EFFECTS OF SHORT AND LONG INTERVAL TRAINING ON AEROBIC ENDURANCE PERFORMANCE

Tapani Mäkinen

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Faculty of health and sport sciences
University of Jyväskylä
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Supervisor: Juha Ahtiainen

ABSTRACT

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Compared to traditional low and moderate-intensity continuous exercise, high-intensity interval training (HIIT) has been shown to improve endurance performance to a greater extent. How to best organize and construct HIIT sessions, is yet to be determined. However, it has been suggested that athletes should maximize the time spent at or near the level of maximal oxygen uptake (VO_2max) to optimize the training stimulus. Additionally, it has been suggested that because the intensity is not a stable function of velocity due to variable conditions, athletes should pace the HIIT sessions by pursuing the highest sustainable speed. The purpose of the present study was to compare the effects of effort-matched short (SI) and long intervals (LI) on endurance performance. Another aim was to compare the time spent at or near VO_2max between SI and LI protocols.

Ten moderately endurance-trained participants (3 males, 7 females) took part in the study. Based on the maximal speed of the incremental running test (VO_2max test), same-level participants were randomly divided into two groups. During the 4-week intervention one group did short intervals, 3 x 10 x 30 s / 15 s / 150 s and the other group long intervals, 4 x 4 min / 2 min. Participants conducted ten sessions at the highest possible speed with active recovery at 50 % of the maximal speed of the VO_2max test. Test weeks before and after intervention included VO_2max test, maximal anaerobic running test (MART) with countermovement jumps and 20 m speed test. All tests were done on different days.

Neither of the groups changed the maximal speed of the VO_2max test significantly ($p > 0.05$). LI improved significantly ($p < 0.05$) VO_2max from 45.5 ± 4.4 to 48.0 ± 5.0 ml/kg/min, the speed of the anaerobic threshold from 12.60 ± 1.14 to 13.00 ± 1.22 km/h and the maximal speed of MART from 20.34 ± 1.43 to 21.08 ± 2.18 km/h. SI lowered the heart rate at the anaerobic threshold from 178 ± 8 to 176 ± 6 bpm, but there were no changes in VO_2max, speed of the anaerobic threshold or the maximal speed of MART. No between-group differences were found in the relative changes of the measured variables. The groups did not differ in the time spent at or near VO_2max. The time spent at or near VO_2max did not correlate with the change in performance. Fitness level did not predict the ability to spend time close to VO_2max.

The results of the present study suggest that long intervals can be used to improve VO_2max, the speed of anaerobic threshold and anaerobic capacity. In contrast to the previous studies, this study indicated that short interval training does not induce superior adaptations in endurance capacity compared to longer intervals. However, individual fitness level, training status and goals need to be considered when programming high-intensity interval sessions.

Key words: maximal oxygen uptake, training intervention, running

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Perinteiseen matalatehoiseen harjoitteluun verrattuna korkeatehoisen intervalliharjoittelun (HIIT) on näytetty parantavan kestävyyssuorituskykyä tehokkaammin. Korkeatehoisen intervalliharjoittelun toimivin rytmitystapa ja yksittäisen intervalliharjoituksen optimaalinen rakenne ovat kuitenkin vielä avoinna. On ehdotettu, että harjoituksen optimoimiseksi urheilijan tulisi pyrkiä työskentelemään mahdollisimman pitkään maksimaalisen hapenottokyvyn (VO_2max) tason lähellä. Koska tuotettu teho ja kuljettu vauhti eivät ole aina toisiinsa lineaarisesti yhteydessä, on suositeltu, että urheilija pyrkisi harjoituksessa yksinkertaisesti vain mahdollisimman kovaan keskinopeuteen. Tämän tutkimuksen tarkoituksena oli verrata koetulta rasitustasoltaan yhtäläisten lyhyiden ja pitkien intervallien vaikutusta kestävyyssuorituskykyyn sekä vertailla intervalliprotokollia maksimaalisen hapenottokyvyn lähellä vietetyn ajan suhteen.

Tutkimukseen osallistui 10 kestävyysharjoittelutaustaista tutkittavaa (3 miestä, 7 naista). Maksimaalisen hapenottokyvyn testin (VO_2max-testi) päätösnopeuden perusteella keskenään samantasoiset osallistujat jaettiin arvalla kahteen eri ryhmään. Neljän viikon intervention aikana yksi ryhmä teki lyhyitä intervalleja (SI 3 x 10 x 30 s / 15 s / 150 s) ja toinen ryhmä pitkiä intervalleja (LI 4 x 4 min / 2 min). Harjoitusjakso sisälsi 10 intervalliharjoitusta korkeimmalla mahdollisella keskinopeudella. Intervallien väliset palautukset olivat aktiivisia ja ne tehtiin 50 % teholla maksimaalisen hapenottokyvyn testin loppunopeudesta. Testiviikot ennen harjoitusjaksoa ja sen jälkeen sisälsivät VO_2max-testin, maksimaalisen anaerobisen juoksutestin (MART) kevennyshypyillä sekä 20 m lentävän juoksutestin.

Kummallakaan ryhmällä ei tapahtunut merkitseviä muutoksia VO_2max-testin loppuvauhdissa ($p > 0.05$). LI paransi merkitsevästi ($p < 0.05$) VO_2max (45.5 ± 4.4 -> 48.0 ± 5.0 ml/kg/min), anaerobisen kynnyksen nopeutta (12.60 ± 1.14 -> 13.00 ± 1.22 km/h) sekä MART:n maksiminopeutta (20.34 ± 1.43 -> 21.08 ± 2.18 km/h). SI:llä anaerobisen kynnyksen syke laski merkitsevästi (178 ± 8 krt/min -> 176 ± 6), mutta VO_2max, anaerobisen kynnyksen nopeus tai MART:n maksiminopeus eivät muuttuneet. Ryhmien välillä ei ollut eroja mitattujen muuttujien suhteellisissa muutoksissa. Aika lähellä maksimaalista hapenottokykyä ei eronnut ryhmien välillä, eikä se ollut yhteydessä yksilön kuntotasoon tai suorituskyvyn muutokseen.

Tutkimuksen mukaan pitkillä intervalleilla voidaan parantaa maksimaalista hapenottokykyä, anaerobisen kynnyksen nopeutta ja MART:n maksiminopeutta. Vastoin useita aikaisempia tutkimuksia, tämän tutkimuksen mukaan lyhyet intervallit eivät aiheuta kestävyyssuorituksen kannalta tärkeitä adaptaatioita pitkiä intervalleja paremmin. Korkeatehoisten intervallien ohjelmoinnissa täytyy aina huomioida urheilijan kuntotaso, harjoitustausta sekä tavoitteet.

Avainsanat: maksimaalinen hapenottokyky, harjoitteluinterventio, juoksuharjoittelu

CONTENT

1 INTRODUCTION

Running endurance performance is mainly determined by three factors: maximal oxygen uptake (VO_2max), lactate threshold level and running economy (Midgley et al. 2007b). However, also anaerobic factors play a role in the endurance performance (Nummela et al. 2006; Sinnett et al. 2001). The increase in VO_2max is positively related to training at the intensities in 50-100 % of VO_2max, but especially to training in 90-100 % of VO_2max (Wenger & Bell 1986). Thevenet et al. (2007) and Midgley et al. (2006) have therefore suggested that the time spent over 90 % of VO_2max could be good criteria to judge the effectiveness of the training.

Velocities at or near the intensity of VO_2max cannot be sustained for a long time in continuous exercise (Bosquet et al. 2002). To increase the time at high intensities in a single session, different interval protocols have to be conducted. In addition to traditional continuous low or moderate intensity training both high intensity long and short interval training have been shown to improve endurance performance (Cicioni-Kolsky et al. 2013; Esfarjani & Laursen 2007; Rønnestad et al. 2015). Compared to continuous exercise, high intensity training (HIT) has been shown to have possibly small beneficial effect on VO_2max in healthy, untrained subjects (Milanovic et al. 2015). Especially for trained individuals HIT is recommended (Midgley et al. 2007b). However, based on literature it is impossible to decide whether short or long intervals have superior effects on endurance performance, possibly because of large variability in HIT protocols. Indeed, the effects of intermittent high intensity training depend on multiple factors (Buchheit & Laursen 2013).

Most of the studies investigating high-intensity aerobic intermittent exercise are using fixed work intensities at a predefined relative power or velocity. Although this is informative, it can be difficult to achieve in practice because intensity is not a stable function of velocity in many endurance sports due to variable conditions. (Seiler & Hetlelid 2005.) Therefore, it is suggested that athletes should pace the HIT sessions by themselves and pursue the "highest sustainable mean velocity". The work intensity would be then integrative outcome of feedback from external and internal receptors, and knowledge of the session demands. (Seiler & Hetlelid

2005.) Seiler et al. (2013) argued that instead of using the so called isoenergetic matching where the total work or energy expenditure is the same between different interval protocols, intervals should be equalized with effort-matched approach. Later on, self-paced intervals and effort-matched approach have got support and they have been used in other studies (Laurent et al. 2014, Rønnestad et al. 2015; Rønnestad et al. 2020; Schoenmakers & Reed 2019).

2 AEROBIC ENDURANCE PERFORMANCE

2.1 Determinants of endurance performance

Endurance performance is predominantly determined by maximal oxygen uptake (VO_2max), the level of the anaerobic threshold (fraction of VO_2max that can be sustained) and running economy (figure 1). These together determine the mean velocity of the performance. (Joyner & Coyle 2008; Midgley et al. 2007b.)

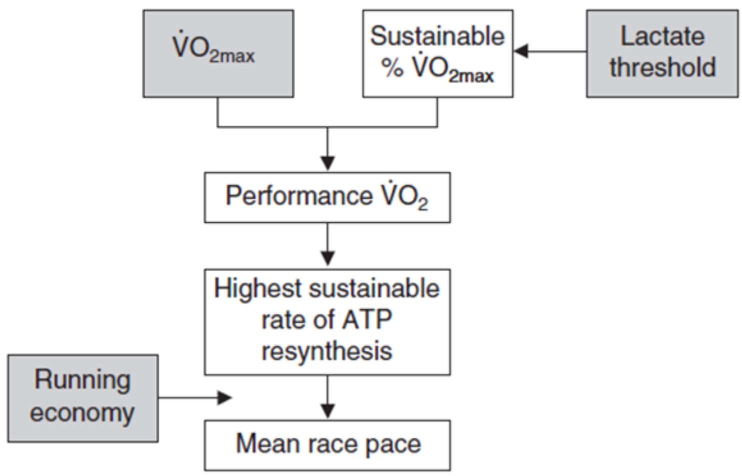

FIGURE 1. Determinants of the endurance performance (Midgley et al. 2007b).

If the tactics and the last sprint to the finish are excluded, athlete who is able to maintain the highest mean velocity throughout the race wins. Though, it is in the nature of many endurance sport events that the last sprint determines the final result which underlines the importance of anaerobic metabolism in endurance performance. Several anaerobic factors have been found to correlate well with 5 km running performance (Nummela et al. 2006) and 10 km running performance (Sinnett et al. 2001). Already Bulbulian et al. (1986) found anaerobic system to account a great part (58 %) of variance in 5-mile (8,05 km) cross-country running performance.

VO_2max is defined as the highest rate of oxygen uptake and utilization in the body during severe exercise and it can be presented as an absolute value (ml/min or l/min) or in relation to the body mass (ml/kg/min) (Basset & Howley 2000). In heterogeneous group VO_2max predicts endurance performance well, but in homogeneous group the correlation between VO_2max and performance is relatively poor (Bosquet et al. 2002). James et al. (2017) noted that not the VO_2max itself but the velocity at VO_2max (vVO_2max) was the best predictor of 5 km running performance. McLaughlin et al. (2010) did similar finding when vVO_2max had the strongest correlation with 16-km running time trial in well-trained distance runners when compared to running economy and fractional utilization of VO_2 at lactate threshold.

The question of what is the limiting factor of VO_2max has been a long-lasting debate. Basset and Howley (2000) presented the central factors and peripheral factors that can impede the O_2 flux. Central factors include the steps where O_2 is delivered to the muscle (pulmonary diffusing capacity, cardiac output and O_2 carrying capacity of the blood). Peripheral factors are related to the muscle characteristics and muscle's ability to utilize oxygen. According to Basset and Howley (2000) cardiac output is the most important limiting factor of VO_2max in cycling and running.

Because vVO_2max can be maintained around 6 minutes, (values varying from less than 3 minutes to over 10 minutes) (Billat et al. 1994; Bosquet et al. 2002), also other factors such as running economy and lactate threshold level have an important role especially in long-distance performance. Joyner (1993) found that the correlations between VO_2max and vVO_2max with performance decreased as the distance increased, which potentially means that the importance of economy and lactate threshold grows as the performance becomes longer. However, McLaughlin et al. (2010) reminded, that most of the studies have been reporting high correlations between VO_2max/vVO_2max and endurance performance across all the distances. The factor explaining the variation in results is also dependent of the characteristics of the subjects. If there are little inter-individual differences in lactate threshold level, most likely other variables would explain the variation in the performance. (McLaughlin et al. 2010.)

Running economy means the ratio of work done to the energy expended and it is presented as VO_2 required in relation to a given running velocity or to a certain distance covered (Basset & Howley 2000). Morgan et al. (1995) studied 4 different level groups of runners and the data showed that trained subjects had higher economy compared to untrained subjects. Though, variation in running economy could also be found among the same level runners. (Morgan et al. 1995).

Noakes et al. (1990) found running economy to predict distance running performance (10 km – 42,2 km) only moderately ($r = 0.41$-0.45, $p < 0.01$) in long and ultradistance runners. Contradictory with those results, running economy has been found to have strong ($r = 0.79$-0.83) correlation with 10 km running performance (Conley & Krahenbuhl 1980; McLaughlin et al. 2010) and it has been observed to explain a great part of variation in endurance performance (Conley & Krahenbuhl 1980). In addition, Paavolainen et al. (1999) observed a correlation between running economy and 5 km time trial ($r = -0,54$) after an explosive strength training period and similarly with Nummela et al. (2006) a correlation with the velocity of maximal anaerobic running test. Nowadays there is a rather strong consensus that economy is one of the key factors determining endurance performance (Basset & Howley 2000; Joyner & Coyle 2008; Midgley et al. 2007b). Methodological issues might explain the possible contradictory results (Basset & Howley 2000).

Blood lactate levels and fractional utilization of VO_2max (%VO_2max) are closely related. Usually the %VO_2max value that can be maintained in long performance is at the level of lactate threshold (LT) and therefore LT is a common way to identify %VO_2max level. High level athletes can sustain higher %VO_2max with relatively low blood lactate values compared to moderately trained individuals. (Costill et al. 1979; McLaughlin, et al. 2010.) As one of the main determinants of the endurance performance lactate threshold has been found to predict various long distance running performances well (McLaughlin, et al. 2010; Noakes et al. 1990).

2.2 Training features

When the main determinants of the endurance performance (VO2max, lactate threshold, running economy, anaerobic factors) are known, training can be directed to improve these characteristics. Both volume and intensity of the training play key roles in long- and short-term development and are related to the performance level. For example, Hagan et al. (1987) found that several volume-related factors were negatively correlated (r = -0,47–-0.77) with marathon performance time in female distances runners when data was collected during the 12 weeks period prior to the marathon race. Also training pace (r = 0,66) predicted faster time in the marathon (Hagan et al. 1987). Billat et al. (2001) reported similar results as top-class marathon runners trained more in total and at higher relative intensity compared to high-level marathon runners. The differences were present both in male and female runners.

While volume itself is easy to measure (distance or time), quantifying training intensity is more complicated. To clarify the intensity distribution in endurance training, 5- and 3-zone intensity scales are often used. Different zones include certain values of VO_2, heart rate and blood lactate which help to follow the time spent at each intensity zone. 3-zone model is anchored by lactate thresholds that are set to the model before and after zone 2. Also 5-zone intensity scale (table 1) fits well to the threshold model as it includes approximately 2 to 4 mM blood lactate concentration range. (Seiler 2010.)

Measuring blood lactate and especially oxygen uptake during training can be unpractical. In addition, often used heart rate time-in-zone method might underestimate the real time of high intensity training that exercise causes because of small delay in heart rate response (Seiler 2010.) Therefore, quantifying the training also subjectively (Borresen & Lambert 2008) might give some useful information of the training exposure.

TABLE 1. An example of the 5-zone intensity scale for training prescription and monitoring for endurance athletes (Seiler 2010).

Intensity zone	VO_2 (% max)	Heart rate (% max)	Lactate (mmol·L⁻¹)	Typical accumulated duration within zone
1	50–65	60–72	0.8–1.5	1–6 h
2	66–80	72–82	1.5–2.5	1–3 h
3	81–87	82–87	2.5–4	50–90 min
4	88–93	88–92	4.0–6.0	30–60 min
5	94–100	93–100	6.0–10.0	15–30 min

Endurance athletes spend most of their training hours at the lowest zones. Esteve-Lanao et al. (2005) studied the intensity distribution of eight sub-elite cross-country runners' training over a 6 months period (ending to the main races) by measuring heart rate during all of the training sessions and putting the data into 3-zone intensity scale. Runners spent 71 % of the training at lowest intensity, 21 % in the zone 2 and 8 % above anaerobic threshold. Interestingly, performance in two cross country running races (4,175 km and 10,130 km) was only related to the absolute time spent at the lowest intensity zone (Esteve-Lanao et a. 2005). Billat et al. (2001) followed top- and high-level marathoners who distributed their training into velocities: below marathon pace, marathon pace, 10-km pace and 3-km pace. Supposedly marathon pace was between thresholds and both 10-km and 3-km paces were above anaerobic threshold. As much as 78 % of the training was carried out below marathon pace, 4 % at marathon pace and 18 % at higher intensities.

Volume and intensity can be periodized in number of ways and the best strategy to organize low and high intensity training (HIT) to achieve the optimal outcome is yet to be determined, but block periodization of HIT has been shown to have some promising effects. Rønnestad et al. (2014) studied 12 weeks of block periodization in trained cyclists. Periodization group did three 4-week cycles where the first week included 5 HIT sessions and the following 3 weeks only one HIT session. HIT sessions were done at 88–100 % HR_{max} and were structured as

5x6min/3min or 6x5min/2,5min. After 12 weeks of training the block periodization group increased their VO_2max more (8.8 ± 5.9 % vs 3.7 ± 2.9 %) compared to the group that did two HIT sessions during each week over the whole 12-week period. García-Pallarés et al. (2010) studied block periodization in world-class kayakers. Even though block periodization period was shorter (13 weeks vs 23 weeks) compared to the traditional training period, improvement in VO_2peak and in VO_2 at anaerobic threshold were similar and improvements in power-related variables (power at VO_2peak and anaerobic threshold) were higher after block periodization training period.

Various strength training protocols have been proven to lead to higher level of endurance performance, primarily because of increased running economy (Paavolainen et al 1999; Støren et al. 2008). Paavolainen et al. (1999) found that 9-week training period of explosive strength training improved 5 km time trial in trained endurance athletes. Similarly, Ramirez-Campillo et al. (2014) showed that 6-week plyometric strength training period improved 2,4 km running performance (-3.9 %) in male middle- and long-distance runners. Also heavy resistance training has been shown to increase endurance performance. In the study of Støren et al. (2008) 8-week training period of maximal strength training improved the time at maximal aerobic speed by 21.3 %.

Although strength training has potential to improve performance, studies show also contradictory results and remind that strength training needs to be carefully implemented to the training program to achieve results. For example, Vikmoen et al. (2016) did not find improvements in the main determinants of endurance performance or in the 40-min all-out running trial after an 11-week period of combined endurance + heavy resistance training in female endurance athletes. The authors speculated that the lack of improvement was related to the unimproved economy, unchanged patellar tendon stiffness and some methodological issues, for example the treadmill's inclination level of 5.3 % in the tests. (Vikmoen et al. 2016.) Barnes et al. (2013) found conflicting results as after a 7 to 10-week period both plyometric and plyometric + heavy resistance exercise training groups improved small amounts in laboratory-based parameters but the training had possibly harmful effects on competition performance. While the strength training was added to the training program during competition season, the authors stated that in-season strength training should be used with caution.

Despite some evidence questioning the implementation of strength training to the training schedule, strength training is widely used among endurance athletes. Esteve-Lanao et al. (2005) reported competitive runners using strength training in their program. Usually in the preparatory period a training week included 1-2 weight lifting sessions or circuit weight exercises while more in the specific training period included 1-2 specific strength training sessions (short hill intervals or intervals with weight vest) per week. During the competition season only one easy session of weight lifting took place, which is in line with the recommendation of Barnes et al. (2013).

3 HIGH INTENSITY TRAINING

3.1 Continuous and intermittent exercise

In the literature continuous, so called traditional endurance exercise is referred to constant low or moderate intensity bouts of 60 minutes at the intensity of 70 % (Tabata et al. 1996) or 75 % of vVO_2max (Esfarjani & Laursen 2007), 45 minutes at the intensity of 70 % HRmax (Helgerud et al. 2007) and 90-120 minutes at the intensity of 65 % VO_2peak (Gibala et al. 2006). Continuous high-intensity endurance training (>80%VO_2max/>85%VO_2max) seems to be less studied topic as only Franch et al. (1998) and Jarstad and Mamen (2019) have investigated its effects on endurance performance. This might be due to the strenuous nature of the exercise type.

Franch et al (1998) conducted an intervention study comparing continuous 20–30 min bouts (6 weeks, 3 sessions/week) performed at 93 % HRmax and long interval protocol, 6 x 4 min / 2 min performed at 94 % HRmax, in recreational male runners. Protocols improved VO_2max (5.6–6.0 %) and running economy (3.1–3.0 %) similarly, but time to exhaustion at 87 % of vVO_2max increased by 94 % in continuous training group while interval training group improved the time by 67 %. (Franch et al. 1998.) Jarstad and Mamen (2019) found that continuous 20 min runs at ~83% VO_2max (~88 HRmax) during 10-week intervention (3 sessions/week) increased time to exhaustion by 23 % in short ramp test in recreationally trained subjects. Although improvement was similar with moderate intensity training group (40 min bouts at 80% HRmax), increase in VO_2max (~5 %) was significant only in the high intensity group. (Jarstad & Mamen 2019.)

Time to exhaustion at the vVO_2max has been reported to vary from less than 3 to over 10 minutes. Physically active men could sustain the velocity for 5 min 56 s ± 1 min 4 s (Rozenek et al. 2007), whereas elite long-distance runners could carry out this intensity for 6 min 11 s ± 2 min 1 s while a wide scatter of the data was observed: from 3 min 47 s to 11 min (Billat et al. 1994). Millet et al. (2003) reported clearly lower values and smaller standard deviation in elite triathletes (4 min 4 s ± 39 s) in time to exhaustion at vVO_2max. Billat et al. (1994) found that variation in data was partly due to the individual lactate steady state value (% VO_2max) which correlated strongly with the time to exhaustion at vVO_2max ($r = 0.775$). In addition, also anaerobic work capacity plays a role in time to exhaustion tests (Blondel et al. 2001). In general, lower intensities can be maintained for longer periods and vice versa. Intensity and time to exhaustion form a hyperbolic relationship which is valid in performance lasting from 2 up to 20 minutes (Jones et al. 2019).

Intermittent exercise protocol increases the time to exhaustion and enables higher mean power or velocity to be maintained for a certain time. For example, Midgley et al. (2007a) observed that while time to exhaustion at vVO_2max was 5.9 ± 1.8 min, the 30 s / 30 s intermittent protocol including rest intensity of 70 % of vVO_2max was maintained for 10.3 ± 1.6 min in male runners. Similarly, a study group consisting of male runners and triathletes spent 19.3 ± 6.4 min at critical velocity but with protocol of 4 min / 1 min (passive rest) the time was lengthened to 37.9 ± 14.6 min (Penteado et al. 2014). Additionally, Billat et al. (2000) found that intermittent high intensity exercise with 30 s / 30 s (100 % vVO_2max/50 % vVO_2max) protocol induced longer time of high intensity work (HIIT 9 min 30 s ± 2 min 30 s vs CON 8 min 20 s ± 1 min 45 s) even though the intensity was clearly higher than in the continuous run (91.3 % vVO_2max).

Buchheit & Laursen (2013) divided intervals into four main categories (figure 2). A) Long HIT intervals usually at or slightly below the VO_2max intensity are used to develop aerobic power and the anaerobic systems. B) Another HIT category, short intervals, usually at or above the VO_2max intensity are mainly used similarly to long intervals. C) Repeated sprint training (RST) is typically performed with very short actions (5-8s) at intensities around 120% to 160% of the vVO_2max. With a very long recovery periods they are used to develop neuromuscular and metabolic performance that are typical in team sports. D) Sprint interval training (SIT) is traditionally executed using four to six 30 s all-out efforts. In combination with 3–4-minute rest periods, which are not long enough for full recovery, SIT results in very high aerobic and anaerobic stimuli. (Buchheit & Laursen 2013.)

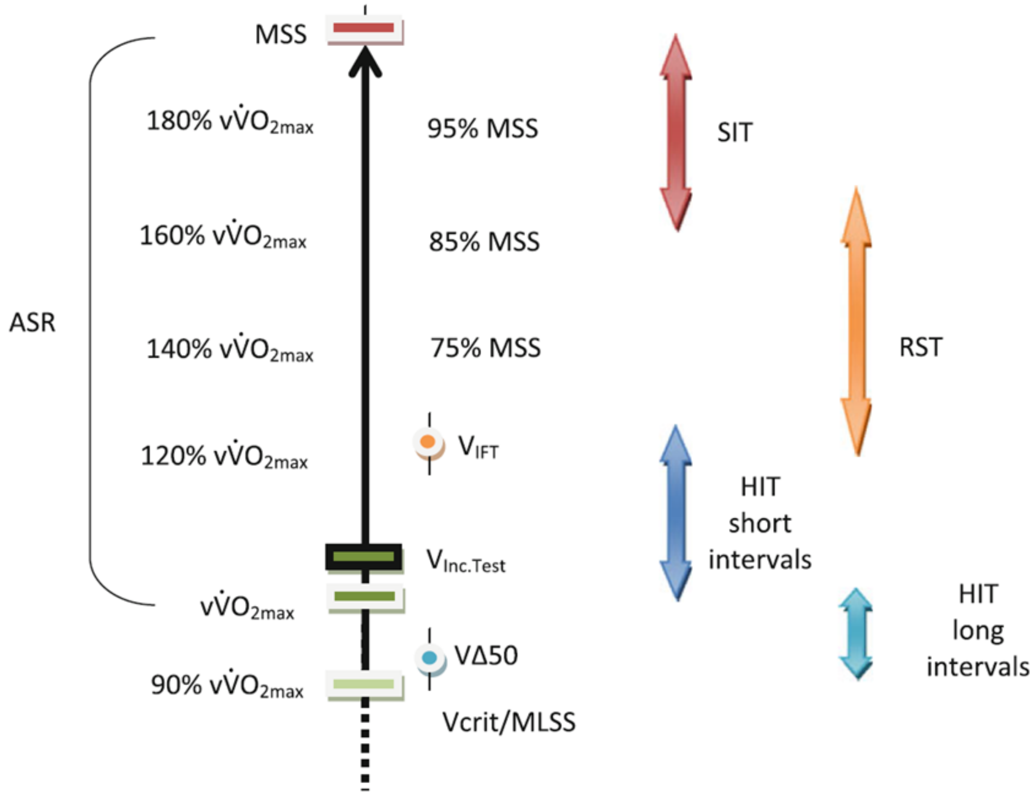

FIGURE 2. Different run-based HIT protocols used and their intensity range (Buchheit & Laursen 2013).

High intensity interval training has been shown to improve aerobic endurance significantly compared to continuous exercise. In the study of Helgerud et al. (2007) high intensity interval training groups (both 4 x 4 min and 15 s / 15 s) increased their VO_2max by 7.2 and 5.5 % while work-matched continuous training at low or moderate intensity (70 or 85 % of HR_{max}) did not show any significant improvements in moderately trained male subjects after an 8-week running training period. Esfarjani and Laursen (2007) found that in moderately trained runners (VO_2max = 51.6 ± 2.7 ml/kg/min) four 60-minute sessions per week at 75% vVO_2max did not improve 3 km performance, VO_2max or time to exhaustion at vVO_2max during a 10-week intervention. In contrast both short (30 s 130% vVO_2max/4.5 min 50% vVO_2max) and long interval protocols (3.5 min 100%vVO_2max/3..5min 50%vVO_2max) produced increments in mentioned variables (Esfarjani & Laursen 2007). When comparing HIT to the traditional, continuous endurance training, a meta-analysis done by Milanovic et al. (2015) revealed a possibly small beneficial effect of HIT on VO_2max. However, both training protocols elicit large improvements in VO_2max in comparison to control group in healthy young to middle-aged adults.

3.2 Time spent at or near VO_2max

Wenger and Bell (1986) reviewed that almost regardless of the frequency, duration or the initial fitness level, greatest improvements in VO_2max occur when the training is carried out at 90–100 % of VO_2max intensity. However, in much later review Midgley et al. (2006) reminded that especially in untrained subjects results can be different and possibly the best way to improve VO_2max is not to maximize the time close to it. Some authors have still stated that the time spent over 90 % of VO_2max could be used as a good criterion to judge the effectiveness of the training (Midgley et al. 2006; Thevenet et al. 2007)

When high intensity exercise is continued until to exhaustion, the time spent at or near the VO_2max is only few minutes. Rozenek et al. (2007) did a constant run at vVO_2max and measured the time above 90%VO_2max to be around three minutes (3 min 6 s ± 1 min 23 s). With the same kind of protocol Dupont et al. (2002) observed rather similar values of 3 min 37 s ± 1 min 54 s. The time at the level of VO_2max was 1 min 56 s ± 42 s. Billat et al. (2000) conducted a time to exhaustion run at intensity between second lactate threshold and VO_2max (~90% vVO_2max). This resulted in longer time at VO_2max: 2 min 42 s ± 3 min 9 s.

As intermittent exercise can increase the total time of the exercise and total high intensity work time, it can also improve the time at or close to VO_2max. For example, Billat et al. (2000) found that intermittent high intensity exercise done to exhaustion with 30 sec / 30 sec (100% vVO_2max / 50% vVO_2max) protocol induced longer time at VO_2max (7 min 51 s ± 6 min 38 s vs 2 min 42 s ± 3 min 9 s) than the continuous run at ~90% vVO_2max. However, they found large inter-individual variations in these responses as some subjects did not reach VO_2max during continuous run but during intermittent exercise the time at VO_2max was several minutes. Some of the subjects showed totally the opposite responses.

Dupont et al. (2002) compared 15 s / 15 s interval protocols with different work intensities (passive recovery) to continuous run at maximal aerobic speed (MAS, VO_2max was determined indirectly). All performances were done until to exhaustion. When the intensity was 130 or 140 % of MAS the exercise terminated earlier than the continuous run and therefore the time at 100 % or above 90 % of VO_2max was much shorter. Intermittent run at 120 % of MAS (120%I) induced the longest time at VO_2max (202 ± 66 s) and it differed significantly from 110%I (120 ± 42 s) and continuous run (116 ± 42 s). However, in the time between 90 and 100 % of VO_2max, 110%I showed the highest value (383 ± 180 s). There was no significant difference to the 120%I (323 ± 272 s) but the time in continuous run was clearly shorter (217 ± 114 s). Based on this study it seems that with passive recovery and 1:1 work-to-rest ratio, intensities above VO_2max (110, 120 %) can be used to achieve time at VO_2max but too high work intensities (130, 140 %) cause early termination of the performance. (Dupont et al. 2002.)

Wakefield and Glaister (2009) studied the influence of different work interval intensities and durations on time spent at or above 95 % of VO_2max (T95). In their study subjects did three intermittent runs at both 105 and 115 % of vVO_2max. The duration of the work interval varied (20, 25 and 30 s) but the stationary resting period (20 s) was not changed. The authors found that even though subjects could carry on longer with lower intensities, there was no difference in T95 between intervals done at the velocity of 105 and 115 % of vVO_2max. However, the results revealed a significant effect of work-interval duration on T95. The longest (30 s) intervals induced longer time compared to 25 s intervals (mean difference = 75 s) and to 20 s intervals (mean difference = 89 s). These results suggest that work-to-rest ratio of 2:1 could be beneficial to attain higher time close to VO_2max. (Wakefield & Glaister 2009.)

Also, Rozenek et al. (2007) observed the effect of different work-to-rest ratios on time spent at or above 90 % of VO_2max. Subjects did three interval exercises with protocols of 15 s / 15 s, 30 s / 15 s and 60 s / 15 s. Therefore, the trials represented the work-recovery ratios of 1:1, 2:1 and 4:1. Intensity of work period was 100 % and the recovery period 50 % of vVO2max. Each interval exercise was planned individually so that the distance during work intervals was approximately 2400 meters. 1:1 work-recovery ratio did not allow any of the subjects to reach the level of 90 % of VO_2max during that distance. The time above 90 % of VO_2max in 30/15 protocol was 247.5 ± 172.5 s and in 60/15 it was 323.7 ± 118.4 s. 60/15 trial was the only one to differ significantly from the continuous run at VO_2max until the exhaustion (186.2 ± 83.2 s). However, 5 of the 12 subjects could not complete the 60/15 trial and cover the distance of 2400 meters during the work intervals. This could indicate that while both ratios (2:1 and 4:1) enable subjects to reach and maintain VO_2max, 4:1 can be seen as upper limit of work-to-rest ratios. (Rozenek et al. 2007.)

Millet et al. (2003) compared different interval protocols of 30 / 30 s, 60 / 30 s and individually calculated interval protocol of 2 x 118 s / 118 s (on average) Each protocol included 3 sets of intervals so that the overall time of the work interval duration was matched as three times the time until to exhaustion at the velocity of VO_2max. Work intervals were carried out at the intensity of VO_2max and repetition recovery periods at 50 % vVO_2max. Set recovery was passive rest. Millet et al. (2003) found that work-recovery ratio of 1:1 in short 30 / 30 s intervals resulted significantly shorter time near VO_2max which is in line with other studies investigating short interval protocols (Rozenek et al. 2007; Wakefield & Glaister 2009). However, Millet et al. (2003) observed similar values in times spent above 90 and 95 % of VO_2max between individual protocol with longer intervals (ratio of 1:1) and 60 / 30 s protocol.

Thevenet et al. (2007) investigated the effects of recovery mode in time spent close to VO_2max. In this study subjects did two different 30 / 30 s interval protocols to exhaustion. While the intensity of the work interval stayed the same (100 % of vVO_2max), the recovery was either 50 % of vVO_2max or passive. Even though the total time to exhaustion was doubled with passive recovery, neither the time above 90 % of VO_2max or 95 % of VO_2max were significantly different between the protocols. However, when expressed as a percentage of time to exhaustion both ≥90 % and 95 % values were clearly higher with active recovery. Active recovery, therefore, could increase the effectiveness of the training and increase the time at or near VO_2max. (Thevenet et al. 2007.) Since most of the studies measuring the time spent close to VO_2max use time to exhaustion protocols the results cannot be directly applied to the real-life training scheme. In practice, the importance of active recovery might increase significantly.

To the writer's knowledge, so far there has not been an intervention study that measures the time spent close to VO_2max and could therefore, interpret that the improvements have occurred due to the longer time spent close to VO_2max. Though, as Buchheit & Laursen (2013) reminded, other physiological factors than the time spent close to VO_2max should also be considered when planning high intensity training.

3.3 Acute responses and short-term adaptations to interval training, SI vs LI

Buchheit & Laursen (2013) suggested that at least nine variables affect the interval training structure, including the intensity and length of work and relief periods as well as number of sets and repetitions per set (figure 3). Naturally, modifying these variables will affect the acute responses but also the long-term adaptations that interval training generates.

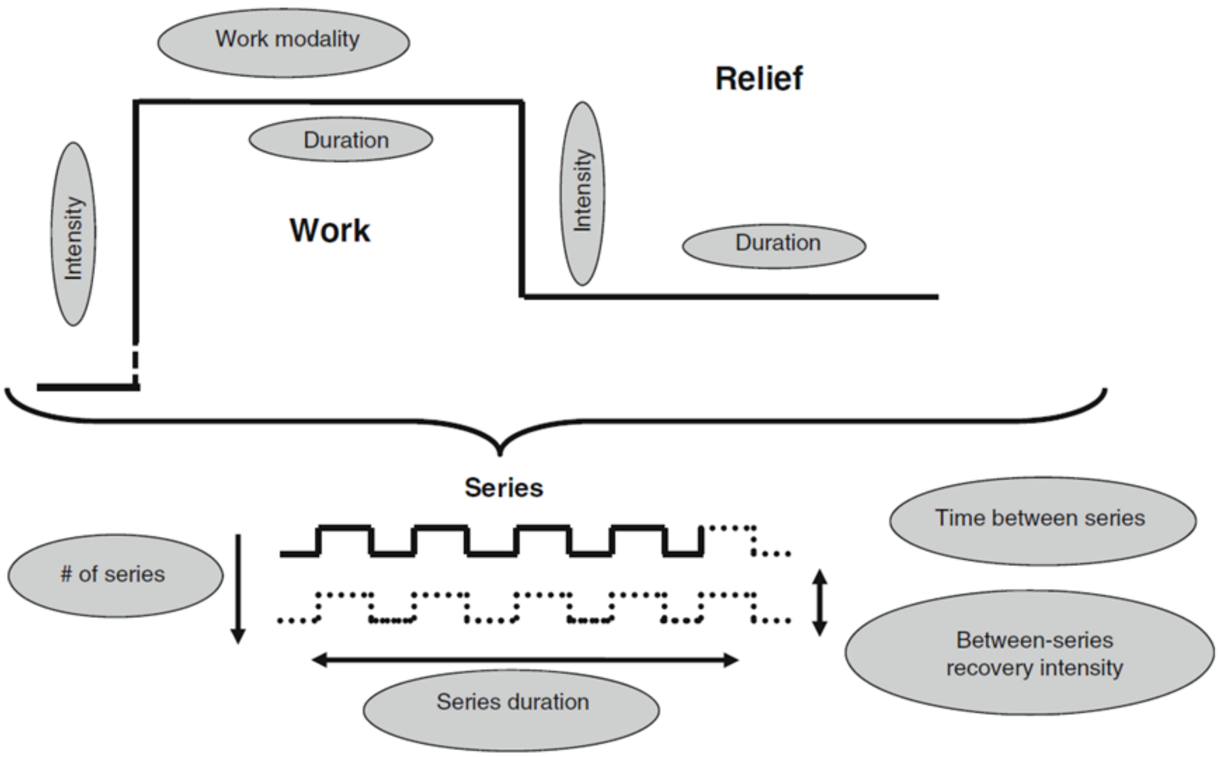

FIGURE 3. Variables affecting the structure of an interval training (Buchheit & Laursen 2013).

Laurent et al. (2014) investigated the acute effects of varying the length of the recovery period (1 min, 2 min, 4 min) on the velocity of the intervals during long interval protocol (6 x 4 min).

The results suggested that work-to-rest ratio of 2:1 seems to be sufficient recovery since differences in physiological and perceptual responses were observed between 1 and 2-min recovery protocols but not between 2 and 4-min recovery protocols. This means that even though the recovery period was increased from 2 to 4 minutes, the speed at self-paced maximal intervals did not increase anymore. This is supported by Seiler & Hetlelid (2005) with similar finding. Laurent et al. (2014) also noted that even though men could sustain higher relative velocity (84.9–86.1 % vs 80.2–83.6 % of VO_2max) compared to women when longer recovery period was conducted, women tended to sustain higher strain and fatigue. This could be noticed from the higher relative heart rate and VO_2 values. Seiler & Hetlelid (2005) observed similar relative velocity values as elite male runners sustained 85 % of their peak velocity of the incremental running test in protocol using 2-min recovery periods.

During the last two decades, sprint interval training (SIT), traditionally including 4-6 bouts of 30 sec all-out work with 3–4 min passive recovery, has been researched. Hazell et al. (2010) found that in physically active young adults 2-week intervention (6 sessions, 4–6 bouts/session) of SIT improved 5-km cycling time trial by 3.0–5.2 % independent of the length of the work and recovery bouts. 30 sec/4 min and 10 sec/4 min groups increased VO_2max 9.3 and 9.2 % while 10 sec/2 min group did not increase it significantly. Relative peak power output in 30 sec all-out test was also increased most in the 4 min recovery groups (12.1 and 6.5 %). Gibala et al. (2006) compared 4–6 x 30 sec / 4 min protocol with 90–120 min constant low intensity (ET) cycling (65 % VO_2peak) in 2-week intervention (6 sessions) in physically active men. Results showed clear but similar between group improvements in 30 km time trial (SIT 10.1 %, ET 7.5 %) and 2 km time trial (SIT 4.1 %, ET 3.5 %). (Gibala et al 2006.)

While having an effect on both aerobic and anaerobic characteristics SIT can improve endurance performance (Hazell et al. 2010). Gibala et al. (2006) found that SIT and ET increased similarly muscle buffering capacity, oxidative capacity via increased enzyme activity and muscle glycogen content. The benefits of SIT protocol on endurance and anaerobic performance via peripheral adaptations has been shown consistently. Despite the promising results in untrained/physically active subjects SIT based interventions for trained endurance athletes have not been conducted and therefore conclusions about SIT program's usefulness for the endurance athletes remain to be made. (Sloth et al. 2013.)

3.4 Long term adaptations to interval training, SI vs LI

Both short (Stepto et al. 1999; Tabata et al. 1996) and long intervals (Sandbakk et al. 2013; Seiler et al. 2013) have been shown to improve long-term endurance performance and performance related variables. Table 2 lists some of the intervention studies that are comparing short and long interval protocols. Varying protocols, especially in short intervals make the interpretation of the results somewhat hard. The two latest studies (Rønnestad et al. 2015; Rønnestad et al. 2020) however suggest that short intervals may induce larger adaptations compared to effort matched long intervals.

Rønnestad et al. (2015) investigated the effects of short and long intervals in moderately trained cyclists. After 10-week intervention (2 trainings / week) the cyclists in SI group, who did interval protocol of 3 x 13 x 30 s / 15s / 180 s improved their VO_2max by 8.7 ± 5.0 %. This was significantly higher compared to the LI group, 2.6 ± 5.2%, who trained with protocol of 4 x 5 min / 2.5 min. SI had also a moderate-to-large mean effects sizes of the relative improvement in mean power outputs in 40-min all-out, 5-min all-out and 30-s all-out tests compared to LI. Rønnestad et al. (2020) did a study with similar interval protocols (3 trainings / week) but in elite cyclists and with only a 3-week intervention. SI group had significantly higher relative improvement in mean power output during the 20-min all-out test (4.7 ± 4.4 % vs -1.4 ± 2.2 %) and maximal aerobic power (Wmax) during the incremental test (3.7 ± 4.3 % vs -0.3 ± 2.8 %). Although no significant difference between group occurred, SI group increased VO_2max significantly by 2.6 ± 2.7 % whereas LI group did not (0.9 ± 3.6 %).

TABLE 2. Intervention studies comparing the effects of short (SI) and long interval (LI) training protocols on endurance performance.

reference	subjects	duration/sessions	training protocols	recovery	main finding
Rønnestad et al. (2020)	9+9 elite male cyclists	3 weeks, 9 sessions	SI 3x13x30s, LI 4x5min max avg effort	SI 15s and 3min, LI 2.5min at 50 % of the workload PO	SI ↗ 3.7%, LI ↘ 0.3% in PPO, SI ↗ 4.7%, LI ↗ 1.4% in MPO in 20-min all-out trial
Rønnestad et al. (2015)	7+9 well trained male cyclists	10 weeks, 20 sessions	SI 3x13x30s, LI 4x5min max avg effort	SI 15s and 3min, LI 2.5min at 50 % of the workload PO	SI ↗ 8.7%, LI ↗ 2.6% in VO2max, SI ↗ 12%, LI ↗ 4% in MPO in 40-min all-out trial
Cicioni-Kolsky et al. (2013)	20 + 19 physically active individuals, females and males	6 weeks, 18 sessions	SI 7-12x30s 130% avg of 3k time, LI 4-6x4min 100% avg of 3k time	SI 150s, LI 4min passive recovery	SI ↘ 9.2%, LI ↘ 7,4% in 3-km time, only SI different compared to control
Helgerud et al. (2007)**	10+10 moderately trained male subjects	8 weeks, 24 sessions	SI 47x15s 90-95%, LI 4x4min 90-95% HRmax	SI 15s, LI 3min at the velocity of 70% HRmax	SI ↗ 5.5%, LI ↗ 7.2% in VO2max
Esfarjani & Laursen (2007)	6+6 moderately trained male runners	10 weeks, 20 sessions	SI 7-12x30s 130 %, LI 5-8x60%Tmax (3.5min + 0.7 min) 100	SI 4.5 min, LI 8x60%Tmax (1:1 W/R ratio) at 50% vVO2max	SI ↘ 3.4%, LI ↘ 7.3% in 3-km time, SI ↗ 6.2%, LI ↗ 9.1% in VO_2max
Laursen et al. (2002)	8+9+10 well trained male cyclists and triathletes	4 weeks, 8 sessions	SI 12x30s 175% PPO, LI[a] and LI[b] 8x60%Tmax at 100 % PPO	SI 4,5min, LI[a] 1:2 W/R ratio, LI[b] HR to 65%max at 100 W	All groups ↘ 4.4-5.8 % in 40-km TT, Li[a] 5.4% and LI[b] 8.1% different compared to control in
Stepto et al. (1999)**	4+4 male endurance cyclists	3 weeks, 6 sessions	SI 12x30s 175 % PPO, LI 8x4min 85 % PPO	SI 4,5min, LI 1,5min at 100W	SI ↘ 2.4%, LI ↘ 2.8% in 40-km TT

60%Tmax = 60 % of the time to exhaustion at 100% vVO2max, PO = power output, PPO = peak power output in incremental exercise test, MPO = mean power output, TT = time-trial, * = significantly different compared to LI, ** = some interval training groups left out from the table

Tabata et al (1996) showed that high intensity interval training (7-8 x 20 s with intensity of 170 % vVO_2max, 4 times / week) can elicit changes in VO_2max and anaerobic capacity after a 6-week intervention whereas moderate aerobic endurance training led to improvements only in VO_2max. Stepto et al. (1999) compared multiple different interval protocols in cyclists with a 3-week intervention and found that long intervals (8 x 4 min) at 85 % PP (peak aerobic power) increased the 40-km time trial performance. They also found some improvement in group with totally different protocol, 12 x 30 s at 175 % PP, and therefore suggested that performance increments occurred via different mechanisms.

Helgerud et al. (2007) found work-matched interval protocols (15 / 15 s and 4 x 4 min) to be similar in improving VO_2max, stroke volume and the speed at lactate threshold after an 8-week program. Esfarjani and Laursen (2007) noticed that during 10-week intervention in moderately trained runners, long intervals (3.5 ± 0.7 min) at vVO2max with 1:1 work-recovery ratio produced similar improvements compared to short intervals (30 s with 4.5 min recovery) at 130% vVO_2max. Both HIT protocols included 2 sessions per week and during the intervention the number of bouts in a single session was increased from 4.8 ± 1.0 to 7.5 ± 0.7 for long intervals and from 7.5 ± 1.2 to 9.0 ± 2.6 for short intervals. Both long and short intervals induced higher improvement in vVO_2max and time to exhaustion at vVO_2max compared to control group (4 x 60 min at 75%vVO_2max) but long intervals improved significantly more in VO_2max and was the only group to increase the speed at lactate threshold significantly from pre to post.

4 RESEARCH QUESTIONS AND HYPOTHESES

This study follows the two studies carried out in Norway (Rønnestad et al. 2015; Rønnestad et al. 2020) and implements the training interventions with not the same, but similar effort-matched training protocols. The two training protocols are short intervals (3 x 10 x 30 s / 15s / 150 s) and long intervals (4 x 4 min / 2 min). However, this study is carried out by running and with only moderately endurance trained individuals. The aim of the study is to compare the effects of SI and LI in endurance performance and performance related variables. Another aim is to compare the time spent at or near VO_2max between SI and LI protocols.

Research question 1. Will LI and SI produce different changes in aerobic endurance performance, maximal oxygen uptake, speed of anaerobic threshold and running economy?

Yes. Higher improvements for SI.

In a 10-week study with similar training sessions (Rønnestad et al. 2015) cyclists who did SI improved their VO_2max and maximal power in the incremental test (Wmax) significantly more than cyclists who carried out LI training. SI group had also tendency for greater improvements in power output at 4 mmol/l bLa and mean power output in 40-min all out trial. Rønnestad et al. (2020) found similar results in a study where after a 3-week intervention SI group increased VO_2max and Wmax significantly whereas LI group did not.

Research question 2. Is the time spent above 90 %, 95 % and 100 % of VO_2max different between the SI and LI?

Yes. SI induces longer time spent above 90 %, 95 % and 100 % of VO_2max.

Rønnestad & Hansen (2016) found that when cycling until the exhaustion at maximal aerobic power with 2:1 work-recovery ratio, 30 s intervals induced longer time above 90 % of VO_2max than 170 s and 272 s intervals which supports the SI protocol in this study. Dupont et al. (2002)

showed that intermittent runs of 15 s / 15 s at 110% and 120% of maximal aerobic speed (MAS, indirectly measured vVO_2max) resulted in greater time spent above 90 % VO_2max than continuous run at MAS. Also, Billat et al. (2000) found that intermittent runs at the velocity of VO_2max with 30 s / 30 s protocol induced longer time above 90 % of VO_2max than the continuous run at the velocity between vVO_2max and lactate threshold. According to these studies higher intensity is a key factor to enable longer time close to VO_2max. While it is expected that with the setting of this study the mean velocity will be higher in SI compared to LI (Rønnestad et al. 2015; Rønnestad et al. 2020), it is hypothesized that SI induces longer time at or near VO_2max.

Research question 3. Does the time spent at or near VO_2max predict improvement in endurance performance?

Yes. Individuals who spend more time at or near VO_2max improve more in the endurance performance.

Although intervention studies measuring the time close to VO_2max have not been conducted it has been widely shown that training in the intensities close to VO_2max induce larger improvement in VO_2max (Wenger & Bell 1986). Also, it has been suggested that the time close to VO_2max is important factor in improving VO_2max and endurance performance. (Midgley et al. 2006; Thevenet et al. 2007)

5 METHODS

5.1 Participants

15 participants who had at least two years background of regular running endurance training volunteered for the study. The level of the participants varied from recreationally trained to elite level. Some of the participants were competitive endurance athletes (running, triathlon, orienteering) and some participants had background from other sports where regular running was part of their fitness training. Five participants were withdrawn from the study, reasons being overuse injury related to the study (2), accidental injury unrelated to the study (1) or flu symptoms (2). Altogether 10 participants (table 3) could go through the study period.

Recruitment was done by sending an announcement via email lists of local university and publishing it in social media during October 2020. During the second round of recruitment email was sent to the local endurance sport clubs. In addition, word-of-mouth advertising was used. Inclusion criteria for participants were 1) regular running endurance training of at least for two years 2) age of 18–40 3) no absolute contraindications (ACSM 2017) which was based on self-report.

TABLE 3. Anthropometric data of the participants.

Group	N	Males	Females	Age (yrs)	Height (cm)	Weight (kg)	BMI (kg/m^2)
LI	5	1	4	32.9 ± 6.0	170 ± 7	68.7 ± 9.3	24.0 ± 3.7
SI	5	2	3	24.8 ± 0.9	171 ± 10	68.6 ± 10.7	23.4 ± 1.7

All volunteered participants were taken into the study. All participants signed a consent form prior to the participation after being informed of the risks associated with the study and possibility to terminate their participation at any time. The study was approved by the ethical committee of the local university and it was performed according to the ethical standards established by the Helsinki Declaration of 1975.

5.2 Experimental design

The design of the study can be seen in the figure 4. The study consisted of pre-tests, 4-week intervention period and post-tests that started 4–7 days after the last interval training of the training period. During the test weeks three different test protocols were conducted: 1) incremental running test on a treadmill to determine participants' VO_2max and other endurance performance related variables 2) anaerobic running test (MART) on a treadmill with vertical jumps on a contact mat before and after the test and 3) 20m speed test on a track and field indoor track. Based on the pre-test results (max velocity of the VO_2max test) subjects were randomly divided into two same level groups. During the training period other group did short intervals 3 x 10 x 30 sec / 150 sec (SI) and the other group long intervals 4 x 4 min / 2min (LI).

1	2	3	4	5	6	7
Pre-tests	II	II	III	III	Post-tests	
VO_2max		Intervention			VO_2max	
MART		SI 3 x 10 x 30 s / 15 s / 150 s			MART	
20m		LI 4 x 4 min / 2 min			20m	

FIGURE 4. Study design. 7-week program included pre- and post-tests and a 4-week training intervention.

During the first two weeks of the training period participants had two interval sessions /week while during the last two weeks three interval sessions /week were set to the program. Altogether 10 high intensity exercises were carried out during the 4 week-training period. Successful execution of at least 90 % of the interval sessions was required. One session in a week was so called control session and it was carried out at the laboratory treadmill in a standardized environment. The rest of the sessions were executed where participant felt they were best to conduct: flat road, treadmill or track and field court.

Both SI and LI groups had similar time of high intensity work during each session (15 min for SI and 16 min for LI) and in both protocols this time was executed at the highest sustainable speed. The speed of the recovery periods was set to 50 % of the maximal speed of the baseline VO_2max test. Protocols were effort-matched, which in theory was supposed to lead to similar values of rate of perceived exertion (RPE) between the two groups. Participants continued their normal training during the intervention but they were advised not to train above their anaerobic threshold level (Z3).

5.3 Data collection procedures

The incremental VO_2max test was carried out in the laboratory setting on an OKJ-1 treadmill (Telineyhtymä Kotka, Kotka, Finland). Anthropometric measurements were conducted before VO_2max test. Height (0.5 cm accuracy), weight (0.1 kg accuracy) and fat % using 4-point skinfold method (Durnin & Rahaman 1967) were measured. The test was preceded by a 10-minute warm-up including 2 x 30 second intervals at velocity decided by the participant. During the test, the velocity of the treadmill was increased by 1 km/h after every 3 minutes. The test was started at low velocity aiming to the length of 24–30 minutes (8–10 x 3-minute load). Treadmill was stopped after each 3-minute interval for lactate measurement. Fingertip lactate sample of 20 µl was taken at rest and after each load. Samples were analyzed with Biosen S_line Lab+ lactate analyzer (EKF Diagnostic, Magdeburg, Germany). If the measurement break exceeded 45 seconds, 1 minute was added to the following load. Elevation of the treadmill was 0.6° during the test. Test was carried out until volitional exhaustion.

Heart rate was measured during the whole test with Polar V800 (Polar Electro, Kempele, Finland). In addition to the maximum heart rate value, average heart rate from the last 30 seconds of each load was recorded. RPE was measured with Borg's scale from 6 to 20 (attachment 1) after each 3-minute stage. Respiratory variables were measured breath-by-breath by using Vyntus CPX metabolic cart (Jaeger-CareFusion, Hoechberg, Germany) and similarly to heart rate, they were expressed as 30 second average values in the end of the each stage. VO_2max was then defined as the highest possible average of the two consecutive 30 second VO_2 values. Due to the breakdown of the gas exchange analyzer during the intervention, post-tests were carried out with different analyzer, MasterScreen CPX (Jaeger, CareFusion Germany 234 GmbH, Hoechberg, Germany).

Certain submaximal values were taken into account from the incremental test from every measured variable. In addition, lactate thresholds were determined by using Klab method. Described by Vesterinen et al. (2016) "lactate threshold 1 was set at 0.3 mmol/l above the lowest lactate value. Lactate threshold 2 was set at the intersection point between 1) a linear model between LT1 and the next lactate point and 2) a linear model for the lactate points with a lactate increase of at least 0.8 mmol/l." If the automatic threshold determination seemed wrong, thresholds were revised based on lactate and respiratory values by the testing personnel.

Similar to the VO_2max test, MART was carried out on an OJK-KOMI treadmill (Telineyhtymä Kotka, Kotka, Finland) until to exhaustion. 20 second stages with 5 second acceleration phase were followed by 95 second passive rest. Increase in the velocity between stages was ~1,4 km/h (4 ml/kg/min increase in theoretical VO_2) and inclination of the treadmill was set at 3.0°. 10-minute warm-up including 2 x 10 second intervals at moderate velocity preceded the test. Countermovement jumps (CMJ) on a contact mat (built on laboratory) were practiced few times before the start of the test.

Again, treadmill test started at low velocity and it was aimed to last around 10 stages (18 minutes). Test included three CMJs before the treadmill run but also immediately after and 5 minutes after the termination of the test. Fingertip lactate samples (20 µl) were taken at rest, after each stage and post 0 min, post 2,5 min, post 5 min and post 10 min. RPE was measured after each treadmill stage. Heart rate was measured as the highest 5 second value following each stage and at rest 10 second before the next stage. Certain submaximal values were taken into account from MART from every measured variable

Speed tests were carried out on an indoor track. Warm-up included 10 minutes self-paced easy running, 5 minutes instructed dynamic flexibility exercises for leg muscles, 3–4 x 60 m accelerations with increasing effort (60–90 % max) and two different kinds of elastic jump exercises (2 x 3–4 drop jumps, 2 x 4–5 calf jumps). Altogether warm-up lasted close to 25 minutes. If participant did not feel ready for the speed test, own extra warm-up was allowed. After the warm-up 3 x 20 meters maximal sprints with 20 m acceleration ("flying 20 m") were conducted. Rest between sprints was over 3 minutes but not standardized by time. Time of the

20 m test was measured with portable photocells (Spintest Oy, Tallinn, Estonia) that were set on their locations based on tape measurement.

Based on the pilot measurements, as a guidance for training period, the velocity to start the interval session was set at around LT2 for long intervals and around halfway between LT2 and maximal velocity of the VO_2max test for short intervals. During the intervention velocities were revised based on learning, improvement and feeling. Participants knew their velocity during the control sessions. Same variables were measured during the monitored interval sessions compared to VO_2max test. RPE and lactate were measured after each interval (LI) or series (SI). Heart rate was measured as the average of the last 20 seconds of each interval (LI) or series (SI). Time spent ≥90 %, ≥95 % and ≥100 %, of VO_2max were measured from breath-by breath respiratory data and presented in absolute time and in relation to the time of the whole session. The unsupervised sessions were measured by participants' own heart rate monitors and collected in .csv or. fit format. Heart rate and velocity were collected. Training of the intervention period was monitored by training diary. Total volume, intensity distribution (Z3-model) of all training and running mileage and running volume (h:mm) were collected.

5.4 Statistical analysis

All the results are expressed as mean (avg) and standard deviation (SD). Because of the number of the participants the results were analyzed by using nonparametric methods. Therefore, the distribution of the data was not checked. Between-group differences at baseline and in the training adaptations were tested with Mann-Whitney U-test. Within-group differences between pre- and post-tests were analyzed by using Wilcoxon signed rank test. Mann-Whitney U-test was similarly used to check between-group differences in the training diary data, control session data, data from the self-paced interval sessions and the data related to the time spent at or near VO_2max. To compare within-group differences between different control sessions, Wilcoxon signed rank test was used. Spearman's correlation coefficient was used to determine the relationships between different variables. Statistical significance was accepted as $P < 0.05$. To describe "nearly significant", the word tendency was used between p-values of 0.05 and 0.08.

Statistical analyses were carried out using IBM SPSS Statistics 24 (IBM Corporation, Armonk, NY, USA) and Microsoft Excel 2019 softwares (Microsoft Corporation, Redmond, WA, USA).

6 RESULTS

6.1 Pre- and post-test measurements

There were no statistically significant differences between LI and SI in the baseline measurements. LI improved significantly VO_2max l/min, VO_2max ml/kg/min, velocity of anaerobic threshold, maximal velocity of MART and pretest CMJ, while SI had lower heart rate at anaerobic threshold in the post-test (tables 4 and 5, figure 5) in comparison to the pre-test. In addition, post-test CMJ result was significantly lower compared to pretest for SI. There were no statistically significant between-group differences in the relative changes of the tested variables. A tendency for significant changes from pre- to post-test was found in maximal lactate (P = 0.068) for LI and in maximal heart rate (P = 0.080) for SI. In addition, a tendency for significant between-group differences in relative changes was seen in VO_2max ml/kg/min (P = 0.056) and in pretest CMJ (P = 0.056).

TABLE 4. Test results for long (LI, n = 5) and short (SI, n = 5) interval training groups before and after the 4-week training intervention in the maximal anaerobic running test and 20 m speed test.

	LI PRE	LI POST	SI PRE	SI POST
MART				
$Vmax_{MART}$ (km/h)	20.34 ± 1.43	21.08 ± 2.18*	22.47 ± 2.26	22.80 ± 2.44
BLamax (mmol/l)	10.9 ± 3.1	11.2 ± 2.4	11.8 ± 3.7	12.9 ± 4.1
CMJ pre (cm)	27.7 ± 10.5	29.0 ± 11.2*	33.6 ± 6.6	33.5 ± 6.0
CMJ post 0’ (cm)	27.8 ± 9.7	28.8 ± 10.2	32.8 ± 5.2	31.2 ± 4.9*
20 m test				
Time (s)	2.87 ± 0.28	2.87 ± 0.33	2.68 ± 0.31	2.66 ± 0.29

$Vmax_{MART}$ = maximal velocity of the maximal anaerobic running test. BLamax = maximal lactate measured in MART. CMJ pre = countermovement jump height before MART. CMJ post 0’ = countermovement jump height immediately after MART. * Different from pretest ($P < 0.05$).

TABLE 5. Test results for long (LI, n = 5) and short (SI, n = 5) interval training groups before and after the 4-week training intervention in the anthropometric measurements and incremental running test (VO_2max test).

	LI PRE	LI POST	SI PRE	SI POST
Anthropometric data				
Weight (kg)	68.7 ± 9.3	67.8 ± 10.2	68.6 ± 10.7	68.1 ± 9.7
Fat (%)	23.8 ± 8.2	23.0 ± 8.6	17.5 ± 6.0	18.2 ± 7.4
Incremental test				
VO_2max (l/min)	3.12 ± 0.37	3.24 ± 0.47*	3.44 ± 1.10	3.31 ± 0.93
VO_2max (ml/kg/min)	45.5 ± 4.4	48.0 ± 5.0*	49.5 ± 10.5	48.1 ± 8.4
HRmax (bpm)	190 ± 10	188 ± 8	197 ± 7	191 ± 8
BLamax (mmol/l)	8.7 ± 1.9	10.3 ± 1.7	10.5 ± 1.5	10.7 ± 2.3
Vmax (km/h)	15.74 ± 1.29	15.96 ± 1.60	17.02 ± 2.47	17.14 ± 2.15
$T2VO_2$ ml/kg/min	39.9 ± 2.7	41.7 ± 4.3	44.0 ± 9.4	42.5 ± 8.1
T2HR (bpm)	174 ± 13	171 ± 11	178 ± 8	176 ± 6*
T2velocity (km/h)	12.60 ± 1.14	13.00 ± 1.22*	13.90 ± 2.53	14.04 ± 2.28
T2BLa (mmol/l)	2.7 ± 0.6	2.9 ± 0.6	2.5 ± 0.3	2.8 ± 0.5
$T1VO_2$ ml/kg/min	33.3 ± 3.0	34.2 ± 3.1	36.5 ± 7.7	35.8 ± 8.6
T1HR (bpm)	156 ± 18	153 ± 13	162 ± 5	159 ± 6
T1velocity (km/h)	10.28 ± 0.76	10.54 ± 0.62	11.72 ± 2.21	11.78 ± 2.56
T1BLa (mmol/l)	1.4 ± 0.2	1.5 ± 0.3	1.4 ± 0.5	1.4 ± 0.4
$12VO_2$ ml/kg/min$^{£}$	37.8 ± 2.6	38.9 ± 2.3	37.1 ± 1.7	36.8 ± 2.2
12BLa (mmol/l)$^{£}$	2.5 ± 0.8	2.4 ± 1.0	2.2 ± 0.2	2.3 ± 0.5
12HR (bpm)$^{£}$	171 ± 18	165 ± 14	175 ± 11	171 ± 9

£ = n for SI was 4. Vmax = maximal velocity of the incremental running test. $T2VO_2$ = oxygen consumption at anaerobic threshold. T2HR = Heart rate at anaerobic threshold. T2velocity = velocity at anaerobic threshold. T2Bla = blood lactate at anaerobic threshold. T1 = aerobic threshold. $12VO_2$ = oxygen consumption at 12 km/h velocity. 12BLa = blood lactate at 12 km/h velocity. 12HR = heart rate at 12 km/h velocity. * = Different from pretest ($P < 0.05$).

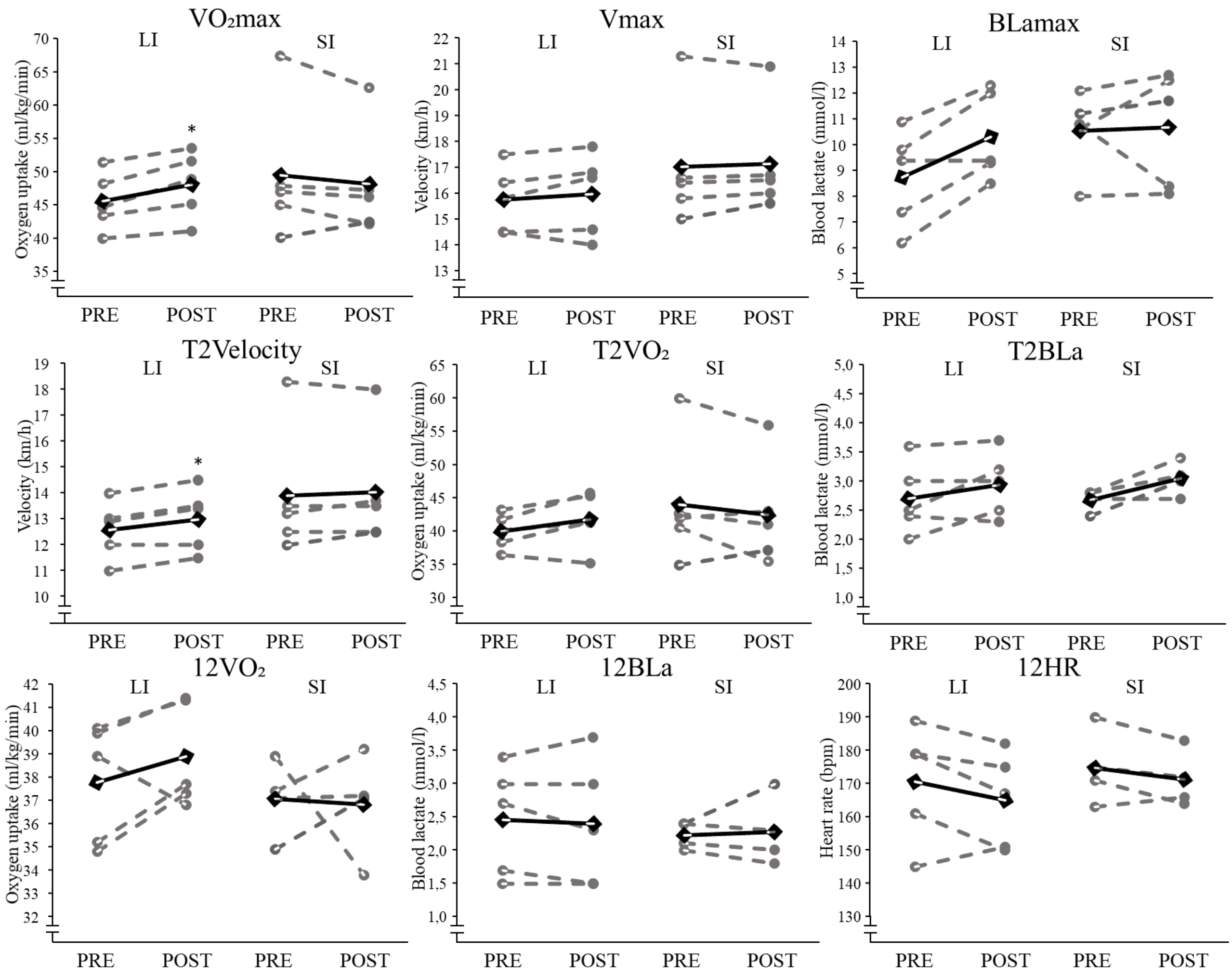

FIGURE 5. Changes in some of the key variables related to the incremental running test with individual (gray lines) and group (black line) values presented. Vmax = maximal velocity of the incremental running test. T2velocity = velocity at anaerobic threshold. $T2VO_2$ = oxygen consumption at anaerobic threshold. T2Bla = blood lactate at anaerobic threshold. $12VO_2$ = oxygen consumption at 12 km/h velocity. 12BLa = blood lactate at 12 km/h velocity. 12HR = heart rate at 12 km/h velocity. * Different from pretest ($P < 0.05$).

For LI, high ($r > 0.900$) and significant ($P = < 0.05$) correlations with the change in VO_2max (ml/kg/min) were found in the changes of $12VO_2$ l/min ($r = 0.900$), $12VO_2$ ml/kg/min ($r = 0.975$), $T2VO_2$ l/min ($r = 0.975$), $T2VO_2$ ml/kg/min ($r = 0.900$) and 20 m test ($r = -0.900$). For SI, respective variables were $12VO_2$ l/min ($r = 1.000$), $12VO_2$ ml/kg/min ($r = 1.000$), T2Velocity ($r = 0.949$), $T2VO_2$ ml/kg/min ($r = 0.904$), $T2VO_2$ l/min ($r = 1.000$), VO_2max l/min (r = 0.900) T1HR (r = -1.000), 20m test (r = -0.975) and theoretical T1VO$_2$ ml/kg/min (r = -0.960). For LI, variables that correlated well with the change in Vmax (incremental running test) were theoretical VO$_2$max (r = 0.894) and 20 m test (r = -0.900). For SI there were no variables that correlated well and significantly with the maximal velocity of the incremental running test.

6.2 Training intervention

Training related statistics and days between the last interval session and the first post-test day are presented in the table 6. There were no differences between groups in any presented weekly variable, although there was tendency for higher total volume for SI in the second week (P = 0.056). The days between the last interval training and the first post-test day did not differ between LI (5.6 ± 2.0 days) and SI (6.6 ± 2.8 days)

TABLE 6. Training diary statistics from each week for both groups.

LI (n = 5)	Run (km)	Run	Z1 (h:mm)	Z2 (h:mm)	Z3 (h:mm)	All (h:mm)
Wk 1	23.0 ± 10.7	2:42 ± 1:32	3:51 ± 2.46	0:34 ± 0:36	0:35 ± 0:13	5:32 ± 2:08
Wk 2	23.6 ± 18.4	2:34 ± 2:05	3:15 ± 2:24	0:43 ± 0:49	0:30 ± 0:02	5:13 ± 2:10
Wk 3	30.8 ± 13.4	3:09 ± 1:22	3:53 ± 3:14	0:22 ± 0:50	0:41 ± 0:08	5:30 ± 2:30
Wk 4	29.4 ± 14.6	2:47 ± 1:20	3:49 ± 2:00	0:08 ± 0:18	0:41 ± 0:14	5:06 ± 1:49
SI (n = 5)	Run (km)	Run	Z1 (h:mm)	Z2 (h:mm)	Z3 (h:mm)	All (h:mm)
Wk 1	42.2 ± 31.0	3:32 ± 2:08	4:48 ± 1:35	0:12 ± 0:27	0:31 ± 0:00	6:43 ± 1:37
Wk 2	42.6 ± 38.6	3:13 ± 2:25	5:44 ± 2:22	0:19 ± 0:44	0:35 ± 0:07	8:22 ± 2:19
Wk 3	46.8 ± 38.2	3:46 ± 2:19	4:25 ± 2:39	0:19 ± 0:41	0:48 ± 0:00	6:40 ± 3:30
Wk 4	28.6 ± 8.1	2:33 ± 1:16	4:16 ± 2:24	0:12 ± 0:23	0:39 ± 0:19	5:50 ± 3:09

Run (km) = running mileage, Run (h:mm) = running volume in hours and minutes, Z1 = all training below aerobic threshold intensity, Z2 = all training between aerobic and anaerobic threshold intensitites, Z3 = training above anaerobic threshold intensity, All = total volume in hours and minutes

Both groups increased their mean velocity of the control intervals throughout the intervention period (figure 6), but there were no statistical differences between groups in weekly values even though SI had approximately 1,5 km/h higher velocity on average each week. Differences in mean velocities were close to significant in week 1 and 2 (both P = 0.056). If the velocity was viewed in relation to the maximal velocity of the pre-intervention incremental running test, groups differed significantly on each week (P = 0.048). SI conducted the control sessions at 89, 93, 94, and 96 % of Vmax whereas LI at 80, 84, 86 and 88 % of Vmax.

Similar to the control sessions, there were no between-group differences in self-conducted intervals absolute velocity (table 7). For LI, during the first and the third week the velocity of the self-conducted intervals was significantly higher in comparison with the control sessions. During the second week heart rate in the self-conducted intervals differed from control session for SI.

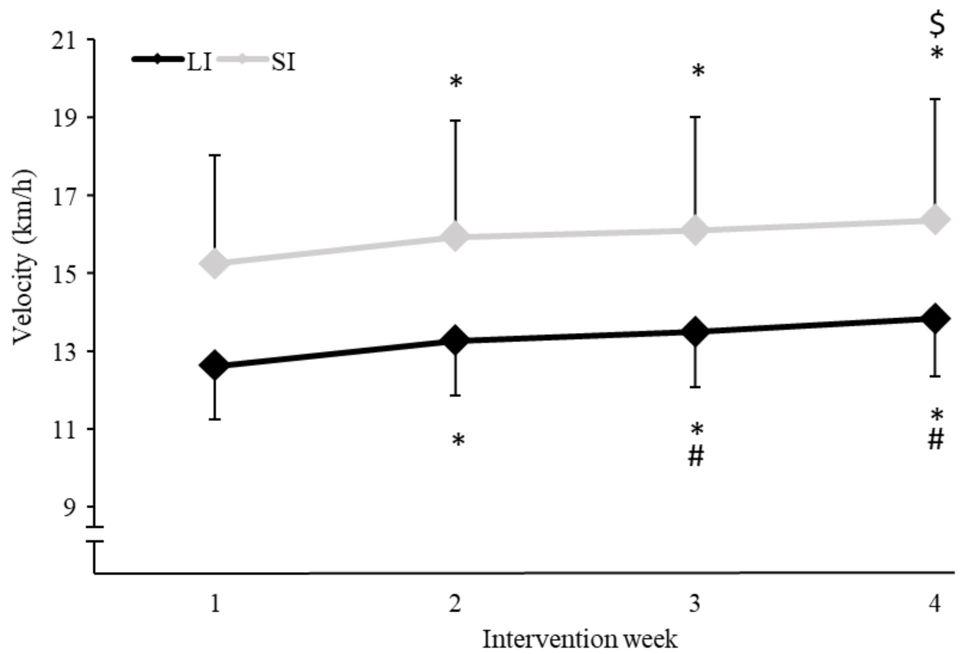

FIGURE 6. Mean interval velocity of the weekly control sessions during the intervention period. * Different from week 1. # = different from week 2. $ = different from week 3.

TABLE 7. Data of the controlled interval sessions in the laboratory settings and self-conducted intervals sessions.

LI	Control session intervals				Self-made intervals	
(n = 5)	Velocity	HR	BLa (mmol/l)	RPE	Velocity	HR (bpm)
Wk 1	12.6 ± 1.4	173 ± 9	3.9 ± 1.5	16.7 1.2	13.7 ± 1.7*	175 ± 11
Wk 2	13.3 ± 1.4	176 ± 9	5.8 ± 1.8	16.9 0.9	13.7 ± 1.8	172 ± 11
Wk 3	13.5 ± 1.4	176 ± 9	5.7 ± 1.7	16.8 0.8	14.1 ± 1.7*	175 ± 11
Wk 4	13.8 ± 1.5	175 ± 10	6.0 ± 3.2	17.2 0.9	14.0 ± 1.7	175 ± 10
SI	Control session intervals				Self-made intervals	
(n = 5)	Velocity	HR	BLa (mmol/l)	RPE	Velocity	HR (bpm)
Wk 1	15.2 ± 2.8	175 ± 5	3.6 ± 0.6	15.9 0.8	16.1 ± 2.9	175 ± 8
Wk 2	15.9 ± 3.0	179 ± 6	4.9 ± 1.4	16.8 0.3	16.4 ± 3.2	177 ± 7*
Wk 3	16.1 ± 2.9	180 ± 9	5.7 ± 1.3	16.5 0.4	15.6 ± 3.4	177 ± 5
Wk 4	16.4 ± 3.1	181 ± 9	6.7 ± 1.1	17.1 0.6	15.9 ± 3.2	178 ± 7

* Different from control session intervals.

6.3 Time spent at or near VO_2max

The time spent at or near VO_2max was analyzed from the data of the first two control sessions. Figure 7 shows the absolute time spent at each level (90, 95, 100 %) while in figure 8 the time is presented in relation to the total time (intervals + active recovery). The time at or near VO_2max did not differ between LI and SI at any variable nor in any measurement point (week 1 or 2). Only LI could increase the time at or above 90%, 95 % and 100 % of VO_2max significantly ($P < 0.05$) from week 1 to week 2, although there was clear tendency for improvement also for SI.

When investigating the whole group (n = 9) fat percent measured in the baseline had significant correlations (r = 0.686) with the time spent at or above 95 % and 100 % of VO_2max presented in relative terms. Blood lactate at aerobic threshold correlated significantly (r = -0.672, -0.689) with the absolute time spent at or above 90 % and 95 % of VO_2max, respectively. Blood lactate at anaerobic threshold correlated with the absolute time spent at or above 100 % and relative time at or above 90 %, 95 %, and 100 % of VO_2max. From the adaptive responses the only significant correlation produced with the time spent at or near VO_2max was the change in 12BLa ($r = 0.709$-0.869, $P = 0.002$-0.032). The participants' level at the baseline or the change in VO_2max (ml/kg/min) did not predict the ability to spend time close to VO_2max.

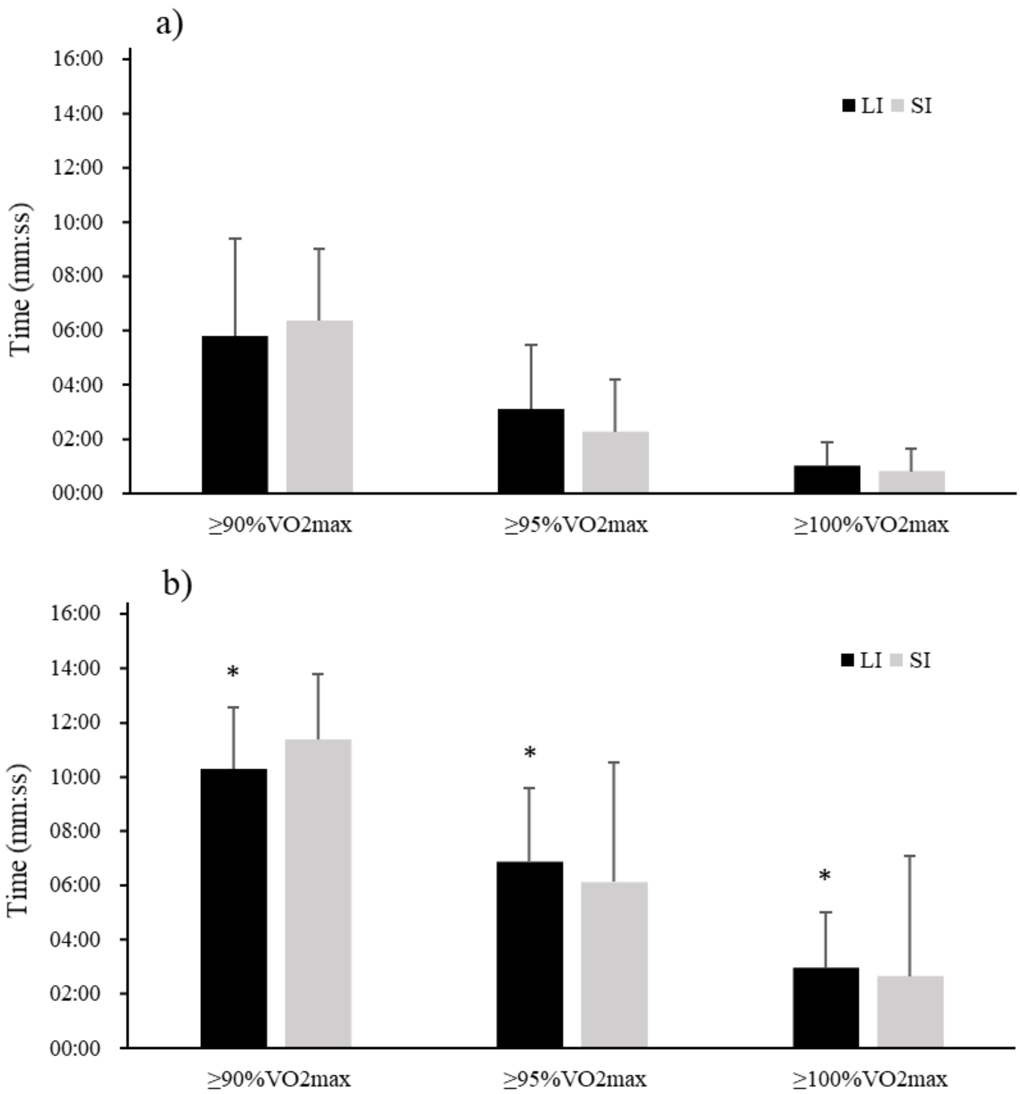

FIGURE 7. The absolute time measured in the whole session at or near VO_2max in three different levels during the first (a) and the second (b) week of the intervention. LI n = 5, SI n = 4. * Different from week 1.

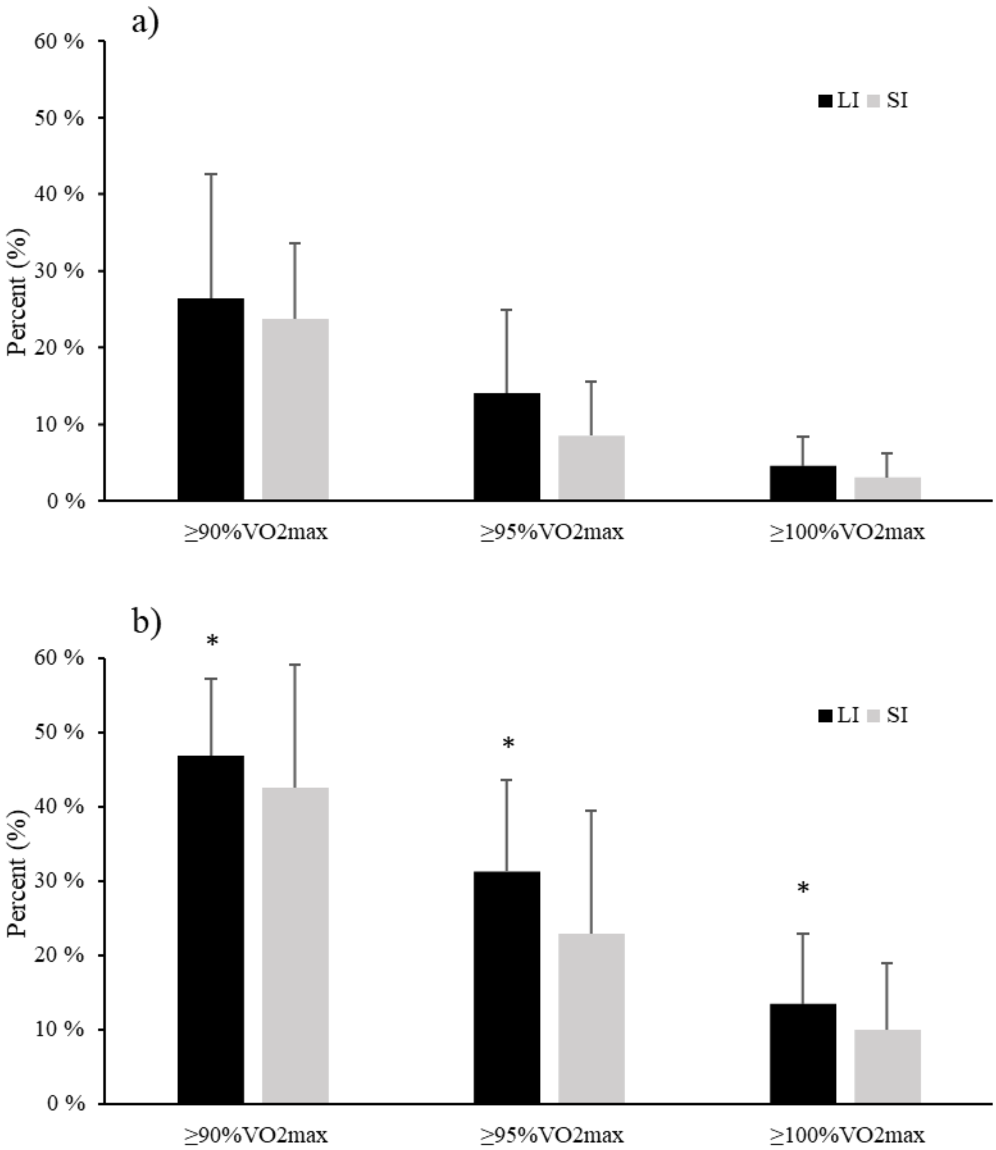

FIGURE 8. The time at or near VO_2max measured in three different levels during the first (a) and the second (b) week of the intervention, presented in relation to the total time of the session including intervals and active recovery. LI n = 5, SI n = 4. * Different from week 1.

7 DISCUSSION

The main finding of the study was that LI could improve VO_2max, the speed of the anaerobic threshold and the maximal speed of MART significantly while SI could not. However, relative changes from pre- to post-test did not differ between the groups. Another finding was that LI and SI did not differ in the time spent at or near VO_2max.

7.1 Endurance performance and performance related variables

The results related to the pre- and post-test measurements were generally against hypotheses. In both groups the relative improvements in maximal velocity of the incremental running test were non-significant. In addition, there were no between-group differences which do not support the hypothesis of SI producing superior effects compared to LI. According to the previous studies, both long interval protocols and short interval protocols have been shown to improve endurance performance. With varying testing methods, both short (Cicioni-Kolsky et al. 2013; Rønnestad et al. 2015; 2020) and long (Esfarjani & Laursen 2007; Stepto et al. 1999) intervals have been shown to induce superior adaptations compared to each other – evidence giving slightly more support to the SI.

Partly contradictory evidence with the hypothesis can also be seen in the changes of VO_2max as a result was increased for LI but remained the same for the SI group. The significant changes for LI are in line with the literature as the training period of long intervals has been seen to increase VO_2max by 7.2 % after 8 weeks (Helgerud et al. 2007) and by 9.1 % after 10 weeks (Esfarjani & Laursen 2007) in moderately trained male participants. Slight, but not significant decrement in VO_2max for SI, however, is in contrast to the previous studies as Rønnestad et al. (2015) found 8.7 ± 5.0 % improvements in VO_2max after a 10-week SI program in competitive cyclists and in the study of Rønnestad et al. (2020) improvement was 2.6 ± 2.7 % after 3 weeks training in elite-level cyclists. Additionally, many other interval studies using SI support the findings of Rønnestad et al. (2015; 2020) that VO_2max can be increased by implementing SI to the training schedule (Laursen et al. 2002; Helgerud et al. 2007; Esfarjani & Laursen 2007).

Possible reasons for differences between groups and the results that were against the hypothesis remain speculative. Without a doubt, interval training elicited acute cardiovascular stress for participants in both groups. Based on heart rate and oxygen consumption in control and self-conducted sessions, groups did not differ from each other. When considering the other studies, it can be argued that the present training load was enough to induce adaptations that lead to improvement in endurance performance. Namely, endurance performance can be improved by implementing high-intensity interval work time of around 30 to 60 minutes to the weekly training schedule (Cicioni-Kolsky et al. 2013; Esfarjani & Laursen 2007; Rønnestad et al. 2015; Rønnestad et al. 2020). Therefore, it can be argued that the weekly volume of 30–48 minutes of high-intensity intervals in this study should have been sufficient enough to induce adaptations. Although the majority of the studies have used longer training periods from 6 up to 10 weeks (Cicioni-Kolsky et al. 2013; Esfarjani & Laursen 2007; Helgerud et al. 2007; Rønnestad et al. 2015), improvement in endurance performance has also been found after 3- and 4-week training interventions (Laursen et al. 2002; Rønnestad et al. 2020; Stepto et al. 1999). This indicates that in addition to the weekly volume, the length of the training period was in theory long enough for adaptations to occur.

One possible reason for the lack of improvement in endurance performance or performance-related variables for SI could be based on the specificity of the interval training protocols. Shorter periods of work at higher intensity including accelerations and decelerations could in theory have more effect on anaerobic metabolism (Brooks 2009) and neurosmuscular system (Denadai et al. 2006). However, lactate values were similar between the two groups which indicates that the usage of fast-twitch muscle fibers was similar during the protocols (Brooks 2009), although it has to be remembered that absolute blood lactate values vary individually. Acute neuromuscular fatigue was not measured after the training sessions. Thus, effects on the neuromuscular system cannot be proven. Moreover, it was LI but not SI that increased the maximal velocity of MART which does not necessarily support the specificity principle. To find out more about the effects at an individual level, different protocols should be studied also with cross-over design.

On the other hand, it is possible that the training program was too intensive, and post-tests were conducted in a fatigued state, especially in case of SI. Participants' average in maximal oxygen consumption was below 50 ml/kg/min in the present study. Therefore, the participants of this study were on a much lower level compared to the participants in the studies of Rønnestad et al. (2015; 2020) where average VO_2max varied between 65 and 73 ml/kg/min. Even though the volume per session was ~20 % lower in this study, it can be possible that the interval training program was too hard for some of the participants. Hence, the post-test measurements were carried out in a fatigued state. Recovery monitoring was not used in this study so this remains speculative.

7.2 Time spent at or near VO_2max

The results of the present study related to the time spent at or near VO_2max were against the hypothesis as no differences were found between the two training methods. The lack of gas exchange data from studies using similar intervals and the fact that the majority of the studies investigating time spent close to VO_2max use protocols until to exhaustion make the comparison of this study with the rest of the literature challenging. Both of the protocols had important aspects that have been found to increase the time close to VO_2max. These characteristics were work-to-rest ratio of 2:1 (Rozenek et al. 2007) and active recovery (Thevenet et al. 2007). However, SI could maintain higher relative mean velocity which is noticed to be an important factor defining the time spent close to VO_2max (Billat et al. 2000; Dupont et al. 2002).

Although Rønnestad et al (2015; 2020) mentioned that their SI protocol (similar to this study) used 2:1 work-recovery ratio, this description of the training protocol has to be questioned. While short intervals might be more practical to complete in series in terms of achieving higher mean velocity, this changes the actual work-recovery ratio of the current SI method to 1:1 which has been shown to be a weaker solution for inducing time close to VO_2max (Millet et al 2003; Rozenek et al. 2007; Wakefield & Glaister 2009). An easier recovery period lengthens the time required to achieve VO_2max (Midgley et al. 2006). However, removing the recovery periods would in turn lower the mean velocity of the intervals. Further research is needed to determine whether there would be positive outcomes from changing SI protocol to 30 x 30 sec / 15 sec.

Finally, the time spent at or near VO_2max did not predict the improvement in endurance performance, contradictory to what has been previously indirectly showed (Wenger and Bell 1986) and suggested (Thevenet et al. 2007 Rönnestad et al. (2015). To my knowledge, this was the first interval intervention study that has published the values of times spent close to VO_2max and tried to prove the importance of exercising a long time at or near VO_2max when focusing on endurance performance. Therefore, reasons for the nonexistent correlation between the time spent close to VO_2max and improvement in endurance performance remain to be explained.

7.3 Strengths and limitations

The strengths of this study can be seen in its novelty. To the writer's knowledge, this was the first running-based study to make comparison between effort-matched short and long interval protocols. At the same time, this seems to be the first intervention study to actually measure and publish the time spent at or near VO_2max and investigate its relationship with the adaptations in endurance performance and performance-related variables. The effort-matched approach represents better of how athletes typically carry out their high-intensity interval training when compared to the usually used isoenergetic approach (Seiler et al. 2013). Therefore, this study gives better practical knowledge to the athletes and coaches about what kind of interval training should be implemented to the training schedule if improvements are pursued in few weeks of time.

The present study also includes some limitations that hinder the validity of the study and generalization of the results. First of all, the number of the subjects limits the power of the study remarkably and further research around the topic is undoubtedly needed. In a small group also the probability for bias due to one person's abnormal result increases. Better familiarization with the interval protocols for the subjects before the intervention would have decreased the learning effect. Additionally, with a controlled training period before the intervention the actual effects of the interval training could have been specified better.

It has to be also noted that due to the breakdown of one of the gas exchange analyzers pre- and post-tests were measured with different devices. Finally, while the majority of the subjects were females and the timing of the menstrual cycle was not taken into account in this study, this may have had effects on either pre- or post-test measurements and thus created some bias to the results (McNulty et al. 2020).

7.4 Conclusions

The major finding of this study was that traditional longer intervals (4 x 4 min / 2 min) produced more favorable adaptations in endurance performance related variables compared to shorter intervals (3 x 10 x 30 s / 15 s / 150 s). Additionally, time spent at or near VO_2max did not differ between the two protocols and it was not associated with the changes in endurance performance, contradictory to what has been previously suggested.

This study is in line with the previous research showing that 2:1 work-recovery ratio is a successful concept to build up an interval session (Millet et al 2003; Rozenek et al. 2007). According to this study higher relative mean velocity during intervals was not connected to the changes in the endurance performance-related variables or time spent close to VO_2max. However, this finding is in contrast to the previous studies as higher mean power output has been shown to induce higher improvement in endurance performance (Rönnestad et al. 2015; 2020) and higher velocity has been suggested to increase the time close to VO_2max, respectively (Billat et al. 2000; Dupont et al. 2002).

Due to the several limitations of this study and mixed results across the literature, more research around the topic is needed. Although the importance of the high-intensity interval training is well-established, it remains unclear how to organize best different interval protocols (Rönnestad et al 2020). Knowledge about the benefits of the effort-matched approach in the high intensity interval training needs to be rationalized further. Also, research lacks well-controlled interval intervention studies where the importance of time spent at or close to VO_2max is defined in different populations.

7.5 Practical applications

According to this study, peaking up before an important competition using 2-3 weekly long interval sessions (4 x 4 min / 2 min) during 4 weeks is a successful method to improve VO_2max. The highest sustainable speed during the work intervals should be pursued, while active recovery between intervals is recommended to maximize the time close to VO_2max. Based on previous research also short intervals might induce positive adaptations on endurance performance, even superior compared to long intervals. However, this is contradictory with the present study. It could be argued that due to higher mean speed and multiple accelerations and decelerations short intervals produce extra stress on the neuromuscular system and its functions. In relation to the results of the present study, this emphasizes the importance of monitoring and successful periodizing of the exercise sessions so that the training stimulus remains optimal. Individual fitness level, training status and goals need to be considered when programming high-intensity interval sessions.

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ATTACHMENTS

Rating	Perceived Exertion
6	No exertion
7	Extremely light
8	
9	Very light
10	
11	Light
12	
13	Somewhat hard
14	
15	Hard
16	
17	Very hard
18	
19	Extremely hard
20	Maximal exertion