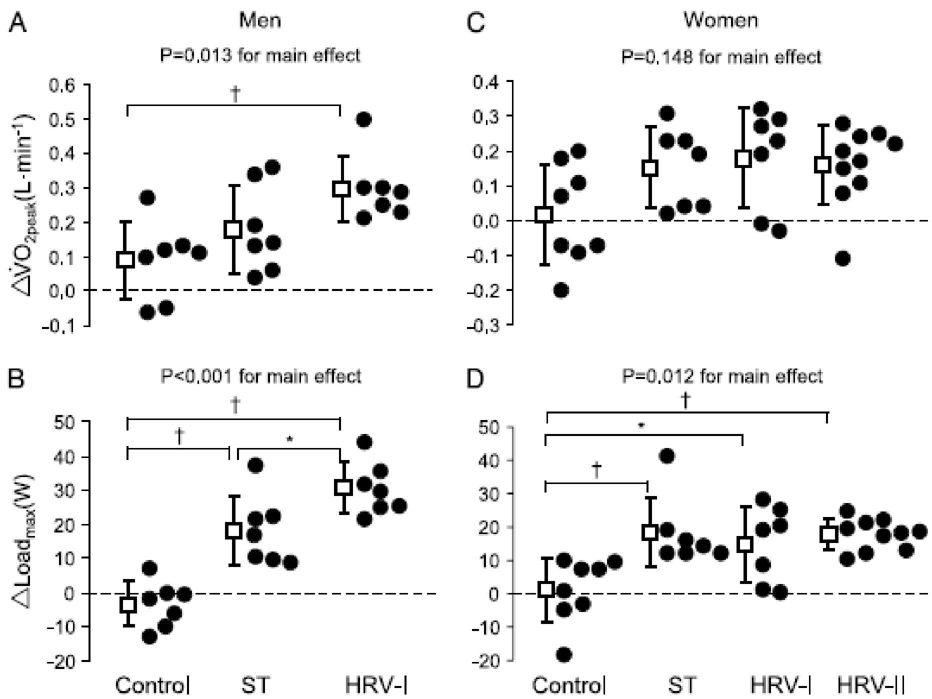

FIGURE 12. Changes in peak oxygen consumption (VO_{2peak}, A and C) and maximal workload ($Load_{max}$, B and D) in men (A and B) and women (C and D) divided into HRV-guided training (HRV-I and HRV-II), standard training (ST), and control groups. In men, a better response to endurance training in $Load_{max}$ was observed in the HRV-I group, while in women there were no significant differences between the groups. Values are means ± SD. *P < 0.05, †P < 0.01. (Kiviniemi et al. 2010.)

5 PURPOSE OF THE STUDY AND RESEARCH QUESTIONS

The aim of this study was to find out if individualized, HRV-guided endurance training results in a better outcome compared to a traditional training model. The study included a four-week long preparation phase followed by eight weeks of training either according to a pre-determined training plan or based on 7-day rolling averaged daily HRV values. The idea was to decrease training intensity on days when morning HRV value was below or above the individually determined optimal zone, and to do high intensity training on days when HRV was inside this area. Research questions and hypotheses were as follows:

1. **Does a HRV-guided, block periodized training program result in better improvements in endurance performance compared to a traditional model?**

H1: HRV-guided training results in better improvements in endurance performance compared to a pre-determined training program.

Studies have shown that HRV is a good indicator of ANS recovery and may indeed reflect the athlete's state of fatigue (Uusitalo et al. 2000; Plews et al. 2012; Le Meur et al. 2013). However, most of the studies have focused on monitoring changes in HRV with training (Plews et al. 2012, 2014a) instead of planning daily training based on HRV (Kiviniemi et al. 2007, 2010). Training at high intensity on days when cardiac parasympathetic activity is elevated, and thus the body is well recovered from previous exercise, has been suggested to maximize endurance training adaptation (Stanley et al. 2013, Plews et al. 2014a). Studies investigating HRV-guided training have shown that this method is superior to the traditional periodization model (Kiviniemi et al. 2007, 2010). However, in these studies only two consecutive hard training sessions at highest were allowed, after which rest or low intensity training was prescribed, regardless of the HRV. In contrast, our study used a different, novel approach in which the subjects' training reflects more closely that of real-life athletic training. As a result, in our study the subjects did hard training as long as their HRV values fell within the individually determined SWC, which is close to the quite common block periodized training model (Garciá-Pallarés et al. 2010; Issurin 2010; Rønnestad et al. 2014a, 2014b) used in athletic training. It remains to be seen whether HRV-guided block periodized training improves aerobic fitness more than HRV-guided more conservative approach previously used.

2. **Does a 7-day rolling averaged HRV result in a different outcome compared to isolated single day data points?**

H2: Due to a high day-to-day variability of HRV, averaging daily values over multiple days offers a more reliable method for assessing ANS recovery from and adaptation to endurance training.

Compared to single day values, averaged HRV data offers a more truthful view on the actual recovery state of the athlete, which results in better training adaptation and improved endurance performance (Plews et al. 2012, 2013a, 2013b, 2014b; Buchheit 2014).

6 METHODS

6.1 Subjects

Forty healthy (20 men, 20 women), recreational runners (age 34.7 ± 7.2 yr, height 172.8 ± 8.2 cm, weight 68.5 ± 10.4 kg, VO_{2max} 52.1 ± 5.9 ml/kg/min) were recruited by advertising in the local newspaper (table 4). The inclusion criteria were the age of 18 - 45 and 18 - 50 for men and women, respectively, and BMI less than 30 for all the subjects. Smokers and those with chronic diseases or prescribed medications were excluded from the study. The subjects were expected to have a background of at least two years of endurance training on entering the study. Before participation, all subjects underwent medical screening to ensure that they presented normal ECG patterns and could take part in the study. After comprehensive verbal and written explanations of the study, all subjects gave their written informed consent to participate. The study was approved by the Ethics Committee of the University of Jyväskylä, Finland.

TABLE 4. Characteristics of subjects at the beginning of the study (mean ± SD).

	Women (n = 20)	Men (n = 20)	All (n = 40)
Age (yr)	34.0 ± 7.8	35.4 ± 6.6	34.7 ± 7.2
Height (cm)	167.3 ± 6.9	178.3 ± 5.1	172.8 ± 8.2
Weight (kg)	61.1 ± 7.0	75.9 ± 7.5	68.5 ± 10.3
Fat%	24.8 ± 4.4	14.6 ± 4.0	19.7 ± 6.6
BMI (kg/m^2)	21.8 ± 2.3	23.8 ± 1.6	22.8 ± 2.2
VO_{2max}(ml/kg/min)	48.6 ± 4.3	55.5 ± 5.3	52.1 ± 5.9
V_{max} (km/h)	14.3 ± 1.3	16.3 ± 1.3	15.3 ± 1.6
HR_{max}	184 ± 8	189 ± 10	187 ± 9
3000m (km/h)	13.6 ± 1.3	15.4 ± 1.2	14.5 ± 1.5
Training background (yr)	12.5 ± 8.4	15.4 ± 8.4	13.9 ± 8.4
Running background (km/wk)	33.7 ± 21.7	38.9 ± 19.4	36.3 ± 20.5

Fat%, percentage of body fat; BMI, body mass index; VO_{2max}, maximal oxygen uptake; V_{max}, maximal velocity; HR_{max}, maximal heart rate

6.2 Study protocol

The study protocol included a total of 12 weeks of training, with pre-, mid- and post-measurements done between each period (on weeks 0, 5, and 14, respectively). The first phase of the study was a four-week long preparation period, during which subjects maintained their training volume at the same level as before the study. This period followed a classical periodization model of three hard training weeks followed by an easy training week with progressively increasing intensity throughout the period. The training included one long low intensity run, 2 - 4 normal low intensity runs, 1 - 3 moderate/high intensity runs, and muscle endurance circuit training once a week. 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, cross-country skiing). All subjects had 1 - 3 rest days per week.

The intensity of training increased throughout the four-week preparation period, while the volume was unchanged (table 5). During the first week, moderate/high intensity run was done at 80 - 85% of HR_{max} for 30 minutes, on the second week the subjects did a 40-min long tempo run at 80 -85% HR_{max} and a high intensity interval session of 4 x 4 minutes at 90 - 95% HR_{max}. On the final week the runners had a total of three moderate/high intensity sessions: the same sessions as on week two, and in addition a 30-min continuous run at 85 - 90% HR_{max}. All low intensity training was done below lactate threshold determined in the maximal incremental running tests at weeks 0 and 5 of the study.

TABLE 5. Training program during the 4-week preparation period for all the subjects, with regard to the type and order of moderate/high-intensity training sessions. In addition, subjects did low intensity training throughout the period.

Training week	Moderate/high intensity session		
	1	2	3
1	30 min @80 - 85% of HR_{max}		
2	40 min @80 - 85% of HR_{max}	4x4 min @90 - 95% HR_{max}	
3	40 min @80 - 85% of HR_{max}	4x4 min @90 - 95% HR_{max}	30 min @85 - 90% HR_{max}

For the second phase of the study, the subjects were randomly assigned to either the control (TRAD) group or the experimental (HRV) group according to a matched group experimental design based on sex, age, training background, endurance performance (VO_{2max}, V_{max}, velocities at lactate thresholds and 3000 m time) and heart rate variability. The second phase consisted of eight weeks of endurance training according to either a predefined (TRAD) or HRV-guided (HRV) training plan. The HRV-guided group maintained the volume at the same level as during the first phase of the study, meanwhile the intensity of training was regulated by a HRV based method. The idea was to manipulate daily training based on morning averaged HRV (rMSSD) values. If the morning rMSSD was inside of an individually determined optimal area (the SWC), moderate/high intensity training was prescribed for that day. On the other hand, if the rMSSD was above or below the SWC, the subject did either low intensity training or had a rest day. High intensity training was prescribed once the rMSSD returned to the mean level within the SWC. The training modes were the same as described for the preparation period. Thus, each subject followed an individual training program with individual amounts of training sessions and rest days per week. The moderate/high intensity sessions were cycled throughout the eight-week period so that the subjects did an equal amount of all three previously mentioned moderate/hard training sessions. The control group trained throughout the eight-week intervention period according to a pre-determined training plan, which included approximately 50% of weekly training sessions done at low intensities and the other 50% at moderate/high intensities in a periodized (3 + 1) fashion. The training volume was maintained at the same level as during the preparation phase. For all subjects during the study high intensity training had to be done by running while lower intensity sessions could be replaced by other endurance activities once or twice a week if necessary.

6.3 Data collection and analysis

All the tests were done in the laboratory of Research Institute for Olympic Sports (KIHU, Jyväskylä, Finland), or at the nearby indoor running track. Before the study all subjects were examined carefully during health assessment including ECG, height, weight, BP, blood tests, and a questionnaire on health status and training background.

Performance tests. The subjects were asked not to do any vigorous physical activity two days prior to running tests. Before each maximal incremental running test, body weight and percentage body fat was calculated using scales and skinfold assessment. Also, each subject gave a written consent before each test and the testing protocol was thoroughly explained to subjects before the testing began. Subjects were informed on their rights to end the test by raising their hand whenever they felt so. However, they were strongly encouraged to continue the test until exhaustion. Maximal incremental running tests were done on a treadmill (inclination 0.5°) before the study (pre, week 0), after the four-week preparation period (mid, week 5), and at the end of the eight-week intervention period (post, week 14). Before the test, subjects were allowed to warm up for 5 min at the speed corresponding to the speed during the first stage of the running test. Tests included 3 min stages and the speed was increased incrementally by 1 km/h after each stage with a starting speed of 7 km/h for women and 8 km/h for men. The treadmill was stopped after each stage for ca. 15 s to obtain blood sample from a fingertip. During the running test, breath-by-breath data of ventilation and respiratory gases (Oxycon Mobile, Viasys Healthcare GmbH, Hoechberg, Germany), as well as HR (Suunto t6 heart rate monitor, Suunto Oy, Vantaa, Finland), were continuously monitored. The maximal level was thought to be reached when the subject's RER reached a level of 1.05 or higher, when the HR no longer increased and when the VO_2 reached a plateau or started to decline. The highest VO_2 value during a 60-s period was considered the VO_{2max}. Blood samples from the fingertip were obtained at 1 and 3 minutes after the test had ended. From the test results, lactate thresholds 1 and 2 as well as HR and speed corresponding to those thresholds were determined for training purposes. Lactate thresholds were determined based on a rise and change in the inclination of the blood lactate curve during the test (Faude et al. 2009) as follows. Lactate threshold 1 (LT1) was set at 0.3 mmol/l above the lowest lactate value. Lactate threshold 2 (LT2) was set at intersection point between 1) a linear model between LT1 and the next lactate point and 2) a linear model for the lactate points with an increase in the lactate level of at least 0.8 mmol/l. The Oxycon Mobile was calibrated before each test. In addition, a 3000 m running test was conducted at a 200 m indoor running track (Jyväskylä, Finland) on three occasions, one week after the treadmill tests (pre, mid, post). The time to finish the task and maximal HR were monitored in the 3000 m test.

Weekly training monitoring. Subjects filled in a training diary throughout the study and reported the duration, distance, HR, own recovery feeling and RPE of every session. HR was monitored during all workouts with Garmin Forerunner 610 HR monitor (Garmin Ltd., USA). Details of the training were daily updated in OneDrive cloud service to make communication between the scientists and subjects as effortless as possible.

HRV recordings. All subjects were asked to record nightly HR and HRV with a Garmin HR monitor at least four times a week. According to some experts, measurements done at night time are most valid due to less error and a minimum amount of distractions such as environment, light, conscious thinking and so on. Also, as sleep is considered a major part of the recovery process, it has been suggested that HRV measurement during night time could serve as a valuable tool in monitoring an individual's adaptation to training and state of recovery. (Hynynen et al. 2006; Nummela et al. 2010; Hynynen 2011; Hynynen et al. 2011; Dupuy et al. 2012; Myllymäki et al. 2012; Vesterinen et al. 2013, 2014.) The night measurement started before subjects went to bed and ended after they woke up. The first 30 minutes was excluded from the analysis and the following 4 hours was then analyzed with a computer, using Firstbeat SPORTS software (version 4.0.0.5 Firstbeat Technologies Ltd., Jyväskylä, Finland). Recordings with an error percent higher than 33% (based on the results from previous studies; Vesterinen et al. 2013, 2014) were excluded from the analysis. Data were inspected with the help of the Firstbeat SPORTS software to identify artifacts and occasional ectopic beats were removed using excel (Microsoft Excel 2010). NN periods were selected for the analysis to determine rMSSD and mean HR. In addition to night measures, HRV-guided training group measured daily HRV (rMSSD) values every morning upon awakening and emptying their urinary bladder. The subjects used a commercial Omegawave device (Omegawave Ltd., Finland) for real-time analysis of rMSSD taken every morning, which is the prescribed exercise for that day. Omegawave measures ECG with a belt, after which the data is exported to a cloud service and analyzed using patented algorithms. Thereafter, data is transformed into a smart phone application (compatible with Apple and Android devices). The morning measurement was done in supine position and the recording lasted 3 minutes. The subjects were encouraged to breathe as normally as possible, and the breathing rate was chosen not to be controlled.

The SWC. The optimal area of rMSSD for each subject in the HRV-guided training group was determined based on the individual variation seen in HRV during the four-week preparation period, and this area was updated after four weeks of training in the middle of the main training period. Based on Kiviniemi et al. (2007) and Plews et al. (2012, 2013b) the SWC was determined as mean ± 0.5 * SD. To clarify the basic idea behind the SWC, the reader is referred to figures 9 and 11, where the SWC is presented as a gray horizontal area. If a 7-day rolling average of rMSSD fell outside the SWC, HIT was discontinued and the subjects did either low intensity exercise or rested, depending on the number of the workouts they had every week. When the rMSSD value returned inside the SWC to the mean level, the subjects were instructed to train hard again. The subjects had the same number of sessions and rest days every week, but the intensity of sessions was altered based on daily HRV measures. Although higher than normal HRV values are thought to be a sign of positive adaptation to training (Buchheit 2014), some studies have showed that increased vagal activity – called parasympathetic hyperactivity – could actually be a sign of functional overreaching (Plews et al. 2013b, Le Meur et al. 2013). This is why HRV values falling either below or above the SWC were considered as a sign of an abnormal situation and, in these occasions, rest or low intensity exercise was prescribed. Also, as Buchheit (2014) concludes, due to changes in ANS activity as a result of endurance training and other factors, the actual magnitude of the SWC needs to be varied over the time.

This is why the optimal area we used in our study was updated in the middle of the eight-week long second period according to changes in individual HRV patterns.

7-day rolling average. Since HRV has a naturally high day-to-day variation (CV = 10 - 20% for Ln rMSSD; Buchheit 2014), it is nowadays suggested that practitioners use weekly or multiple-day (usually 7 to 10 days) rolling averages rather than single data points when analyzing HRV. For example, a 7-day rolling averaging is done with a 7-day window that moves day by day, including the HRV value obtained from the measurement of a certain day and the values obtained from six previous days. These averaged values have been shown to have a better methodological validity because the possibility of errors due to environmental factors or acute changes in homeostasis is minimized. (Kiviniemi et al. 2007; Kiviniemi et al. 2010; Plews et al. 2012; Le Meur et al. 2013; Plews et al. 2013a, 2013b; Buchheit 2014.) A minimum of three to four or four to five measurements per week for higher level athletes or recreational athletes, respectively, should be done in order to get enough data on HRV and to avoid problems of random measuring (Plews et al. 2014b). Based on the recent research findings regarding isolated and averaged values, the 7-day rolling averaging was chosen in this study to analyze changes in daily HRV.

6.4 Statistical analysis

The results are expressed as means ± standard deviations (SD). The SWC was calculated from the RMSSD measures recorded during the four-week-long first training period as follows: SWC = mean ± 0.5 * SD. The SWC was updated in the middle of the eight week's training period based on the values during the first four weeks of the second period. The Gaussian distribution of the data was assessed with the Shapiro-Wilk goodness-of-fit test.

The adaptation to training was analyzed separately for the first and second training period as well as the whole study period with the Student's t-test for related samples followed by Bonferroni as a *post hoc* test. To analyze the differences in the training adaptation between HRV and TRAD after the second training period, Student's t-test for independent samples was used. To further analyze differences between men and women in HRV and TRAD, Kruskal-Wallis test was used due to relatively small sample size. Coefficient of variation (CV) was calculated for training data to compare heterogeneity of data between groups. As not all training and HRV data was normally distributed, correlations between the amount of HIT during the second training period and the adaptation to endurance training from mid to post measurements, and the amount of HIT and HRV, as well as correlations between the change in endurance performance parameters and the change in HRV, were tested with the Spearman's correlation coefficient. Differences in training realization during the second training period between HRV and TRAD were analyzed with Mann-Whitney U-test and for the analysis of the differences in training between genders and training groups Kruskal-Wallis test was chosen. To analyze differences in daily vs 7-day rolling averaged RMSSD values Friday was chosen for the analysis due to consistent data points, and the daily RMSSD of that specific day was compared with the 7-day rolling averaged RMSSD of that specific day. CV was calculated for $RMSSD_{day}$ and $RMSSD_{rollavg}$ to compare difference between single and rolling averaged RMSSD. Differences in baseline HRV between men and women were analyzed with the Mann-Whitney U-test. Because one of the main aims of the study was to individualize endurance training, ten subjects who improved their velocity in the 3000 m run the most, the least, and who did the most and the least HIT during the second training period, were selected for further analysis. Differences between these groups (responders, non-responders, HIT and LIT, respectively) were tested with the Kruskal-Wallis test. Furthermore, one subject (from HRV group) from each aforementioned group was selected for further analysis in a case comparison manner with regard to training adaptation, training intensity distribution and morning RMSSD profile. All data was analyzed using Microsoft Excel 2013 for Windows and IBM SPSS Statistics 20 (SPSS Inc, Chicago, USA). Probability level of $p \leq 0.05$ was applied as an indicator of statistical significance.

In addition to traditional statistics, a qualitative approach based on the magnitudes of change was applied to test differences between study groups (Hopkins et al. 2007). The magnitude of change after training, and the differences between groups were expressed as standardized mean differences (effect size, ES), calculated from pooled means and standard deviations. Threshold values for Cohen's ES statistics were <0,2 (small), 0,2 - 0,5 (moderate) and >0,5 (large). Confidence intervals (90%) for the true mean changes or between group differences in the training response were estimated (Hopkins et al. 2009). For within- and between-group comparisons, the chances that the true changes in performance for HRV group were greater (i.e. greater than the SWC [0,2 multiplied by the between-subject standard deviation, based on Cohen's effect size principle (Cohen 1988)], unclear or smaller than these for the TRAD group were calculated. Quantitative changes of higher or smaller training effects were assessed as follows: <1%, almost certainly not; 1 - 5%, very unlikely; 5 - 25%, unlikely; 25 - 75%, possible; 75 - 95%, likely; 95 - 99% very likely; >99%, almost certain. If the chance of having better or poorer performances were both >5%, the true difference was assessed as unclear (Hopkins et al. 2009).

7 RESULTS

Participants. Nine of the 40 subjects failed to complete the study due to injury (n = 2), illness (n = 2), or lack of training program participation (i.e. <90% of all training sessions in HRV group and more than 2 main training sessions missing in TRAD-group, n = 5), and were not included in the analysis. Finally, a total of 31 subjects (14 women, 17 men) were included in the analysis.

Anthropometrics. During the whole study period, body weight (-1.4 ± 1.8 %, p = 0.020) and BMI (-1.4 ± 1.8 %, p = 0.023) changed significantly in HRV but not in TRAD (-1.1 ± 1.9 % and -1.0 ± 2.1 %, respectively), whereas body fat % did not change in either HRV or TRAD (+5.3 ± 1.9 % and -2.0 ± 8.2 %, respectively).

Endurance training characteristics. There were no significant differences in training time and frequency per week, or percentage of total time in zones 1, 2 and 3 (training at intensities below LT_1, between LT_1 and LT_2, or above LT_2, respectively), between HRV and TRAD during first and second (figure 13) training period (table 6). However, the number of HIT sessions during the second training period was significantly higher (p = 0.021) in TRAD (17.7 ± 2.5 sessions) compared to HRV (13.2 ± 6.0 sessions).

TABLE 6. Training characteristics during the first and second training period in HRV and TRAD. Values are means ± SD.

Training characteristics	HRV		TRAD	
	1. period	2. period	1. period	2. period
Times/wk	5.9 ± 1.2	6.1 ± 1.0	5.9 ± 5.6	7.1 ± 6.2
Hours/wk	6.9 ± 2.1	6.5 ± 1.7	7.1 ± 1.6	6.2 ± 1.5
Time in zone 1 (%*)	88.1 ± 4.1	82.7 ± 11.8	88.2 ± 4.5	84.0 ± 6.9
Time in zone 2 (%*)	10.1 ± 4.3	14.7 ± 10.0	10.4 ± 4.4	12.7 ± 5.3
Time in zone 3 (%*)	1.8 ± 1.5	2.6 ± 2.3	1.4 ± 0.9	3.2 ± 2.7

* of total training time; HRV, HRV-guided training group; TRAD, predetermined training group; zone 1, intensities below the first lactate threshold; zone 2, intensities between the first and the second lactate thresholds; zone 3, intensities above the second lactate threshold.

Individual endurance training adaptation. During the first training period (pre-mid), endurance performance of all subjects improved significantly as follows: 3000 m run (km/h) by 2.7 ± 2.5 % ($p < 0.001$), VO_{2max} by 2.9 ± 4.4 % ($p = 0.003$), V_{max} by 2.0 ± 3.1 % ($p = 0.002$), V_{LT2} by 4.3 ± 7.4 % ($p = 0.001$) and V_{LT1} by 4.8 ± 8.0 % ($p = 0.001$). Changes in endurance performance after the 8-week-long second training period (mid-post) in HRV and TRAD are shown in table 7 and figures 14 and 15.

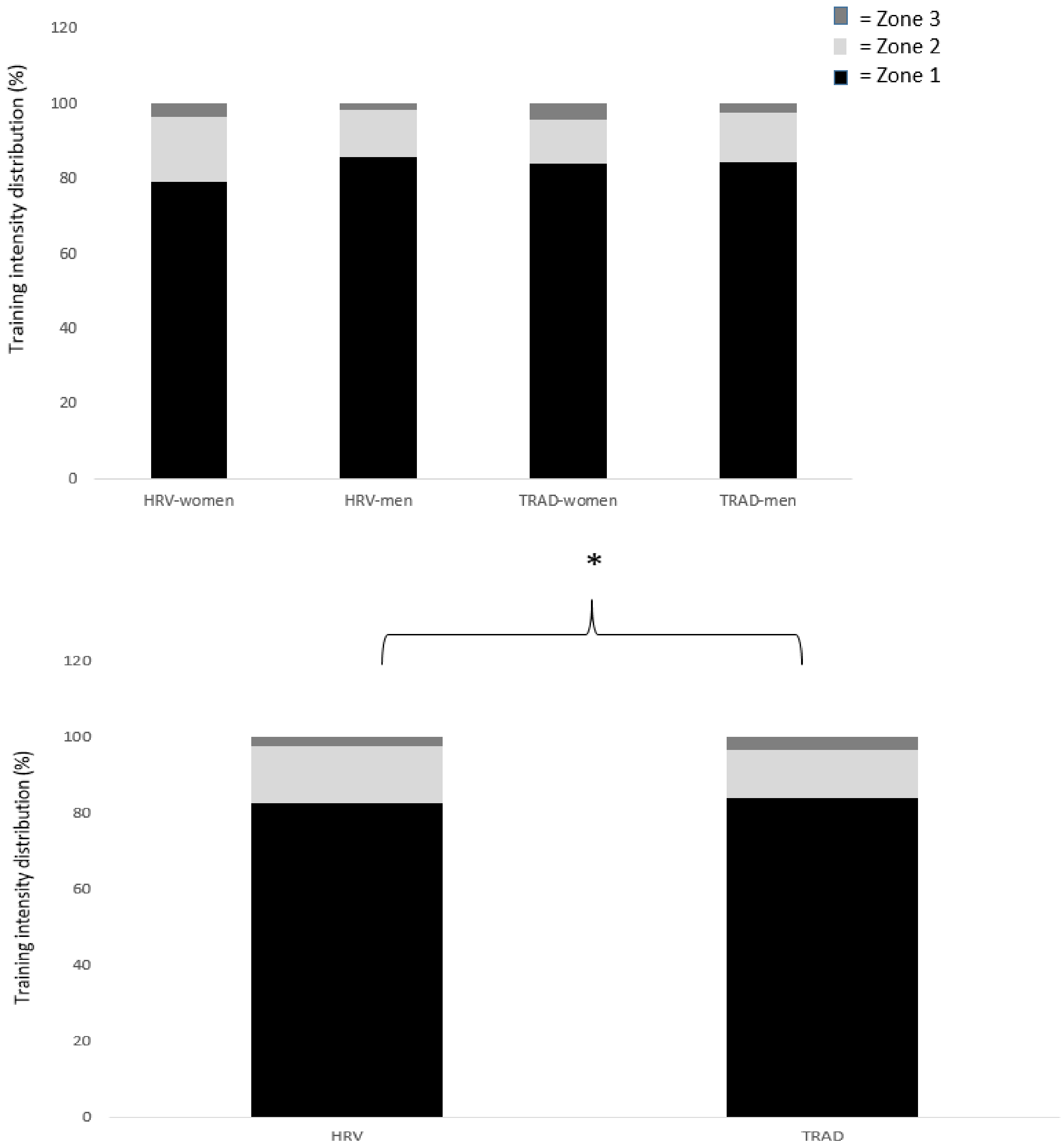

FIGURE 13. Training intensity distribution across three zones during the second training period in HRV-women, HRV-men, TRAD-women and TRAD-men (above), and in HRV and TRAD training groups (below). * $p < 0.05$, significant difference in the amount of HIT during the second training period.

Average speed in the 3000 m test run increased in HRV 2.1 ± 2.0 % ($p = 0.004$) but not in TRAD, the magnitude of difference approaching moderate between the groups (ES = 0.42). HRV and TRAD increased their VO_{2max} by 3.7 ± 4.6 % ($p = 0.027$) and 5.0 ± 5.2 % ($p = 0.002$), respectively, with a small between-group difference (ES = -0.26). Maximum velocity (2.6 ± 2.7 %, $p = 0.005$; 2.1 ± 1.8 %, $p < 0.001$) as well as velocity at LT2 (2.6 ± 3.3 %, $p = 0.025$; 1.9 ± 2.2 %, $p = 0.004$) and LT1 (2.8 ± 3.7, $p = 0.028$) all increased significantly in HRV and all but V_{LT1} increased significantly in TRAD, respectively. The differences between HRV and TRAD in the magnitude of change in these parameters were trivial (ES = 0.11), trivial (ES = 0.06) and small (ES = 0.41), respectively.

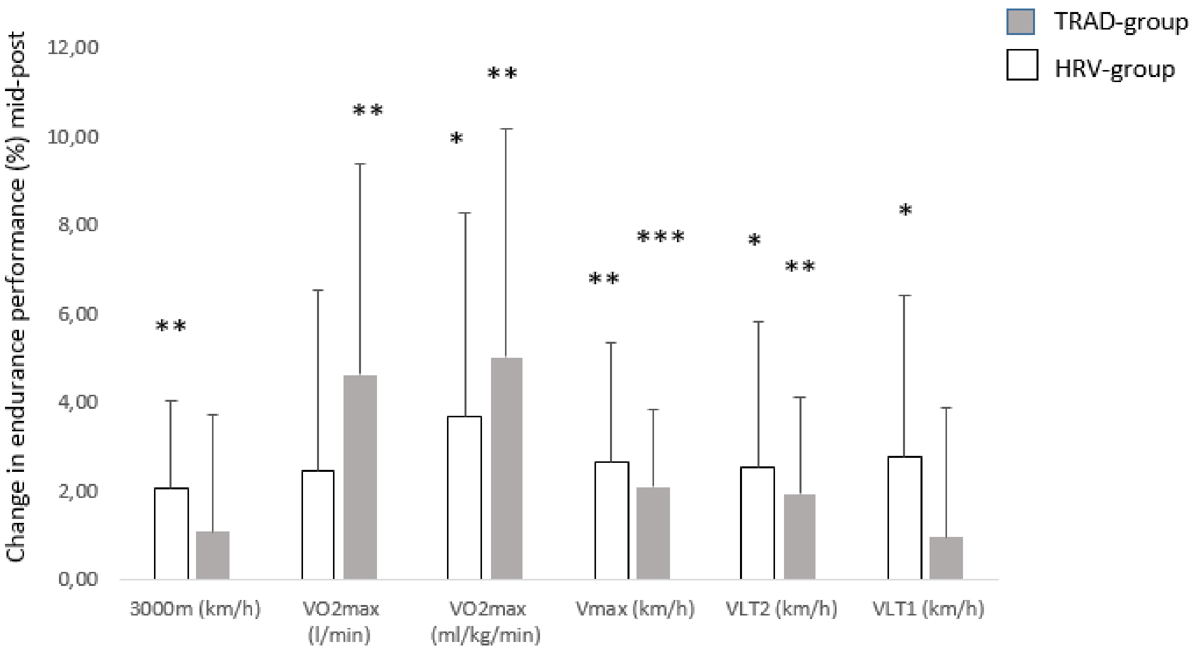

FIGURE 14. Changes (%) in endurance performance between HRV (white bars) and TRAD (gray bars) after the second training period. *Bars* represent the means and *vertical lines* standard deviations. * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$, significant difference from week 5.

HRV-women improved 3000 m run performance significantly (2.5 ± 1.4 %, $p = 0.011$) whereas changes in HRV-men, TRAD-women and TRAD-men were not significant. Instead, VO_{2max} improved significantly only in TRAD-men (4.4 ± 4.5 %, $p = 0.030$) but not in HRV-men, HRV-women and TRAD-women. HRV-women, TRAD-men and TRAD-women achieved highest improvements in V_{max} (3.7 ± 2.5 % $p = 0.021$; 2.0 ± 1.7 %, $p = 0.010$; 2.2 ± 2.0 %, $p = 0.015$, respectively) while HRV-men had no significant improvements. V_{LT2} increased the most in

HRV-women and TRAD-men (3.1 ± 2.4 %, p = 0.049; 2.1 ± 2.4 %, p = 0.045), whereas in other groups improvements were less prominent. No statistically significant changes were observed in the endurance training adaptation between HRV and TRAD, or between HRV-women, HRV-men, TRAD-women and TRAD-men. However, qualitative analysis based on magnitudes of change showed some statistical differences between groups as indicated above.

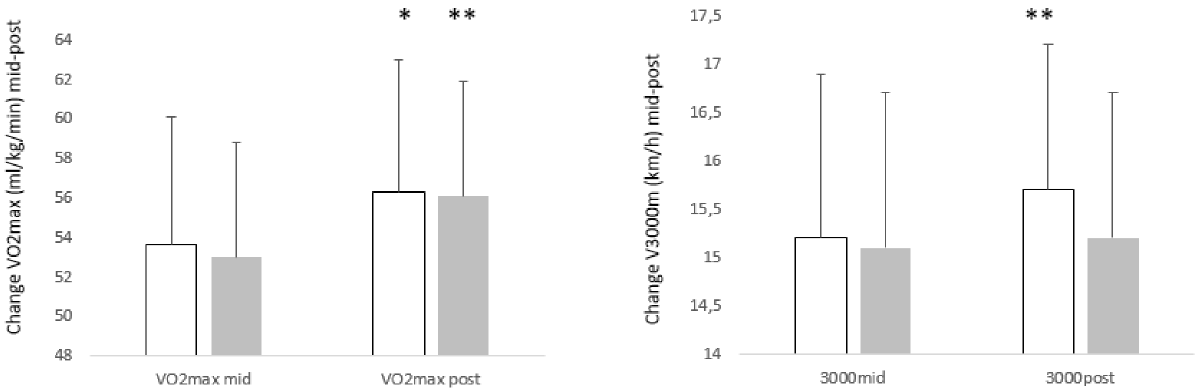

FIGURE 15. Changes in VO_{2max} (ml/kg/min) (left) and V_{3000m} (km/h) (right) from wk5 to wk14 in HRV-group (white bars) and TRAD-group (gray bars). *Bars* represent means, *vertical lines* are standard deviations. * $p < 0.05$, ** $p < 0.01$, $p < 0.001$ significant change from mid to post.

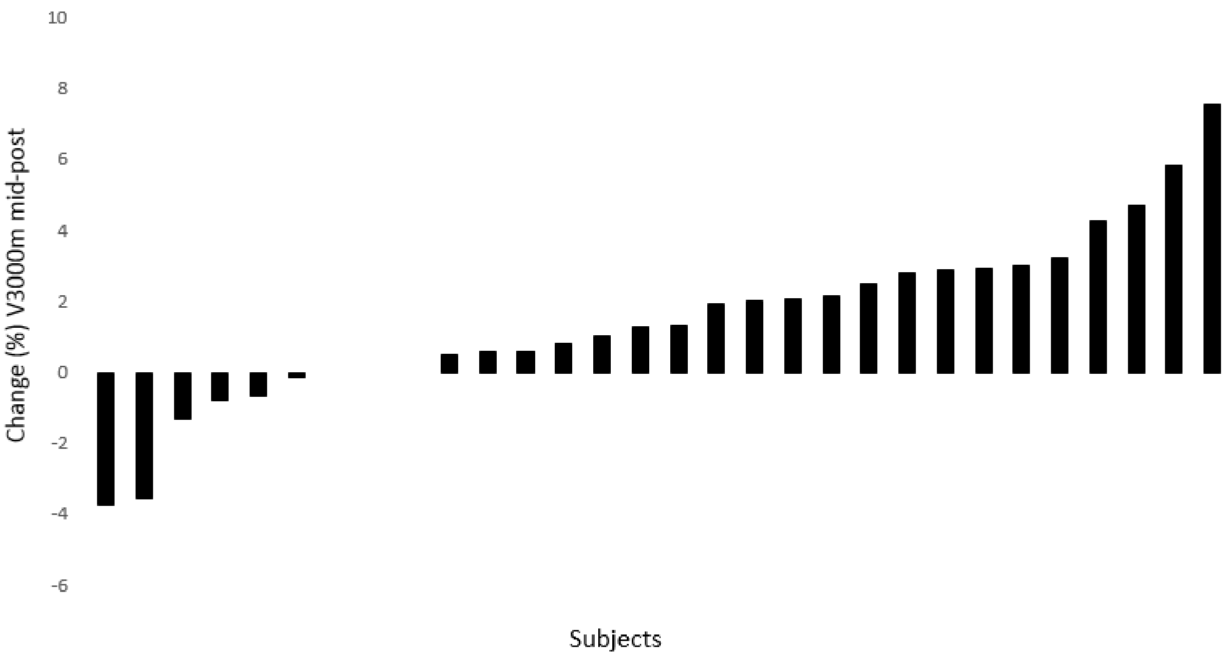

FIGURE 16. Individual differences in change in the velocity in the 3000 m run (V_{3000m}) following second training period in all subjects. *Bars* represent individual subjects.

TABLE 6. Endurance performance, nocturnal HRV indices and daily RMSSD measures in HRV and TRAD during mid (wk 5) and post (wk 14) measurements. Values are means ± SD.

	Mid		Post	
	HRV (n = 13)	TRAD (n = 18)	HRV (n = 13)	TRAD (n = 18)
Endurance performance				
3000m (km/h)	15.2 ± 1.7	15.0 ± 1.6	15.7 ± 1.7 **	15.2 ± 1.5
VO_{2max} (l/min)	3.8 ± 0.9	3.6 ± 0.8	3.9 ± 0.9	3.8 ± 0.8 **
VO_{2max} (ml/kg/min)	53.6 ± 6.5	53.0 ± 5.8	56.3 ± 6.7 *	56.1 ± 5.8 **
V_{max} (km/h)	15.7 ± 1.7	15.5 ± 1.5	16.3 ± 1.6 **	16.0 ± 1.4***
V_{LT2} (km/h)	13.3 ± 1.4	12.8 ± 1.6	13.8 ± 1.3 *	13.1 ± 1.4 **
V_{LT1} (km/h)	10.9 ± 1.2	10.6 ± 1.4	11.3 ± 1.2 *	10.8 ± 1.4
Nocturnal HRV indices				
HR (bpm)	56 ± 5	50 ± 4	54 ± 5	50 ± 4
LFP (ms)	2951.7 ± 1283.2	3147.0 ± 1417.8	2919.3 ± 1342.1	2722.5 ± 1533.4
HFP (ms)	2451.0 ± 2255.0	2223.8 ± 1108.4	2882.3 ± 2304.2	1790.3 ± 1048.7
RMSSD (ms)	58.3 ± 24.1	59.1 ± 17.3	62.5 ± 28.6	54.4 ± 15.0
SDNN (ms)	111.0 ± 24.1	118.3 ± 21.0	114.4 ± 25.6	109.5 ± 19.6
Morning Omegawave measures				
$RMSSD_{day}$	44.2 ± 27.5		58.2 24.5	
$RMSSD_{rollavg}$	65.2 ± 27.5		69.3 30.9	

* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$ (significant difference from wk 5)

HRV, HRV-group; TRAD, traditional training group; VO_{2max}, maximal oxygen uptake; V_{max}, maximal velocity; V_{LT2}, velocity at lactate threshold 2; V_{LT1}, velocity at lactate threshold 1, HR, resting heart rate; LFP, low frequency power; HFP, high frequency power; RMSSD, root mean square of the differences between adjacent R-to-R peak intervals; SDNN, standard deviation of R-to-R peak intervals; $RMSSD_{day}$, morning RMSSD on a single day; $RMSSD_{rollavg}$, 7-day rolling averaged morning RMSSD

$RMSSD_{day}$ vs $RMSSD_{rollavg}$. The weekly averages and the CV's for the $RMSSD_{day}$ and $RMSSD_{rollavg}$ from week 1 to week 14 are shown in table 8. $RMSSD_{day}$ changed -25.3 ± 24.5 % from pre to post, while $RMSSD_{rollavg}$ changed only -8.3 ± 18.4 %, the difference in the magnitude of change approaching large (ES = -0.78). The CV of the mean $RMSSD_{day}$ in all HRV subjects during the whole study period was 14.5 %, whereas the corresponding value for the $RMSSD_{rollavg}$ was 6.7 %.

TABLE 8. Weekly daily and 7-day rolling averaged values of morning RMSSD (means ± SD) and the coefficients of variation (CV) of these values.

Week	$RMSSD_{day}$ (ms)			Cv $RMSSD_{day}$ (%)	$RMSSD_{rollavg}$ (ms)			CV $RMSSD_{rollavg}$ (%)
1	77,1	±	28,9	46,1	71,7	±	30,0	42,4
2	79,0	±	36,4	32,9	76,9	±	32,6	48,8
3	88,8	±	29,2	53,9	77,7	±	37,9	38,1
4	81,8	±	44,1	44,1	71,8	±	27,4	42,2
5	69,3	±	30,6	62,3	65,2	±	27,5	46,9
6	44,2	±	27,5	48,2	68,0	±	31,9	46,7
7	66,1	±	31,9	56,6	65,9	±	30,8	48,1
8	68,5	±	38,7	62,3	68,2	±	32,8	54,9
9	67,3	±	41,9	64,7	62,5	±	34,3	47,3
10	62,4	±	40,3	50,3	63,5	±	30,0	44,0
11	70,0	±	35,2	56,0	64,8	±	28,5	46,2
12	62,6	±	35,0	54,8	67,9	±	31,4	42,6
13	70,3	±	38,5	57,8	70,8	±	30,2	44,6
14	74,7	±	43,2	42,2	69,3	±	30,9	37,5
Mean ± SD	70,1	±	10,2	52,3 ± 8,3	68,9	±	4,4	45,0 ± 4,2

*** large (ES > 0.8) difference between the mean CV's of the $RMSSD_{day}$ and the $RMSSD_{rollavg}$.

moderate (ES = 0.78) difference between the change in the $RMSSD_{day}$ compared to the change in the $RMSSD_{rollavg}$ from pre to post.

Case comparison – individuality of training adaptation. Individual variability in the endurance training adaptation during the second training period was high (figure 16), and therefore for further analysis subjects were divided into responders and non-responders based on the improvement in the velocity in the 3000 m run (V_{3000m}), and HIT and LIT based on the amount of HIT sessions. Ten subjects who had the highest and lowest values in the aforementioned variables were chosen for analysis. There were no significant differences between responders and non-responders in the amount of HIT (15.6 ± 5.1 and 17.6 ± 3.2 sessions, respectively). Neither were there any statistically significant differences between HIT and LIT in any parameters of endurance training adaptation. Subject #52 from the TRAD group improved the most (V_{3000m} +7.6 %) compared to the second best improvement in subject #46 in HRV group (+5.8 %), both subjects did 16 HIT sessions. The least improvement – in fact a decrement – in the V_{3000m} was found in subject #42 (-3.7 %, TRAD group) and the only subject from the HRV among the six least improved was subject #37 who had third least improvement (-1.3 %). Subjects #42 and #37 did 19 and 11 HIT sessions, respectively. Subjects #30 and #8 (V_{3000m} +2.9 % and +4.3 %, respectively) did the most HIT sessions (21 and 22 sessions, respectively) during the second period, while the least HIT sessions (5 and 6 sessions) were recorded by the subjects #11 and #28 (V_{3000m} +0.6 % and +0.8 %, respectively), all from HRV group.

There were also between-subject differences in daily and averaged RMSSD values (table 9). RMSSD profiles of subjects who improved their V_{3000m} the most (subject #46) and the least (#37), and who did the most (#8) and the least (#11) HIT sessions during the second period, were selected for further analysis from the HRV group (figure 17). $RMSSD_{rollavg}$ of subject #8 (responder) was above the SWC on week 15 (post measurements), as was the case also for subject #37 (non-responder). Instead, in subject #11 (non-responder) the value approached the mean, and in subject #46 (responder) the value was at the lower limit of the SWC. On the last week before the measurements, subjects ran 52 km (#46), 12 km (#37), 34 km (#11) and 20 km (#8).

TABLE 9. Individual differences between four subjects from the HRV group in endurance training adaptation and RMSSD values.

	Subjects			
	#46 (responder)	#37 (non-responder)	#8 (responder)	#11 (non-responder)
ΔV_{3000m} (%) mid-post	+5.8	-1.3	+4.3	+0.6
Number of HIT	16.0	11.0	22.0	5.0
Mean RMSSD	46.8	93.7	95.3	21.6
CV for RMSSDday	57.6	35.8	28.7	36.6
CV for RMSSDrollavg	25.6	22.3	11.3	21.6

ΔV_{3000m}, change in the velocity in the 3000 m run; HIT, high intensity training; RMSSD, root mean square of the squared differences between adjacent R-R intervals; CV, coefficient of variation

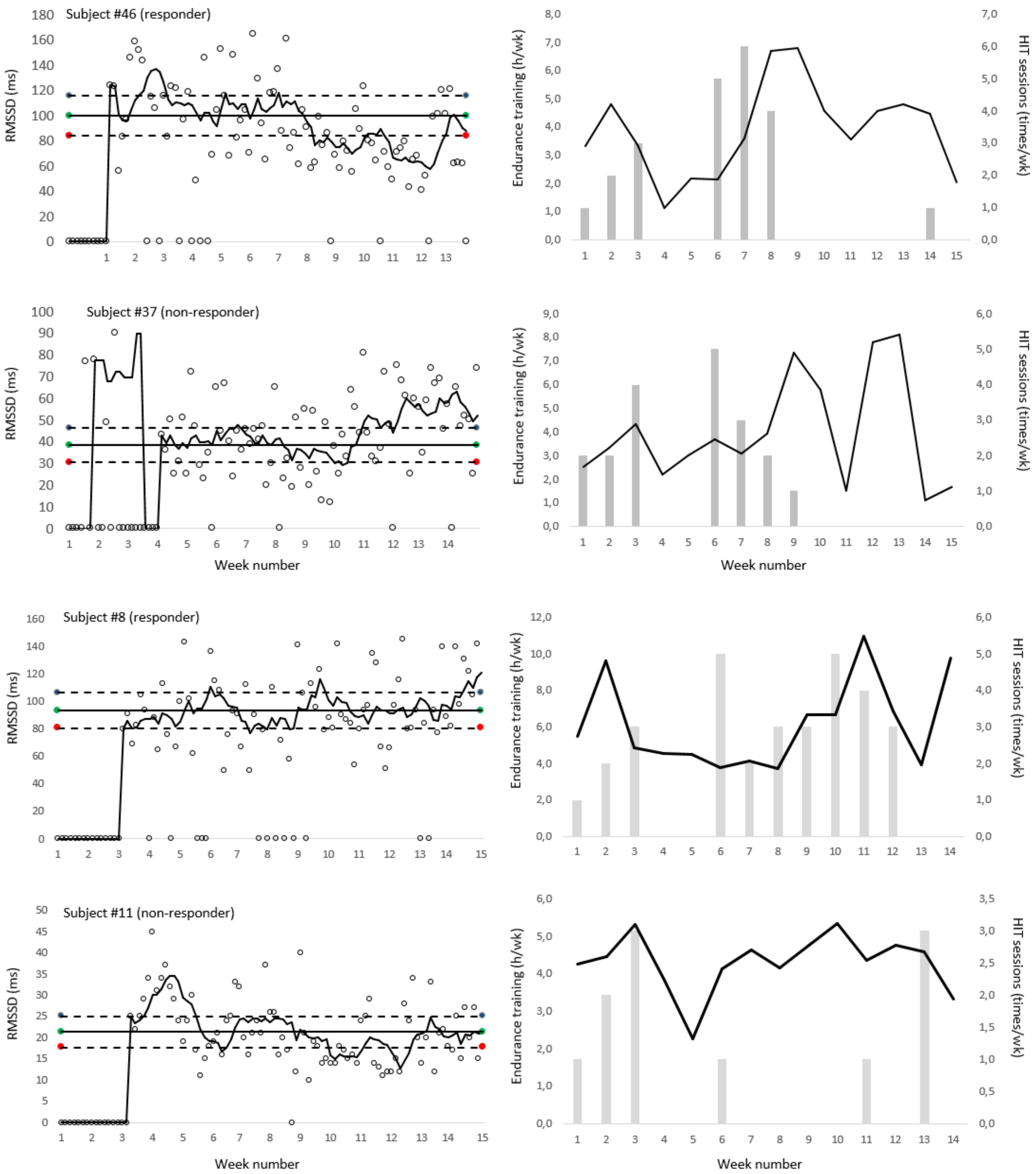

FIGURE 17. RMSSD profiles (left panel) and weekly amount endurance training (h) and HIT sessions (times) (right panel) in subjects #46 and #37, and #8 and #11 (improved the most and the least, and did the most and the least HIT sessions during the second period, respectively). In the left panel, *open circles* represent daily RMSSD values and the *black line* corresponds to the 7-day rolling averaged RMSSD value. *Black horizontal line* indicates the mean RMSSD, *black dashed horizontal lines* indicate the upper and lower limits of the individual SWC. In the right panel, *black bars* lines indicate the amount of endurance training (h) per week, *gray bars* represent the amount of HIT sessions done per week.

8 DISCUSSION

To our knowledge, this is the first study to investigate the effect of HRV guided block periodized training on endurance training adaptation in recreational men and women. The main findings of this study were that endurance training guided by daily HRV resulted in less HIT and significantly better improvements in the 3000 m run compared to TRAD. Additionally, while HRV group improved more in the 3000 m running test and had bigger improvements in the V_{LT1}, TRAD group had slightly better improvements in other endurance performance variables (VO_{2max}, V_{max}, V_{LT2}). Gender differences were relatively small and did not reach statistical significance. There were significant differences in the morning $RMSSD_{day}$ and $RMSSD_{rollavg}$. The CV of a 7-day rolling averaged RMSSD was found to be significantly smaller than that of a single day value. Individual differences were rather high in both endurance training adaptation and morning RMSSD profiles.

Endurance training adaptation. As was expected, HRV guided training resulted in somewhat better improvements in aerobic fitness compared to traditional model. Indeed, HRV improved all parameters of endurance performance (3000 m run, VO_{2max}, V_{max}, $V_{LT2,}$ V_{LT1}) while TRAD improved all but 3000 m run and V_{LT1}. Noteworthy is the significant improvement in the velocity of the 3000 m run in HRV as opposed to no improvement in TRAD even though HRV did less high intensity training. However, it should be noted that the magnitude of improvement in the VO_{2max}, V_{max} and V_{LT2} was more pronounced in TRAD. The findings are in line with previous two studies which have shown better improvements in endurance performance after HRV guided training compared to traditional approach (Kiviniemi et al. 2007, 2010).

However, in a recent study by Botek et al. (2013) the range of improvement after HRV guided training was reported to be from -8.8 % to +8.5 %, which is a rather high range. Our study had a range of improvement in the V_{3000m} from -1.3 % to +5.8 % (in the HRV group), which is a bit more narrow than that of Botek et al. (2013) but still shows there was some individual variability. Interestingly, the range of improvement in the V_{3000m} was higher in TRAD (-3.7 % to 7.6 %) compared to that of HRV, probably due to the fact that training was more general than that of HRV group. The reason why HRV improved V_{LT1} while TRAD did not may be due to the fact that HRV did less high intensity, and thus more low intensity training compared to TRAD. It has been well documented in the literature that low intensity training below one’s first lactate threshold is an efficient way to improve the velocity at that threshold (Jones & Carter 2000; Stöggl & Sperlich 2014). Furthermore, high intensity training has been advocated to be one of the best methods to improve one's maximal aerobic capacity (Helgerud et al. 2007; Midgley et al. 2007; Hatle et al. 2014; Rønnestad et al. 2014a, 2014b; Stöggl & Sperlich 2014). Indeed, probably due to a higher frequency of high intensity training, TRAD had more pronounced improvements in the physiological markers (VO_{2max}, V_{max}, V_{LT2}) related to maximal aerobic capacity. However, what is interesting is that HRV guided training appeared to lead to a better overall improvement in all aspects of endurance performance compared to TRAD. Furthermore, as HRV improved the V_{3000m} – a performance parameter probably more closely related to real-life racing performance compared to the VO_{2max} – significantly but TRAD failed to do so, this may indicate that HRV guided training, despite of or due to the fact that it resulted in less HIT sessions, may be a more cost-efficient training method.

The reason for the fact that TRAD improved equally well than HRV in other aforementioned performance variables may lie in the fact that the subjects in the current study were not highly trained athletes, i.e. their level of fitness was at the level where a more generalized training plan may still work. In addition, the training program for TRAD was actually harder than what generally is advised, i.e. 50 % of all training was carried out at high intensities. This may have further stimulated the beneficial physiological adaptation in response to predetermined training since, as already mentioned, high intensity training is an efficient way to improve endurance performance. It has been shown earlier that highly trained individuals and especially elite athletes need to stress their bodies to the limits by doing high intensity or extremely long duration training sessions to acquire the desired improvement in physiological markers of endurance (Jones & Carter 2000). Thus, the higher the initial level of fitness, the more difficult it becomes to increase the level of aerobic capacity. In line with the current literature suggesting that programming high intensity training on days when cardiac autonomic function is elevated may optimize endurance training adaptation (Stanley et al. 2013; Plews et al. 2014a), our study found that HRV guided endurance training resulted in a better overall improvement in endurance performance, and also a significant improvement in the 3000 m run velocity. Whether the results would have been different had the sample size been larger (i.e. more than 14 subjects in the HRV, 17 in the TRAD) or whether the methodological issues (discussed later) had something to do with it, remains to be decided.

We did not find any clear difference in endurance training adaptation between genders. The only differences were that HRV-women improved their 3000 m test run and V_{LT2} more than other subgroups. In our study, both genders in HRV group had the same instructions on how to program daily training, whereas in a study by Kiviniemi et al. (2010) women and men had different instructions as to when HIT was allowed. Indeed, women were found to benefit from a different (i.e. less frequent HIT sessions) HRV guided training than men (Kiviniemi et al. 2010), and thus it may be possible that the results in our study would have been different if men and women had had separate instructions.

Training characteristics. There was a statistically significant difference in the mean number of HIT sessions during the second training period between HRV and TRAD. Indeed, HRV trained 13 times and TRAD 15 times at high intensity during the main training period. Noteworthy is the fact that the variability in the number of HIT within groups as expressed by the CV was much higher in HRV (5 - 23 sessions, CV = 45.8 %) than in TRAD (10 - 21 sessions, CV = 30.4 %). These findings are in accordance with Kiviniemi et al. (2007, 2010), who showed that HRV guided training leads to less frequent high intensity training compared to predetermined training. There were no gender differences in the training characteristics.

Morning RMSSD. Both daily (-25.3 %) and 7-day rolling averaged RMSSD (-8.3 %) decreased from the first week of the study to the final week. However, the decrease was much more pronounced in the daily RMSSD value compared to the averaged one, indicating that the rolling averaged value is much more stable value for use in practice. Indeed, there were significant differences between single day and 7-day rolling averaged morning RMSSD values, shown by smaller CV's for the latter (6.7 %) compared to the former (14.5 %). This indicates that $RMSSD_{rollavg}$ is a more reliable measure of cardiac function due to more stable data points. This finding is in accordance with previous studies which have repeatedly shown that HRV has a naturally high day-to-day variability (Buchheit 2014) and thus concluded that, compared to single day data points, averaging HRV values over seven or ten days provides a more reliable tool for estimating cardiac function (Kiviniemi et al. 2007; Kiviniemi et al. 2010; Plews et al. 2012; Le Meur et al. 2013; Plews et al. 2013a, 2013b; Buchheit 2014).

However, despite the fact that we used the rolling averaged values of RMSSD to prescribe training for subjects in the HRV group, the adaptation to training was not significantly different between the groups, even if the HRV had better improvements in the 3000 m run. This may be due to the fact that, contrary to previous studies which have used only a lower limit of the SWC to decide whether the subject needs to train hard or rest (Kiviniemi et al. 2007, 2010), in the present study both upper and lower limits of the SWC were used. The reason for limiting hard training to days on which the 7-day $RMSSD_{rollavg}$ was within the SWC was that, in some cases especially in well-trained athletes, HRV can actually increase during periods of intensified training and consequent overreaching due to a phenomenon called parasympathetic hyperactivity (Le Meur et al. 2013; Plews et al. 2013b). This was shown in a study by Le Meur et al. (2013) where intensified training leading into functional overreaching induced parasympathetic hyperactivity as assessed with weekly averaged HRV, although running performance was greatly reduced. However, it can be speculated whether the use of the upper limit of the SWC was necessary in the present study given the moderate level of aerobic capacity in our subjects. Indeed, it has been suggested that in highly trained, or elite level athletes a saturation effect is possible, where HRV is reduced at low levels of resting HR despite an increased level of fitness (Plews et al. 2012; Plews et al. 2013b; Buchheit 2014). To the current knowledge, this usually happens in those with extensive endurance training background and a higher than normal level of endurance capacity, which was clearly not the case in subjects of the present study. Therefore, we cannot rule out the possibility that the results of our study could have been somehow different if only the lower limit of the SWC had been used.

The second difference in HRV-guided training compared to previous studies was that we did not limit the amount of high or low intensity days done in a row. This was due to the fact that, this way, training would resemble much more that of real life athletic training where, at times, athletes may conduct a high intensity training block of several days' duration and thereafter recover from it with a number of easy/rest days. In our study, the only requirements were that each subject had the same amount of training days a week compared to what they had had before the study, and how they had trained during the first period. Thus, each subject trained at high intensity as long as his/her 7-day moving averaged RMSSD fell outside the SWC. Likewise, low intensity training was prescribed for as long as the subject's RMSSD returned to within the SWC and to the mean level. In comparison, Kiviniemi et al. (2007, 2010) had subjects do at highest two hard training days, or two rest days in a row, and at highest nine training days in a row, which is not that close to real life athletic training.

Nonetheless, it can be argued that perhaps the use of the "return to the mean level" was not necessary. For example, one can ask whether a return to the ¼ SD instead of the mean level we used in the current study, would have resulted in more frequent HIT sessions, and a better response to training. The other issue that needs to be considered here is the determination of the SWC from the baseline measurements. This is an important part of the HRV guided training protocol since by monitoring the individual during a period of time when everything is going well and when the person is not stressed mentally or physically, it is possible to create the frames, the SWC, within which training can later be prescribed. However, finding a longer period of time during which the individual is completely relaxed is rather challenging considering the fact that all the subjects in our study were either working or studying and some also had children to take care of. Needless to say, in these kind of situations the determination of the SWC is always more or less a compromise, a mere estimate of the actual condition. Hence, there is a possibility that for some subjects, the SWC may not have been exactly there where it should have, and this in turn may have influenced the results obtained.

Individuality of training adaptation and morning RMSSD. Individual differences in the training adaptation were quite high. To analyze individuals separately the subjects who improved the most and the least in the 3000 m running test, and the subjects who did the most and the least HIT during the second period, were chosen from the HRV group for further analysis. There was no clear trend in the amount of endurance training or HIT, nor did we find any clear trend in the single day or 7-day rolling averaged RMSSD in these subjects. Plews et al. (2012) found that non-functional overreaching in an elite level triathlete lead to a decrease in day-to-day variance of RMSSD, whereas Schmitt et al. (2013) reported on endurance athletes who had increased day-to-day variability of HRV in fatigue. In our study, there was no correlation between the CV of RMSSD and the endurance training adaptation. These results are not in line with the findings of Plews et al. (2012) who suggest that a normal or increased RMSSD pattern may be indicative of an optimal cardiac autonomic system function, and increased level of endurance performance, whereas a decreased RMSSD probably suggests a fatigue state. Perhaps the relatively small sample size in the current study is a limiting factor and may have influenced the results.

There was no clear pattern regarding endurance training adaptation and the amount of HIT, nor changes in RMSSD values in the four selected subjects. This was expected, though, as the idea was to individualize training for each subject. Therefore, while one may do well with a high number of HIT, the other may need more time to recover between training sessions. However, one might ask why did some subjects from the HRV group fail to improve their endurance performance despite an individualized training program? One reason might be the fact that in the current study, HRV was used to optimize, or even maximize, the frequency of high intensity training in an effort to improve endurance training adaptation. This means that those subjects who's body responds better to low intensity training, or perhaps even strength training, may not have benefited from the high intensity focus we had in our study. This is definitely one possible explanation, which has also been shown by earlier studies (Vesterinen et al. 2013, 2014). Also, as mentioned earlier, the failure to improve endurance performance after HRV guided training may be related to how the baseline SWC for each individual was determined and how hard training was programmed. Indeed, whether the baseline SWC determined based on the initial four weeks of training was correct and reflected the individual's actual state of ANS function can be questioned. Afterall, our subjects were working parents or university students with busy lives and stress from outside exercise training. It is a well-known fact that this kind of stress can affect an individual's ANS and thus the baseline SWC for some subjects may have been somewhat erroneous due to illness or unbalanced life situation during the baseline recordings. Finally, in determining when the subjects were allowed to do HIT again, we used the return of the $RMSSD_{rollavg}$ to the mean level and above or under it. It can be hypothesized that had we used a return to e.g. 0.25*SD instead of the return to the mean level, the subjects might have been able to do even more HIT, which could have influenced the outcome. This is also one aspect future studies should take into consideration when studying the influence of HRV guided training on endurance training adaptation.

Limitations of the study. There are a few limitations in the present study. First, morning RMSSD measures were done only in the HRV group, whereas subjects in TRAD did not measure morning RMSSD. This was due to practical reasons but is unfortunate since it would have been interesting to see how morning RMSSD values would have been in the control group as well. Also, as subjects measured their night and morning RMSSD at home there is a possibility the quality of the measurement might not be as good as in the laboratory conditions, though on the contrary in laboratory the situation itself may have an influence on the results if the subject feels nervous. Finally, as autonomic nervous system is extremely sensitive to all kind of stressors independent of the source of the stress (Tharion et al. 2009; Clays et al. 2011; Hynynen et al. 2011), that is, whether one is having a busy time at work, difficulties with social relationships, or training hard, we cannot completely rule out the possibility that HRV of the subjects in the present study may have been influenced by stressors other than exercise training, which may have had especially huge influence on the initial SWC values. On the contrary, in elite level sports where athletes have the possibility to concentrate solely on training and recovery, optimizing every single detail from nutrition to sleep, the use of HRV could be simpler due to reduced stressors from sources outside sports.

Conclusions. The present study found that HRV guided training resulted in a better overall endurance training adaptation and especially improved the 3000 m run more than training according to a predetermined program. However, individual differences were quite high which may have influenced the results. Gender differences in endurance training adaptation were rather subtle. There were significant differences between $RMSSD_{day}$ and $RMSSD_{rollavg}$, which is in accordance the previous findings on HRV's high day-to-day variability and suggests that the use of averaged HRV should be emphasized. The high between- and within group variability in the amount of HIT training between HRV and TRAD during the second training period shows how HRV group trained based on individual cardiac state whereas TRAD had a more general program. Due to methodological differences between different studies investigating HRV and endurance training, interpretation of the results and especially comparing them to other studies is sometimes quite difficult. That being said, in the future the aim should be to standardize studies on HRV at least to some extent, so that it would be possible to compare the results of one study to those of the others.

Practical applications. HRV is a promising tool which, if standardized and studied even more carefully, can provide athletes and coached with a reliable means of monitoring ANS recovery from training. Particularly elite athletes who are training twice or even three times a day might benefit from HRV measurements to optimize training stimulus and response, because as training volume and intensity is increased, so is the risk for going over the line and doing too much. Also, recreational athletes who are trying to balance their life between exercising, work and children, might equally well benefit from HRV to, for instance, prevent burn out. However, since HRV at least for the time being has not been proven to detect other aspects of recovery such as muscle damage or glycogen resynthesis, the best way to use this would perhaps be monitoring training based on not only HRV but also other, both physiological and psychological, markers of recovery. As long as the results from studies are ambiguous, one should be careful when using HRV only to monitor training response and recovery. In addition to listening to their bodies, it is highly recommended that athletes use also objective measures such as HRV, to monitor recovery and training adaptation.

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