JYU DISSERTATIONS 830

Pekka Matomäki

Effects of a 10-Week Low and High Intensity Training Intervention on Performance Abilities—With a Special Reference to Durability

UNIVERSITY OF JYVÄSKYLÄ
FACULTY OF SPORT AND
HEALTH SCIENCES

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Harri Piitulainen
Faculty of Sport and Health Sciences, University of Jyväskylä
Timo Hautala
Open Science Centre, University of Jyväskylä

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ABSTRACT

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Effects of a 10-week low and high intensity training intervention on low and high intensity performance abilities – special reference to durability
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In terms of endurance performance abilities, the potential effects of very high volumes of low intensity training are not thoroughly understood. This information would be essential, as both athletes and recreational individuals spend most of their training time at low intensity. The purpose of this thesis was to investigate the effects on pooled low and high intensity performance on untrained males and females after 10 weeks of training in two groups. The first group (n = 16) cycled extensively (6.8 h weekly on average, and 9.6 h during the last three weeks) at low intensity (97% of total time at or below the power at the first lactate threshold); the second group (n = 19) cycled less (1.6 h/week), but at high intensity (44% at or above the second lactate threshold). The main outcome variables were pooled into low and high intensity performance, each composed of several performance variables. Low intensity training improved low intensity performance, but not high intensity performance. Conversely, high intensity training improved high intensity performance, but not low intensity performance (study III). Notably, durability, measured by magnitude of physiological changes during a three-hour low intensity cycling, improved in both groups (study III). Perceived exercise enjoyment did not predict the individual responses to training (study II). Lastly, the metric used to balance training volumes between training groups significantly affects the content and interpretation of training interventions (study IV). Based on this thesis, the minimum effective training intensity depends on the specific attribute that needs to be improved; low intensity performance improves with lower intensity than high intensity performance. Further, high intensity training cannot be compensated for by high volumes of low intensity training. Lastly, this thesis demonstrated durability to be an independent component of endurance performance, capable of improving without concurrent enhancements in maximal oxygen uptake.

Keywords: low intensity training, high intensity training, durability, endurance performance

TIIVISTELMÄ (ABSTRACT IN FINNISH)

Matomäki, Pekka
10-viikkoisen matala- ja korkeatehoisen harjoitteluintervention vaikutus suorituskykymuuttujiin – Erityismainintana väsymisensieto
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Yllättävän vähän tiedetään, mitä vaikutuksia todella runsaalla matalatehoisella kestävyysharjoittelulla on eri kestävyyssuorituskyvyn tekijöihin. Tämä olisi oleellista, sillä sekä kuntoilijat että urheilijat tekevät leijonanosan harjoittelustaan matalalla teholla. Tämän väitöskirjan tarkoitus oli tutkia mitä tapahtuu matala- ja korkeatehoiselle suorituskyvylle, kun harjoittelemattomat miehet ja naiset harjoittelivat kahdessa ryhmässä 10 viikkoa. Ensimmäinen ryhmä (n = 16) pyöräili paljon (viikoittain keskimäärin 6,8 h, ja viimeisillä kolmella viikolla 9,6 h) matalalla teholla (kokonaisajasta 97% enintään ensimmäisellä laktaattikynnyksen teholla); Toinen ryhmä (n = 19) pyöräili vähemmän (1,6 h / vko), mutta suurella teholla (kokonaisajasta 44% vähintään toisella laktaattikynnyksellä). Päätemuuttujina olivat yhdistetty matalan tehon suorituskyky sekä korkean tehon suorituskyky, joista kumpikin koostui useista suorituskykymuuttujista. Matalatehoinen harjoittelu paransi matalatehoista suorituskykyä, mutta ei korkeatehoista. Korkeatehoinen harjoittelu vaikutti päinvastoin parantaen korkeatehoista, mutta ei matalatehoista suorituskykyä (osatyö II). Erityisesti molemmissa ryhmissä väsymisensieto kolmetuntisen matalatehoisen pyöräilyn aikana parani (osatyö I). Harjoittelun miellyttävyydestä ei voitu ennustaa kuka yksilöllisesti kehittyi milläkin harjoitteluteholla (osatyö III). Lopuksi, laskentametodi, jolla ryhmien harjoittelu tasapainotetaan vaikuttaa suuresti harjoitteluinterventioiden sisältöön ja tulkintaan (osatyö IV). Tämän väitöskirjan tulosten perusteella matalin kehittävä harjoitteluteho ei ole yksiselitteinen, vaan se riippuu siitä, mitä halutaan kehittää: matalatehoinen suorituskyky kehittyy matalammalla teholla kuin korkeatehoinen. Kävi myös ilmi, että korkeaa harjoittelutehoa ei voi kokonaisuudessaan korvata hyvin suurella määrällä matalatehoista harjoittelua, koska korkeantehon suorituskyky ei kehittynyt kuin riittävän korkealla teholla. Lisäksi väitöskirjan tulokset osoittivat väsymisensiedon olevan itsenäinen kestävyyssuorituskykyä kuvaava tekijä, joka voi kehittyä ilman maksimaalisen hapenottokyvyn samanaikaista parannusta.

Avainsanat: kestävyysharjoittelu, väsymisen sieto, kestävyyssuorituskyky, matalatehoinen harjoittelu, intervalliharjoittelu

Author	Pekka Matomäki Faculty of Sport and Health Sciences[*] University of Jyväskylä Finland ORCID 0000-0002-0241-8406
Supervisors	Professor Heikki Kyröläinen, PhD Faculty of Sport and Health Sciences University of Jyväskylä Finland
	Professor Olli J. Heinonen, MD, PhD Paavo Nurmi Centre & Unit for Health and Physical Activity University of Turku Finland
	Chief Specialist Ari Nummela †, PhD Finnish Institute of High Performance Sport KIHU Finland
Reviewers	Professor Bent Rønnestad, PhD Faculty of Social and Health Sciences Inland Norway University of Applied Sciences Norway
	Senior Lecturer Ed Maunder, PhD Faculty of Health and Environmental Sciences Auckland University of Technology New Zealand
Opponent	Professor Andrew Jones, PhD Faculty of Health and Life Sciences University of Exeter United Kingdom

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[*] In collaboration with Paavo Nurmi Centre, University of Turku

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It has been a long journey. I have learned that, unlike in mathematics, in sport science one needs large travel group. Luckily, I have had the opportunity to have a great company during my trip.

In the first part through my sailings, I thought that I was unlucky to have three advisors from different branches of science; Professor Olli Heinonen as a clinician interested in scientific methodology, Professor Heikki Kyröläinen as an exercise physiologist, and docent Ari Nummela closely oriented towards practice. And then there was me with my mathematical upbringing. However, while navigating this crosscurrent, I realized how fortunate I was to view research from so many different perspectives.

I sincerely thank Heikki for being a supportive advisor, always standing by me and also demonstrating how to firmly negotiate with companies. Every time we had a research meeting, he had a cheerful expression and an encouraging word to say. He excellently showed me the path on which research has traditionally been conducted in Jyväskylä.

Olli has challenged me to view research from a new perspective and has sought to bring a clinician's insight into my work. We do not always agree, but he has patience to wait me to change my mind. Admittedly, it has been a working strategy. His continuous sparring has helped to broaden my thinking. I would like to express my gratitude to Olli for his naturally caring and supportive approach in helping me move forward.

Unfortunately, to my sorrow, Ari passed away during my dissertation project. He had a great touch in Finnish endurance coaching and he was at the forefront of endurance training research in Finland. He has taught perseverance through his actions and, like the other supervisors, he also had a supportive approach in his guidance.

Furthermore, I would like to extend my sincere thanks to my mathematics advisor Luis Alvarez. Although he has not been directly involved in my work in sports science, he provided me with my first experience in scientific research and taught me how to write without "shooting myself in both feet”.

Besides the advisors, I came to notice that in sports science, there is a large group of individuals who do and assist with the practical tasks necessary for advancing research projects. Thus, I thank Chief Laboratory Technicians Lasse Kautto, Eero-Pekka Auvinen, and Niina Kajan, as well as Susanna Luoma and Tanja Toivanen, not to forget Senior Laboratory Technicians Jouni Tukiainen and Sirpa Roivas and Laboratory Manager Maarit Lehti. I thought I was a decent lactate sampler until I asked Susanna to show me how it's done. These laboratory staff continuously demonstrate diligence in keeping the laboratories running and, amidst their work, always find time to assist a keen researcher seeking a small favor or guidance. “There probably aren’t many idle moments, are there?” “If I remember correctly, there was one on March 3rd,” as Jouni remarked playfully to me.

I was relieved and pleased to have two highly skilled testers join my project for practical measurements. I express my gratitude for their time and flexibility with work hours. I wouldn't have believed anyone could perform alone three three-hour tests on a Sunday as Eero-Pekka did. Together, our team was strong: Eero-Pekka Auvinen and I were enthusiastic drivers of the project and Leena Pirkola acted as a calm and thorough verifier.

One of the participants mentioned at the post measurements that "My friends have been wondering why they haven't seen me lately." Thus, I would sincerely like to express my heartfelt gratitude to all the participants who committed themselves wholeheartedly to this long and time-consuming project, despite the complications it brought to their own lives.

I was interested in holistic view and wanted to include a psychological viewpoint in my thesis. I had the pleasure to have Marja Kokkonen as my guide to the world of exercise psychology. I was amazed by her strong perspectives on research as well as her dedication to teaching. I hope I was able to catch some of her teaching methods for myself.

I am very grateful to Professors Bent Rønnestad and Senior Lecturer Ed Maunder for accepting the invitation to review my thesis and for providing valuable comments to improve the quality of the work. I was honored to have such highly respected experts as reviewers. Additionally, having Andrew Jones, a highly recognized scholar, as my opponent was a significant privilege.

Since my workplace in Jyväskylä is 300 km away from my home, I have had the rare pleasure of 'belonging to the equipment' during my overnight stays, so I thank the hospitality of Reetta Tenhu and Mikko Lensu. Without them, my visits to the contour would have been much more dull (and, let's be honest, expensive). They, as Firstbeat employees, also provided me with firsthand knowledge of the latest heart rate monitoring analytics on the market. Despite my inquiries, I have noticed, these Firstbeat team members are truly adept at maintaining their trade secrets. Furthermore, Firstbeat is acknowledged for funding and providing the equipment for the measurements. Also Finnish Athletics Federation is acknowledged for their funding.

As living in Jyväskylä was out of reach for me, Olli showed me the end of a table at the Paavo Nurmi Centre, where I have found a homely workspace, usually surrounded by doctors, biomedical analysts, coordinators, and other real workers. I have truly felt warmly welcomed in that small, friendly community. I would like to thank all the current and former staff of the Paavo Nurmi Centre for creating such a fantastic working environment. Thus, I thank Sini Kokkala, Päivi Pihlava, Tia Ventto, Minna Hyppönen, Roosa Latvaniemi, Riina Orrela, Harri Helajärvi, Paula Simula, Kimmo Lajunen, Jukka Kapanen, Miikka Pesola, Katja Pahkala, Outi Rajalin, and of course Olli.

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As a field sport science is large, and I doubt no one can know everything about everything. But one can try, and best way to learn is to learn from the masters. I am amazed at how openly the experienced professionals have welcomed me. Therefore, I would like to thank Jyrki Aho, Ilkka Heinonen, Mika Tarvainen, Heikki Tikkanen, Rami Virlander, Juha Sorvisto, Ibai Mendia, Juha Peltonen, Eetu Karvonen, Tommi Pärmäkoski, Laura Karavirta, Riikka Kivelä, Johanna Ihalainen, and Eero Haapala among others to teach me tricks and things.

I have soft heart for teaching. I had the vision what I would like to teach, and I did that through voluntary study group. Enthusiastic participants got me fired up during our meetings and made me see the value on the lessons learned from my own research. So I thank, among others, Sasu Kaasinen, Maria Päivärinne, Eelis Komppa, Mimmi Iivari, and Saara Loukkola for taking part. Specifically, I would like to mention Aino Kuljukka and Timi Malinen, who have become regular sparring colleagues of mine.

Last, I would like to warmly and lovingly thank my family for enduring me and my constant trips to Jyväskylä. Especially I want to express my deepest gratitude to my beloved wife Kaisa. Her unquestioned support and understanding have been the cornerstone of this sailing trip of mine. I am also grateful to our children: Touko, who has contributed his imaginative illustrations to my presentations; Lotta, who is already eager to assist with my coaching; and Ilmari, who always welcomes me with a joyful spirit. Their presence and support have made this journey deeply rewarding and enjoyable.

Lieto 1.9.2024
Pekka Matomäki

Touko Matomäki

"Here is Edward Bear, coming downstairs now, bump, bump, bump, on the back of his head, behind Christopher Robin. It is, as far as he knows, the only way of coming downstairs, but sometimes he feels that there really is another way, if only he could stop bumping for a moment and think of it."

– A.A. Milne –

ORIGINAL PUBLICATIONS AND AUTHOR CONTRIBUTION

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

I. Matomäki, P., Heinonen, O.J., Nummela, A., Laukkanen, J., Auvinen, E.-P., Pirkola, L. & Kyröläinen, H. (2023). Durability is improved by both low and high intensity endurance training. *Frontiers in Physiology*, 14, 1128111. https://doi.org/10.3389/fphys.2023.1128111

II. Matomäki, P., Heinonen, O. J., Nummela, A., Kokkonen, M., & Kyröläinen, H. (2024). Exercise enjoyment does not predict change in maximal aerobic power during a strenuous 10-week endurance exercise intervention. *Biomedical Human Kinetics,* 16(1), 89-98. https://doi.org/10.2478/bhk-2024-0009

III. Matomäki, P., Heinonen, O.J., Nummela, A., & Kyröläinen, H. (2024). Endurance training volume cannot entirely substitute for the lack of intensity. *PlosOne*, 19(7), e030727. https://doi.org/10.1371/journal.pone.0307275

IV. Matomäki, P., Nuuttila, O.-P., Heinonen, O. J., Kyröläinen, H., & Nummela, A. (2024). How to equalize high- and low-intensity endurance exercise dose? *International Journal of Sports Physiology and Performance,* 19, 851-859. https://doi.org/10.1123/ijspp.2024-0015

The author of this thesis, who is the first author of the above-mentioned original publications, was, in all four publications, in charge of the project and responsible for conceiving and designing the study, designing the research questions, monitoring the participants' training, collecting the data, performing statistical analyses, interpreting the results, and writing the manuscripts.

ABBREVIATIONS

AMP	Adenosine monophosphate
ATP	Adenosine triphosphate
CLES	Common language effect size
EE	Energy expenditure
EPOC	Excess post-exercise oxygen consumption
ES	Effect size
HIT	High intensity training
HR	Heart rate
HR_{max}	Maximum heart rate
HRV	Heart rate variability
LIT	Low intensity training
LT_1	The first lactate threshold
LT_2	The second lactate threshold
MIT	Moderate intensity training
mRNA	Messenger ribonucleic acid
PACES	Physical activity enjoyment scale
PGC-1α	Peroxisome-proliferator-activated receptor gamma coactivator 1
P_{max}	Power associated to VO2max
RER	Respiratory exchange ratio
RMSSD	Root mean square of successive differences of R-R intervals
RPE	Rating of perceived exertion
SD	Standard deviation
$VO2_{max}$	Maximal oxygen uptake
wRPE	Weekly rating of perceived exertion

CONTENTS

1 INTRODUCTION

In the early 1900s, Nordic countries used high intensity interval training to incorporate a high volume of race-pace running for competitive distance running. The approach spread, and progressed in the 1930s in Germany, where training began to incorporate heart rate monitoring to prescribe interval training. By the 1950s, interval training had gained full acceptance in endurance sports and was widely practiced. (Gibala & Hawley, 2017; Lucas, 1977).

Since the beginning of 1960s, physiologists began to systematically investigate potential benefits of interval training. The Swedish research group, led by Professor Per-Olof Åstrand, studied the acute responses to various interval training protocols, including heart rate, blood lactate concentration, and respiratory gases (Åstrand et al., 1960). The acute examinations were accompanied by chronic interventions, and by the 1970's, interval training and its benefits had become familiar to both researchers and coaches. By the 1990's, it had become clear that interval training was as effective as, or even superior to, traditional steady-state endurance training (Atakan et al., 2021; Gibala & Hawley, 2017). In the last ten years, there has been a focus on exploring minimalistic forms of interval training in research: how to achieve the maximum benefits of interval training with the minimum time commitment. Protocols such as 10 x 60 seconds (Little et al., 2010) or 3 x 20 seconds (Jenkins et al., 2019) have appeared to be beneficial. However, recent meta-analyses have shown that longer (>2 minutes) intervals cumulated for over 15 minutes in a single exercise session seem to be the most effective for improving aerobic fitness (Rosenblat et al., 2021; Wen et al., 2019).

Although continuous low-intensity endurance training has been classified as the "traditional" form of endurance training (Burgomaster et al., 2008), it surprisingly has not received as much intense and widespread attention as interval training. To exaggerate slightly, since Pollock's review article on the effects of training intensity, duration, and frequency on endurance training appeared in 1973 (Pollock, 1973), surprisingly little progress has been made in research concerning low intensity training, specifically.

Pollock summarized that at least 50% of VO_{2max} (maximal oxygen uptake) intensity is required for VO_{2max} development. Total energy expenditure is crucial, and when it is balanced between low and high intensity training, the VO_{2max} improvement would align. Further, the duration of exercise correlates with VO_{2max} development, at least when the duration of exercise is less than one hour. (Pollock, 1973). These 50-year old observations have since received further support. For example, it is still recognized today that an intensity of at least 50% VO_{2max} would be the minimum required to achieve positive endurance adaptations (Swain & Franklin, 2002). Further, isoenergetic low and high intensity training has been reported to be almost equally effective in improving VO_{2max} among untrained individuals (Milanović et al., 2015). Finally, it has been reported that the duration of 30–60 minutes of low intensity exercise bouts increases VO_{2max} more than shorter sessions (Foulds et al., 2014).

Although there has been research on frequency (Foulds et al., 2014) and volume (Lin et al., 2021) of low intensity training, systematic comparisons of various training protocols are not as prevalent as those for high-intensity training. For example, there is no clear understanding of how factors like duration and volume of low-intensity training affect VO_{2max}, let alone overall endurance performance. The reviews and meta-analyses on low and high-intensity exercise are largely focused on high intensity exercises. It seems that low intensity training is often used only as a reference point to high intensity training (Burgomaster et al., 2008; Panissa et al., 2016). Low intensity training is akin to a supporting character in a play, mainly utilized to accentuate the excellence of the protagonist.

In the early 1900´s, VO_{2max} was used as a valuable tool for categorizing individuals with varying fitness levels, following the work of Nobel Laureate A.V. Hill. However, it later became evident that individuals with similar VO_{2max} levels could still have significant differences in performance. Therefore, additional factors beyond VO_{2max} were sought to better explain endurance performance. One such factor was found in lactate thresholds in the 1960's. By the 1980's, the absolute intensity at the second lactate threshold, which naturally depends on the VO_{2max}, was reported to be a better marker for endurance performance than maximal oxygen uptake alone. (Faude et al., 2009).

Furthermore, in the 1980's, the economy of movement was reported to differentiate the running performance of elite runners much more clearly than VO_{2max}, as the VO_{2max} is already at a peak level among elite athletes (Conley & Krahenbuhl, 1980). In the 2000's, these three factors—VO_{2max}, lactate threshold, and economy of movement—have been nominated as the primary determinants of endurance performance (Joyner & Coyle, 2008). In the last few years, however, there has been a growing discussion about introducing a fourth determinant, durability, which denotes fatigue resistance during prolonged exercise (Jones, 2023; Maunder et al., 2021). Over the past sixty years, the three major explanatory determinants have been extensively studied and their trainability heavily examined. In contrast, the characteristics of durability are not yet fully understood.

In 1973 Pollock addressed several unresolved factors in training research in his review article (Pollock, 1973). First, could increasing the duration and frequency of low intensity exercise sessions result in similar overall training effects as with high intensity training (Pollock, 1973)? This led to a conclusion that "more definitive investigations conducted at all ranges of intensity and duration are necessary" (Pollock, 1973). Second, many studies concentrated mainly on VO_{2max}, while parameters like response to a standard work load or maximal physical working capacity could also be used. Third, there is a lack of standardized methods related to training protocols and quantifying them, which complicates the comparison of different protocols and the interpretation of results. These unresolved factors are still as relevant today as they were 50 years ago. This thesis addresses all three aforementioned factors.

I studied very high-volume low intensity training (LIT) in prolonged exercise sessions and compared it to high intensity training (HIT). The aim was to answer the following questions (FIGURE 1). Are there specificity in the low and high intensity training? Could very high volume and prolonged exercises compensate for the lack of intensity? Could exercise enjoyment predict individual responses to exercise regime? To get a comprehensive view, in comparing LIT and HIT, I used not only VO_{2max} but also a broader range of performance variables at both low and high intensities, including durability. I also compared theoretically how the strain of low and high intensity exercise sessions could be balanced: How many low intensity minutes equal to one high intensity minute using different methodological approaches?

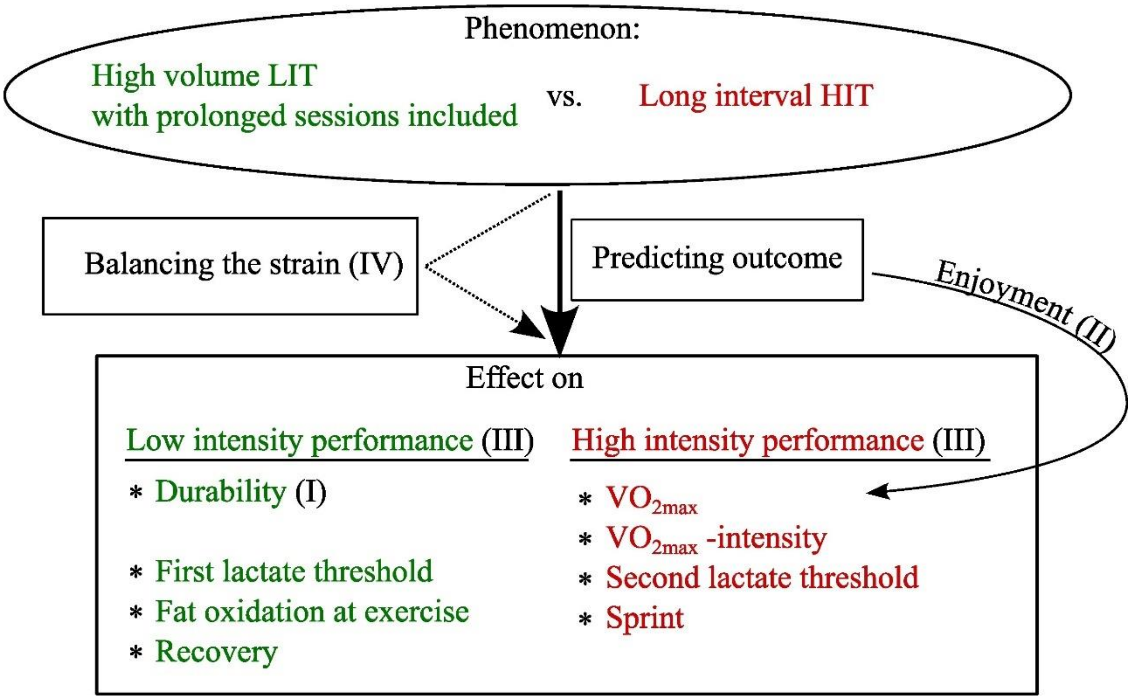

FIGURE 1. Study outline of this thesis. The studied phenomenon was to compare high volume of low intensity training to high intensity training with long intervals. *LIT* Low intensity training; *HIT* High intensity training; *VO_{2max}* Maximal oxygen uptake.

2 REVIEW OF THE LITERATURE

2.1 Basis of endurance training

Understanding low and high intensity endurance training typically requires, first, a clear definition of different intensity zones and, second, a deep dive into the characteristics of these endurance training zones.

2.1.1 Defining low and high intensity training zones

Two thresholds divide the exercise intensities into three training zones (FIGURE 2): Low (LIT), moderate (MIT), and high intensity training (HIT) zones. The two thresholds classifying the zones can be defined by blood lactate (Faude et al., 2009), respiratory gases (Keir et al., 2022), or critical power between the MIT and HIT zones (Galán-Rioja et al., 2020). The individual characteristics of these three training zones greatly influences the metabolic, neuromuscular, and cardiovascular demands of exercise (Seiler & Tønnessen, 2009).

Exercising at the LIT, MIT, and HIT zones leads to distinctive blood-acid base responses and physiological strain (Keir et al., 2022). Therefore, muscle fatigue (Black et al., 2017; Burnley & Jones, 2018; Thomas et al., 2016), exercise tolerability (Iannetta et al., 2018), perception of effort (Scherr et al., 2013) as well as recovery times from exercise (Stanley et al., 2013) differ between the zones.

In this thesis *exercise* is defined as a single planned session including repetitive movements. Performing multiple exercises systematically over an extended period is defined as *training.*

2.1.2 Neuromuscular fatigue at the low and high intensity training zones

Origin of neuromuscular fatigue differs between the zones: At the LIT zone, neuromuscular fatigue develops slowly and predominantly originates from the central nervous system and it is caused by depleting glycogen stores and the inability to activate muscle centrally (Black et al., 2017; Burnley & Jones, 2018). At the HIT zone, the fatigue is primarily of peripheral origin caused by progressive disturbance of muscle metabolic homeostasis. At the MIT zone, both central and peripheral neuromuscular fatigue is present. (Black et al., 2017; Burnley & Jones, 2018; Thomas et al., 2016).

Muscle metabolic perturbation at exhaustion after HIT is greater than after MIT and LIT, and greater after MIT than LIT (Black et al., 2017). In practice, exercise tolerance effectively reflects these differences in the causes of muscle fatigue (Azevedo et al., 2021; Iannetta et al., 2018): Increasing the intensity by 10% over the first lactate threshold (LT_1) reduces time to exhaustion by 40% (Burnley & Jones, 2018). Increasing the intensity by 4% over the second lactate threshold (LT_2), time to exhaustion can be reduced by 60% (Iannetta et al., 2018).

2.1.3 Cellular level upregulations induced by acute low and high intensity exercises

The differences in homeostatic perturbation in different zones leads to different activation pattern of pathways. These pathways are thought to lead to peripheral endurance training adaptations including mitochondrial biogenesis, capillary angiogenesis, increase of glycogen stores, and increase in activity of oxidative enzymes (Hoppeler, 2016; Ydfors, 2019). The upstream events that lead to an increase PGC-1α (peroxisome-proliferator-activated receptor gamma coactivator 1) mRNA (messenger ribonucleic acid) expression, the believed master regulator of mitochondrial biogenesis (Gurd et al., 2023), happen through different pathways. Two highly studied pathways are AMP (adosine monophosphate) activated protein kinase and calcium/calmodulin-dependent protein kinase signaling pathways. Simplified, AMP-activated protein kinase senses the increased energy turnover of activated muscle and is typically activated after intensive high intensity exercise (Hoppeler, 2016), which causes large disturbances in cellular energetics and increases adosine monophosphate to adenosine triphosphate concentration ratio, i.e. [AMP]/[ATP] ratio (Chen et al., 2003; Gurd et al., 2023). Calcium/calmodulin-dependent protein kinase activation is caused by an increase in intramuscular calcium associated with muscle contraction and is seen especially after LIT, but also after HIT (Gurd et al., 2023).

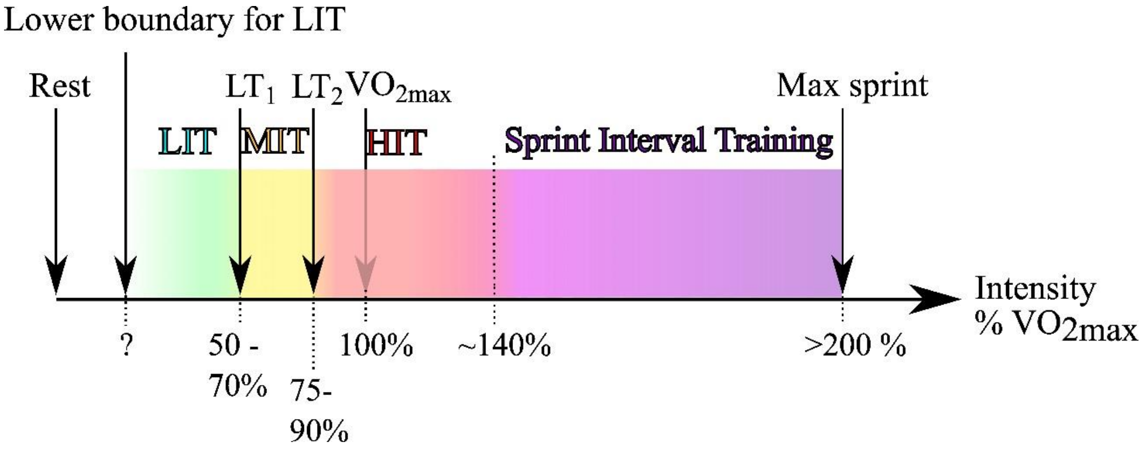

FIGURE 2. Endurance training intensity zones. Lower boundaries for LIT and SIT and upper boundary for HIT zones are not tied to explicitly defined thresholds. *LIT* Low intensity training; *MIT* Moderate intensity training; *HIT* High intensity training; LT_1 First lactate threshold, LT_2 Second lactate threshold. VO_{2max} Maximal oxygen uptake. The zones transition intensities are from (Buchheit & Laursen, 2013).

2.1.4 Quantification of low and high intensity training doses

Exercise dose is defined here as a physiological strain resulting from the combination of the intensity and duration during a single exercise session (Desgorces et al., 2020; Lambert & Borresen, 2010). Apart from duration and intensity, exercise dose is also affected by nutrition and hydration before and during the exercise (Baker & Jeukendrup, 2014; James et al., 2017; Utter et al., 1999), mental stress (Webb et al., 2008), ambient temperature, (Nybo & Nielsen, 2001) and mode of exercise (Utter et al., 1999). However, they are not often considered when quantifying exercise doses. Multiply exercise doses over an extended period constitute a *training dose*.

Differences in homeostatic perturbation and peripheral/central fatigue after LIT exercises versus HIT exercises make it difficult to compare exercise doses at these zones appropriately. There are vastly different approaches used to quantify exercise doses. These are based on, for example, external measurements such as work done (Andreato et al., 2021), or internal measurements such as rating of perceived exertion (RPE) of the acute exercise (Foster, 1998), blood lactate concentration (Manzi et al., 2009), loss of performance (Passfield et al., 2022), and comparison to intensity dependent maximum duration (Normand-Gravier et al., 2022).

As these metrics attempt to quantify the elusive concept of “physiological strain”, it ultimately depends on how this “strain” is defined: Is it: “a dose that causes adaptations”, “a dose that exhausts the body, leading to performance decline”, or “a dose that causes an increase in the sensation of tiredness”? These all require different metrics. Essentially, no single metric can comprehensively contain all the different aspects (Impellizzeri et al., 2023).

2.1.5 Prescribing training

Endurance training intensity can be prescribed either relative to the maximum (e.g. % VO_{2max}) or to the threshold (e.g. % LT_1/LT_2). Since the 1980s, it has been argued that determining intensity in relation to thresholds is preferable (Lansley et al., 2011; MacLellan & Skinner, 1981; Mann et al., 2013). The main reason for favoring thresholds is their individual variability. For example, the first lactate threshold has been reported to range between 35% and 65% of VO_{2max} in untrained men (MacLellan & Skinner, 1981). For this reason, it is well established that an exercise bout at a fixed %VO_{2max} or %HR_{max} (maximum heart rate) can individually fall on different sides of the thresholds, which in turn produces high interindividual variation in responses and physiological strain. It follows that training prescribed relative to the thresholds is expected to provide a more consistent training stimulus compared to training prescribed relative to maximum. However, not many training interventions have been conducted to confirm these expectations.

The downside of threshold-based prescription is that determining thresholds from a single test can involve more uncertainty than using VO_{2max} or HR_{max} (Mann et al., 2013). Additionally, determining intensity based on an estimated maximum heart rate is a notably quick, effortless, and inexpensive method, and thus tempting.

2.2 Endurance performance and factors affecting it

Endurance performance often means a maximal performance speed (m/s) at a given distance. On the other hand, a simple equation (Foss & Hallèn, 2005) reveals that

$$\text{Speed (m/s)} = \text{Energy turnover rate (J/s)} \times \text{Economy of movement (m/J)}.$$

Consequently, endurance performance can be improved by either enhancing energy turnover rate during the endurance performance or, the economy of movement. The energy turnover rate cannot be substantially elevated in endurance performance by augmenting anaerobic capacity, since the amount of anaerobic energy production is very limited. For example, when doing a 20-minute time trial, at an average power of 250 W, requires 300 kJ of work. Above the second lactate threshold (or more precisely critical power), one can work only ~20 kJ before exhaustion (Jones & Vanhatalo, 2017). This number includes anaerobic energy production, and 20 kJ is ~7% of 300 kJ work. Consequently, endurance performance is primarily enhanced by improving aerobic energy metabolism through increased oxygen transport, by raising the oxidative capacity of skeletal muscles, and the diffusion in the working muscles and utilization at muscle level (Gibala, 2015).

Economy of movement, VO_{2max} and the absolute intensity as well as fractional utilization of VO_{2max} at the second lactate threshold (Jones & Carter, 2000; Joyner & Coyle, 2008) are commonly defined as the primary factors influencing endurance performance (FIGURE 3). Neuromuscular capacity is also suggested as a factor (Nummela et al., 2006; Paavolainen et al., 1999). Lately there has been debate on whether durability, which can be described as fatigue resistance during prolonged exercise, would be an important factor, at least in prolonged endurance performances, such as marathon races or road cycling competitions (Jones, 2023; Maunder et al., 2021; Smyth et al., 2022). For example, critical speed decreases 10 % during a 2-h MIT exercise, which suggests a clear decrease in the intensity at which a stable metabolic state can be achieved. This seriously impairs prolonged endurance performance. More significantly, individual variations in the decline of critical power are substantial, ranging from < 1% to >30%, favoring individuals who can endure fatigue without a crucial change in their physiological profile (Jones, 2023).

While physiological factors primarily determine the endurance performance, multiple psychological factors also contribute to variability. Mental techniques, such as imagery, self-talk, goal setting, and motivational statements, can positively impact endurance performance (Blanchfield et al., 2014; McCormick et al., 2015). Mental toughness, defined as positive qualities that allow an athlete to persevere through challenging situations (Gucciardi, 2017), has been associated with longer time to exhaustion (Crust & Clough, 2005). Achievement motivation, defined as a need for success and striving for excellence, is associated with improved athletic performance (Röthlin et al., 2023; Zuber & Conzelmann, 2014). Additionally, external motivators, in the form of competition and verbal encouragement, appear to enhance performance (McCormick et al., 2015). Mental fatigue, resulting from engaging in a demanding cognitive task prior to endurance exercise, impairs the endurance performance (MacMahon et al., 2014). Lastly, action-oriented athletes, who quickly refocus after failure, have an advantage in performing under stress (Kröhler & Berti, 2019).

Hydration and nutritional factors also play a role in determining a peak performance. Endurance sessions lasting more than 30 minutes require attention to hydration levels, as hypohydration more than 2% body mass can degrade aerobic exercise performance (Baker & Jeukendrup, 2014). Presence of sodium in a beverage, up to 75 mmol/l, stimulates the physiological drive to drink and the renal water reabsorption, which helps to prevent hypohydration (Baker & Jeukendrup, 2014). Moreover, to prevent a decline in performance due to glycogen depletion, a carbohydrate intake, from 30 g/h up to 90 g/h, is recommended in endurance events lasting more than 1 h. Carbohydrate loading, by consuming carbohydrates 5 to 12 g/kg/d before an exercise session, can improve performance by 2 – 3% in events lasting more than 90 minutes. (Jeukendrup, 2011). On a daily basis, high carbohydrate availability is needed to recover glycogen stores in athletes, with requirements varying from 5 to 12 g /kg/d (Jeukendrup, 2011). Sleep deprivation also negatively affects endurance performance, mostly by increasing perceived effort and decreasing motivation

(Lopes et al., 2023). Lastly, an optimal pacing strategy for a performance is based on individual strengths and the length of the race (St Clair Gibson et al., 2006).

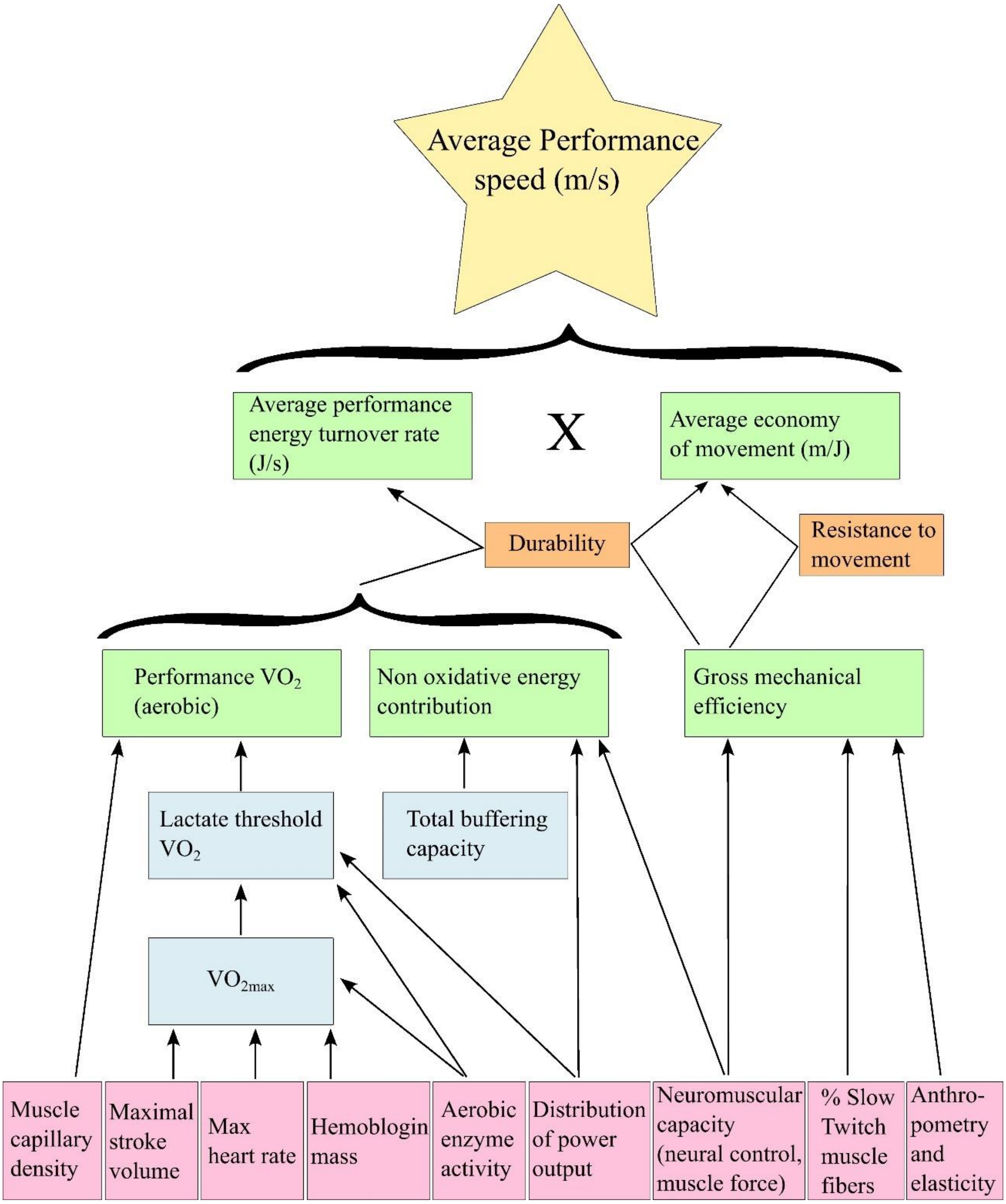

FIGURE 3. Factors interacting with average performance speed. Basic platform of the figure redrawn from (Joyner & Coyle, 2008), with ideas from (Foss & Hallèn, 2005; Jones, 2023; Paavolainen et al., 1999). *VO2max* Maximal oxygen uptake; *VO2* Oxygen uptake.

In summary, endurance performance is a multifaceted phenomenon including factors of physiology, psychology, and to some extent pacing strategy. Therefore, dissecting performance into isolated components may dismiss the holistic perspective, even though physiology has the most significant influence (Röthlin et al., 2023).

Often a division is made between *central* and *peripheral* physiological factors. The central factors contain attributes that influence oxygen transport, and peripheral factors pertain to the utilization of oxygen at the level of the working muscles. The main central factor is cardiac output, which is a product of heart rate (HR) and stroke volume. Stroke volume and oxygen carrying capacity of blood are further explained by parameters such as blood volume, red blood cell volume, and cardiac structure, including left ventricular dimension and mass (Arbab-Zadeh et al., 2014; Bonne et al., 2014; Montero et al., 2015), and cardiac compliance and performance (Arbab-Zadeh et al., 2014). These central factors primarily account for VO_{2max}, which is a key determinant of maximal time trial performances (Nuuttila et al., 2023) and speed/power at VO_{2max}.

Lactate thresholds (expressed relative to maximum) are associated with peripheral factors, such as general oxidative capacity of muscles, fiber type composition, capillary density, and mitochondrial volume and density (Burgomaster et al., 2005; Conley et al., 2001; Holloszy & Coyle, 1984; Ivy et al., 1980). These peripheral properties also regulate fat oxidation capacity at submaximal exercises (Conley et al., 2001; Holloszy & Coyle, 1984), which enables the body to conserve limited glycogen stores. Since VO_{2max} sets the upper limit of the body's aerobic capacity, it inherently impacts absolute threshold intensities. Hence, a central component also plays a role in intensity thresholds as well.

Genetics play a central role by dictating the above-mentioned factors. For example, it is suggested that genetics alone could explain ~50 - 70% of VO_{2max} (Bouchard et al., 1998; Miyamoto - Mikami et al., 2018). However, finding clear-cut genetic markers that would predict endurance performance or trainability to endurance training is a challenging, if not an impossible task. As endurance performance is affected by many limiting factors, which are subsequently affected by genetic variation, the endurance performance itself is a polygenic trait (Roth & Wackerhage, 2022). There are many cultural and environmental confounding factors interacting with each other (Joyner & Coyle, 2008). After all, outstanding endurance performances have emerged from all over the world: East Africa, Europe, Australia, America, etc. This great geographical diversity suggests that a straightforward genetical explanation for elite performance is unlikely (Joyner & Coyle, 2008).

2.3 Acute responses to an exercise

The acute responses to low intensity exercise differ significantly from those of high intensity at the onset of an exercise. However, as the duration of low intensity exercise increases, the nature of the exercise and its acute responses begin to take on a new perspective.

2.3.1 Acute responses to low and high intensity exercises

The pronounced acute responses observed with HIT exercises compared to iso-energetic LIT exercises are results of the body's effort to maintain homeostasis, or "Milieu Intérieur" (Holmes, 1986), in response to increased physiological strain. These acute responses include increased in heart rate and stroke volume to meet the increased oxygen demand at the muscular level (Zhou et al., 2001); exponential elevation in blood lactate concentration, which correlates with the metabolic acidosis of the body (Keir et al., 2022); increased hormonal responses, e.g. blood catecholamine concentration increases exponentially in relation to intensity (Zouhal et al., 2008); increase in cortisol above a critical intensity (~50% VO_{2max}) and a decrease in cortisol below critical intensity during 1 h exercise (Davies & Few, 1973); elevation in testosterone concentration after HIT exercise, but not after LIT (Sutton et al., 1973); an intensity-dependent progressive transition in energy substances from lipids to glycogen (Achten & Jeukendrup, 2003); and an intensity-dependent increase in key signaling proteins involved in launching the mitochondrial biogenesis (Gurd et al., 2023). For example, skeletal muscle AMP-activated protein kinase is mostly intensity dependent and is activated only after a sufficiently large metabolic perturbation (Chen et al., 2003). Lastly, increasing the intensity elevates firing rate and recruitment of motor units (Green & Patla, 1992). During the LIT exercise, all slow twitch fibers and a minimal number of fast IIa fibers are being recruited, whereas during the HIT exercise, all slow and IIa fibers and most of type IIab and IIb are activated (Sale, 1987).

The autonomic nervous system reflects disruptions in homeostasis and physiological strain. Heart rate variability (HRV) is a typical marker for the balance of sympathetic and parasympathetic activation, especially the parasympathetic side. The ventricles have limited parasympathetic innervation, so changes in systolic time interval measures, like pre-ejection period and left ventricular ejection time, are primarily associated with fluctuations in cardiac sympathetic activity. (Michael et al., 2017).

As exercise intensity increases, HRV decreases until it reaches a minimum at approximately 50-60% of VO_{2max} intensity (~the first lactate threshold), where RMSSD (root mean square of successive differences of R-R intervals), typical marker of HRV, reaches its nadir (Michael et al., 2017). A similar phenomenon is seen in the HRV frequency domain measures of low- and high frequency powers (Michael et al., 2017). Thes shifts, as exercise intensity increases, indicates a reduced influence of the parasympathetic nervous system and an increase in sympathetic activity. Furthermore, RMSSD, which indicates the parasympathetic nervous system activity and fluctuations, returns to baseline more rapidly after the LIT exercise compared to the HIT exercise, indicating lower physiological strain (Seiler et al., 2007).

Excess post-exercise oxygen consumption (EPOC) is also a general indicator of disturbance of homeostasis and physiological strain. It is attributed to several factors, including: the replenishment of oxygen, adenosine triphosphate, and phosphocreatine stores; lactate metabolism; increase in ventilation; changes in body temperature; alterations in circulation; the influence of endocrine factors; emphasis of fat oxidation after exercise and protein breakdown and synthesis (Børsheim & Bahr, 2003). EPOC increases exponentially related to intensity (Laforgia et al., 2006).

2.3.2 Acute response to a prolonged low intensity exercise

At the onset of the exercise session, the acute responses to different intensities are distinct. However, as the duration of the exercise increases, the physiological strain also increases. Therefore, the duration can surprisingly strongly impact the acute responses as the body aims to maintain homeostasis.

The intensity-dependent responses between LIT and HIT may diminish when the duration of the LIT session is extended. For example, at the beginning of a LIT exercise, the fast-twitch fibers are not initially recruited. However, as the duration of the session is extended, the glycogen stores of the slow-twitch fibers are depleted, after which the fast-twitch fibers are recruited. Therefore, the fast-twitch fibers may be in use after 3 h, even at intensities as low as 30% of VO_{2max} (Ball - Burnett et al., 1991; Gollnick et al., 1974). This transition in recruitment pattern may have a significant impact on potential adaptations. When 3 h and 45 min LIT exercises were compared (Hildebrandt et al., 2003), 3 h LIT session resulted in a substantial increase in acute metabolic transcription in gene expressions in the fast-twitch fibers, which was several times greater than those observed after a 45-minute LIT session. At the same time, no differences were observed in the slow-twitch fibers. However, the increase in gene expressions at the fast twitch fibers after 3 h LIT exercise were not as pronounced as after 45-minute MIT/HIT exercise sessions (Hildebrandt et al., 2003).

Moreover, while the activation of the AMPK signaling pathway is commonly associated with intensity dependent stimulation, it is actually stimulated by metabolic perturbation. Hence, it can be activated not only by high intensity exercises, but also following an exhaustive LIT session which leads to a large metabolic perturbation (Wojtaszewski et al., 2002). Additionally, there is limited evidence that prolonged LIT sessions might enhance post mRNA upregulation of PGC- 1α peroxisome-proliferator-activated receptor gamma coactivator 1 (Gurd et al., 2023).

One changing response during prolonged LIT is the alteration in the source of lipids: After 2 h, the source of lipids shifts from intramuscular triacylglycerol to plasma derived free fatty acid and glycerol (Watt et al., 2002). The duration of a LIT exercise also has a substantial effect on endocrine response. As the sympathoadrenal activity increases, the plasma catecholamine concentration is continuously increasing until exhaustion, irrespective of intensity (Galbo et al., 1976; Zouhal et al., 2008), even though the HIT exercise results in stronger responses (Galbo et al., 1975). In addition, although no response was noticed during short LIT exercises, prolonged running decreases serum testosterone and increases cortisol concentrations (Dessypris et al., 1976).

During prolonged exercise without energy intake, there is an increased utilization of lipids for energy as glycogen stores become depleted (Ahlborg & Felig, 1976; Utter et al., 1999). The increased physiological strain of the prolonged submaximal exercise also reflects immunodepression, especially without carbohydrate intake (Gunzer et al., 2012). A low concentration of blood glucose leads to higher cortisol and epinephrine concentrations. The high concentrations of stress hormones may have immunosuppressive effects (Gunzer et al., 2012). Prolonged exercise also increases plasma cytokine concentration, C-reactive protein, and blood leukocyte counts (Gunzer et al., 2012; Nieman, 2008). Lastly, the increased strain from prolonged LIT exercise increases RPE (Utter et al., 1999) and EPOC (Laforgia et al., 2006) linearly in response to duration.

To underline the importance of duration at submaximal intensities, a concept of *duration threshold* has been introduced (Tschakert et al., 2022; Viru, 1992). Lactate thresholds are a concept of intensity threshold: when exercise intensity surpasses certain thresholds (e.g. lactate thresholds or critical power), physiological responses are altered, often noticeably. Analogously, in the concept of duration threshold, when duration of an exercise surpasses a certain threshold (i.e. duration threshold), the physiological responses are altered (FIGURE 4): hormonal responses increase as well as some markers of internal intensity including oxygen uptake (VO_2), HR and RPE. At the MIT-zone, duration threshold occurs at ~68% of maximum duration (Tschakert et al., 2022). It is suggested that there is no duration threshold at the HIT zone (Tschakert et al., 2022).

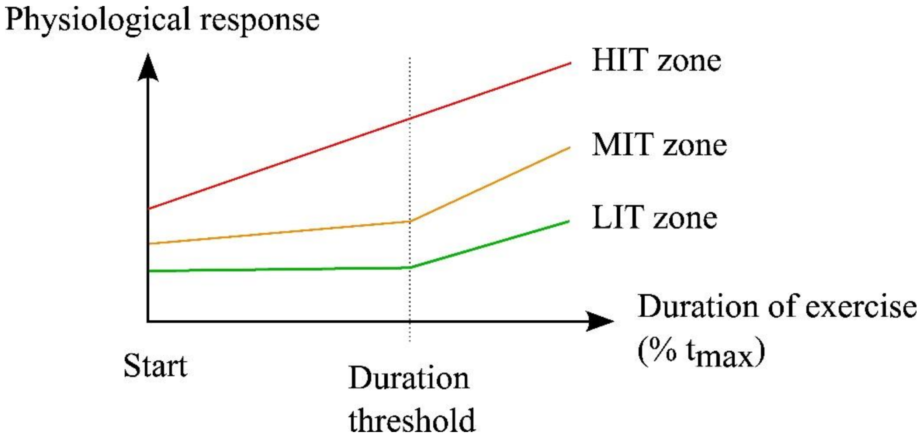

FIGURE 4. Duration threshold as a schematic figure, modified from Tschakert et al. (Tschakert et al., 2022). At the submaximal intensity (LIT & MIT -zones), after a certain point, duration threshold, physiological responses, such as drifts and hormonal responses, are pronounced. At HIT-zone, no duration threshold exists. *LIT* Low intensity training; *MIT* Moderate intensity training; *HIT* High intensity training; t_{max} Time to exhaustion at the chosen intensity.

2.3.3 Drifts during prolonged exercise

During prolonged submaximal exercise, there are many physiological *drifts*, defined here as a *gradual change in variable during prolonged submaximal exercise*. Gradual changes in physiological variables are clearly present in exercises at the HIT -zone. The most well-known example is VO_2 drift, called VO_2 slow component at the HIT -zone. This refers to an oxygen consumption level surpassing the anticipated value (Jones et al., 2011), as VO_2 gradually increases even to, but not always, VO_{2max} at the HIT -zone (Hill et al., 2021). The underlying cause of the VO_2 slow component in the HIT zone is primarily peripheral in nature. It involves the recruitment of less efficient motor units, especially the fast twitch muscle fibers, alongside an increase in the metabolic requirements of fatiguing muscle fibers. The elevated cardiac and pulmonary work and use of auxiliary muscles are less pronounced in the case of slow component of VO_2. (Jones et al., 2011). Additionally, the fatiguing process within the HIT zone triggers drifts, for example, in heart rate, blood lactate concentration, and RPE (Chaffin et al., 2008).

In the LIT zone, physiological drifts occur during several hours of prolonged exercise (FIGURE 5), even when they are not evidently present during the first hour of the session. One of the most well-documented physiological drift is the cardiovascular drift, characterized by a gradual increase in heart rate (Coyle & González-Alonso, 2001). Suggested factors contributing to cardiovascular drift include increased sympathetic activation, elevated core temperature, and neuromuscular fatigue (Coyle & González-Alonso, 2001).

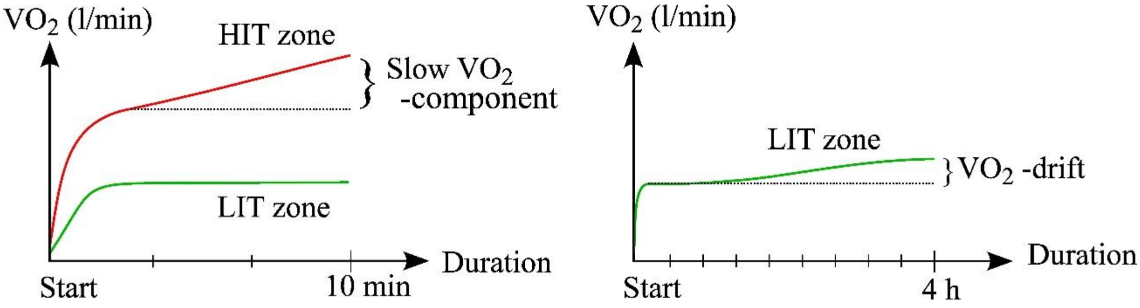

FIGURE 5. A schematic figure of the VO_2 slow component and drift. (A) In a HIT session, oxygen uptake never reaches a plateau; instead, it continuously increases, potentially up to VO_{2max}. The slow VO_2 component is the difference between the theoretically expected VO_2 and the actual observed one. In contrast, in a short LIT session, VO_2 appears to reach a clear plateau. (B) During a prolonged LIT session, VO_2 begins to rise from its initial apparent plateau. The drift is the difference between the first plateau and observed final value. *LIT* Low intensity training; *HIT* High intensity training; *VO_2* oxygen uptake.

While heart rate changes noticeably, cardiac output does not change at the same rate, leading to a concurrent decrease in stroke volume (Coyle & González-Alonso, 2001). The exact cause and effect of increased HR and decreased stroke volume have not been definitively established. Remarkably, during extremely prolonged 24-hour exercise involving well-trained athletes, after six hours, a reverse cardiovascular drift can be observed, with heart rate gradually returning to their initial level by the end of 24-hour exercise. The underlying reasons for this reversal remain unclear. (Mattsson et al., 2010).

VO_2 drift, or energy expenditure drift, is another clear physiological drift. The reason behind it is reduced mitochondrial efficiency. After a 24 h LIT session, mitochondrial efficiency has been reduced by 6–9%, which accounts for a significant portion of the observed 13% VO_2 drift (Fernström et al., 2007). The elevated O_2 cost of fatigued muscle is also documented in previous studies (Hopker et al., 2017; Vanhatalo et al., 2011).

An additional explanation for VO_2 drift is a decreased economy of movement, which results from recruiting less efficient fast twitch muscle fibers and co-agonists. This recruitment pattern occurs due to the depletion of glycogen stores of the slow twitch muscle fibers in agonist muscles (Barclay, 1996; Krustrup, et al., 2004), or due to the local muscle fatigue and damage which occurs during running (Dick & Cavanagh, 1987; Kyröläinen et al., 2000). Increased energy cost associated with changes in metabolic cost, such as higher rate of fat utilization, increased demand on body temperature regulation, alterations in pulmonary ventilation, muscle damage (Kyröläinen et al., 2000; Westerlind et al., 1992), or increased workload of the myocardium (Westerlind et al., 1992), typically plays a minor role in the VO_2 drift. It should be noted that HR and VO_2 drifts are not necessarily associated (Zuccarelli et al., 2018).

Basically, the VO_2 drift during LIT and HIT shares a common primary cause: the need to activate less efficient motor units and the elevated O_2 cost of mitochondria energy production. However, there is a clear distinction in the magnitude of drifts. In the HIT zone, VO_2 can increase more than 25%, whereas in the LIT zone, even during 24 h long exercise, VO_2 drift is typically at most 15% (Mattsson et al., 2010).

Other drifts during prolonged LIT exercise include e.g. ventilation (Almquist et al., 2020; Ekelund, 1967; Hopker et al., 2017; Martin et al., 1981), RPE (Almquist et al., 2020; Hopker et al., 2017; Rønnestad et al., 2011; Warber et al., 2000), HRV (Moreno et al., 2013), core temperature (Coyle & González-Alonso, 2001), and plasma catecholamine concentration (Galbo et al., 1976; Zouhal et al., 2008). The duration threshold concept suggests that the drifts may not be strongly pronounced at the beginning of the exercise, but become more significant after the duration threshold has been reached (Tschakert et al., 2022). However, this has not been confirmed within the LIT zone.

2.4 Durability

For decades, it has been understood that performance and acute responses at the end of an endurance exercise differ from those at the beginning. Surprisingly, it is only in recent years that this has been systematically investigated, revealing that the ability to resist fatigue could also be an individual trait, a trainable characteristic, and a crucial component of endurance performance.

2.4.1 Definition of durability

The concept of “fatigue resistance” has been used for decades (Dearborn, 1902) to describe an ability to resist fatigue. As muscle activity pattern may last from a fraction of seconds up to many hours, and involve isometric, eccentric, concentric, and combined muscle actions, including both single tasks and continuous repetitions, fatigue resistance has evolved in diverse directions. Fatigue resistance can be, for example, the ability to resist a decline in potentiated twitch force (Ducrocq et al., 2021) or force production during electrical stimulation (Morris et al., 2008), increased time to exhaustion (Garren & Shaffner, 1954; Lindsay et al., 1996), and a fraction of VO_{2max} used during a time trial (Hawley et al., 1997).

To specifically describe fatigue resistance in the context of prolonged (several hours) submaximal exercise, a recent concept of *durability* has been introduced. Durability is defined as: *Time of onset and magnitude of deterioration in physiological-profiling characteristics during prolonged exercise* (Maunder et al., 2021).

Durability can be further divided into two subclasses. *Physiological durability* measures deterioration of physiological variables (e.g. VO_{2max}, thresholds, and anaerobic capacity) due to prolonged exercise. On the other hand, *performance durability* measures deterioration of performance (e.g. time trials). There are different ways to interpret physiological durability:

1. Evaluating the magnitude of physiological drifts during a prolonged submaximal exercise (Smyth et al., 2022), (I).
2. Evaluating the onset of physiological drifts during a prolonged submaximal exercise (Smyth et al., 2022), (I).
3. Contrasting the graded exercise test (Stevenson et al., 2022) or critical power test (Clark et al., 2019) conducted after prolonged submaximal exercise with that performed in a rested state.

Performance durability has been investigated by:

4. Quantifying the reduction in performance following a prolonged submaximal exercise in comparison to performance achieved in a rested state (Leo et al., 2021; Spragg et al., 2022; Van Erp et al., 2021).
5. Examining the maximal performance achieved following a prolonged submaximal exercise, without reference to a test conducted in a rested state (Rønnestad et al., 2011).

The ‘prolonged submaximal exercise’ may have various meanings. A general recommendation could be that the athlete induces fatigue in a manner that is natural for their sport. Accordingly, submaximal exercise can be a marathon race (Smyth et al., 2022), 2–3 h LIT session (Rønnestad et al., 2011; Stevenson et al., 2022), 2 h MIT session containing several maximal sprints (Christensen et al., 2023), or expending 1000–3000 kJ of mechanical work during a cycling race (Leo et al., 2021; Van Erp et al., 2021). It would also be reasonable to investigate durability after a shorter, but more intense, exercise. For example, in races shorter than 30 min, such as 5-10 km runs, durability is likely to have a clear impact on the final outcome.

2.4.2 Applications of durability

It is becoming increasingly clear that endurance athletes with better durability have an advantage in longer endurance performances. Billat et al. (Billat et al., 2020) and Smyth et al. (Smyth et al., 2022) have illustrated that faster marathon runners have superior durability, as indicated by a lower heart rate drift and a delayed onset of this drift. Furthermore, an increased heart rate drift has been associated with a decreased running speed during the later stages of a marathon (Billat et al., 2020) and a lower VO_{2max} (Hirakoba & Asano, 1983). Moreover, compared to trained runners, untrained participants had a greater decrease in running economy (Unhjem, 2024) as well as drifts in carbon dioxide production, ventilation, and HR (Hirakoba & Asano, 1983) during a 1 h run. Additionally, increased heart rate drift is as a predictor of reduced VO_{2max} during a fatigued state (Wingo et al., 2005), and an increased VO_2 drift is associated with a decreased 5-minute maximum performance in a fatigued state (Passfield & Doust, 2000). Moreover, successful professional cyclists demonstrate a lesser decline in their power profiles after a prolonged fatiguing cycling when compared to less successful counterparts (Van Erp et al., 2021). The same phenomenon has been seen when young cyclists, who have attained elite levels, were compared to those who have not reached elite level (Leo et al., 2022).

Interestingly, the decrease in 5-minute time trial performance after a 150-minute LIT session is strongly associated with a decrease in the first ventilatory threshold (Hamilton et al., 2024). This finding demonstrates that performance durability is strongly correlated with physiological durability, as expected. Furthermore, no single explanation for better durability has been found in mitochondria proteins or muscle fiber type in trained athletes (Hamilton et al., 2024).

Durability can be seen to be related to the duration threshold concept. It has been reported that the first ventilation threshold power does not decrease linearly with time in prolonged exercise (Gallo et al., 2024). Instead, it appears to decrease only after a certain period and follows a more curvilinear pattern on an individual basis. Therefore, it can be viewed that individuals with good (physiological) durability (i.e. those who can withstand exercise without a rapid decline in threshold power) have a high duration threshold.

In soccer, performance declines during a match are measured by decreased high intensity running distance (Andersson et al., 2010; Datson et al., 2017; Mohr et al., 2008) or decline in sprinting distance (Mohr et al., 2008). Further, it has been reported that elite players experience these declines later and to a lesser extent compared to lower-level players (Mohr et al., 2008), but not always (Mohr et al., 2003). Hence, durability would be a necessary attribute, not only in endurance sports, but also in team sports.

In military training, VO_{2max} might not be the most suitable indicator of soldiers' physical performance. Instead, there is a desire for soldiers to appear fit and alert even after completing prolonged marching (Rudzki, 1989). Consequently, studies have examined the responses to prolonged loaded walks (Knapik et al., 2012; Mullins et al., 2015), as well as the performance capacity of soldiers following such marches (Knapik et al., 1997), and training adaptations to such marches (Rudzki, 1989; Wills et al., 2019, 2020). Therefore, durability and strategies to enhance it are also clearly sought-after attributes in military training.

2.5 Endurance training adaptations

By repeating individual low-, moderate, and high-intensity endurance exercises, the goal is to achieve physiological changes that enhance endurance performance.

2.5.1 Adaptations to low and high intensity training aligns

Endurance training include central adaptations, like increased heart function and its remodeled structure (Abergel et al., 2004; Baggish et al., 2008) and improved compliance (Levine et al., 1991), increased plasma and red blood cell volume (Bonne et al., 2014; Montero et al., 2015), and enhanced skeletal muscle and cutaneous blood flow (Laursen & Jenkins, 2002). Peripheral adaptations to endurance training include increased mitochondrial content and its respiratory capacity (Bishop et al., 2014; Murias et al., 2011), increased aerobic enzyme activity (Laursen & Jenkins, 2002), increased reliance on lipids as energy substrate (Phillips et al., 1996), decreased cortisol and catecholamine responses during submaximal exercise (Laursen & Jenkins, 2002), decreased vascular resistance (Klausen et al., 1982), increased muscle capillary density (Murias et al., 2011), improved skeletal muscle buffer capacity (Weston et al., 1997), improved thermoregulation (Laursen & Jenkins, 2002), increased skeletal muscle ion transport protein activity, e.g. Na^+-K^- pump and lactate transporter (monocarboxylate transporter 1 and 4) activity (Mohr et al., 2007), increased glycogen stores (Laursen & Jenkins, 2002), potential transformation of muscle fibers from fast to slow (Rusko, 1992), and improved blood flow distribution (Kalliokoski et al., 2001).

These physiological adaptations are responsible for enhancing the determinants of endurance performance (see section 2.1.2), that is VO_{2max}, lactate thresholds, economy of movements, neuromuscular capacity, and durability. As was seen in section 2.2, a coarse division suggests that central adaptations improve stroke volume, which in turn enhances maximal cardiac output and consequently VO_{2max}. On the other hand, peripheral adaptations improve oxygen extraction and utilization, indicated by improvements in the arteriovenous oxygen difference (Daussin et al., 2007).

In untrained participants, maximal cardiac output, in short term interventions, is primarily increased by an increase in blood volume. Structural or functional adaptations within the myocardium, such as muscle mass of the left ventricle, require several months (Arbab-Zadeh et al., 2014; Bonne et al., 2014; Montero et al., 2015). On the other hand, plasma expansion is one of the quickest adaptations, and it can be noticeable, up to +20%, already after three days of training (Green et al., 1990). Peripheral adaptations can also be rapid. For example, in untrained individuals, mitochondrial volume can increase up to 40% and capillary density up to 20% after a few weeks of training (Saltin et al., 1977).

Although the LIT and HIT zones have distinct acute characteristics, their long-term adaptations appear surprisingly similar, especially when considering untrained participants (TABLE 1). In the short-term interventions, lasting at most a few months, the magnitude of changes among untrained individuals are slightly more pronounced after HIT compared to LIT. This is true, for example, with VO_{2max} (Milanović et al., 2015), capillary angiogenesis (Liu et al., 2022), and vascular function (Ramos et al., 2015). Moreover, a hypothesis suggests that total training volume leads to improved mitochondrial mass, while intensity is more associated with improved mitochondrial function (Bishop et al., 2019).

Peripheral adaptations may be pronounced by a large LIT volume (Seiler, 2010). While HIT has been seen to affect both peripheral and central adaptations (Daussin et al., 2007; Spina et al., 1992), LIT can only affect peripherally, without simultaneous central adaptations (Daussin et al., 2007).

TABLE 1. Endurance performance related adaptations for untrained people following the LIT and HIT interventions.

Performance factor	LIT intervention	HIT intervention
Lipid oxidation capacity and efficiency	+ (Phillips et al., 1996)	+ (Coggan et al., 1990)
VO_{2max}	+ (Milanović et al., 2015)	+ (Milanović et al., 2015)
LT_2 LT_1	+ (Londeree, 1997)	+ (Londeree, 1997)
Economy of movement	+ (González-Mohíno et al., 2020)	+ (Barnes & Kilding, 2015)
Muscle buffering capacity	= (Edge et al., 2006)	+ (Edge et al., 2006; Weston et al., 1997)
Recovery ability from an exercise	+ (Cornelissen et al., 2010)	+ (Buchheit et al., 2008)
Durability	+ (Spragg et al., 2023) (I)	+ (Coggan et al., 1993) (I)
Capillary density	+ (Liu et al., 2022)	+ (Liu et al., 2022)
Mitochondrial volume	+ (Bishop et al., 2019)	+ (Bishop et al., 2019)
Left ventricle mass & wall thickness	+ (Arbab-Zadeh et al., 2014)	+ (Arbab-Zadeh et al., 2014)

VO2max Maximal oxygen uptake; *LT_1* First lactate threshold; *LT_2* Second lactate threshold; + Positive effect; = No effect

2.5.2 Sprint adaptation to endurance training.

Determinants of sprint performance are sprinting technique, maximal power, and sprint-specific endurance. Among these, maximal power is explained by muscle mass, strength, anaerobic enzyme capacity, and muscle fiber distribution. Sprint-specific endurance refers to the ability to sustain maximal power output, which essentially relates to anaerobic capacity. (Haugen et al., 2019; Martin et al., 2007; Seitz et al., 2014).

These factors that explain sprint performance differ from the factors that are typically improved after endurance training, shown in TABLE 1 above. However, in untrained individuals, endurance training, especially cycling, can enhance muscle strength in working muscles (Farup et al., 2012). Also, both HIT and LIT enhance economy of movement (Barnes & Kilding, 2015; González-Mohíno et al., 2020), and potentially a technique of a sprint. Additionally, HIT can especially improve anaerobic capacity by enhancing muscle buffer capacity (Edge et al., 2006) and central fatigue resistance (O'Leary et al., 2017). Glycolytic enzyme activity is only minimally affected (Kubukeli et al., 2002), even though HIT involves anaerobic energy contribution.

It follows that HIT (Edge et al., 2005; Foster et al., 2015), MIT (Edge et al., 2005; Glaister et al., 2007) and LIT (Foster et al., 2015; Litleskare et al., 2020) have the potential to also improve sprinting performance for untrained individuals, though not always (Buchheit & Ufland, 2011; Hardman et al., 1986).

2.5.3 Endurance training and improved recovery

The cardiovascular system plays a major role in assisting recovery of many systems, including thermoregulation, as well as the removal and delivery of nutrients and waste products. Cardiovascular recovery can be measured by heart rate variability, which gives a proxy for changes in autonomic input and blood flow requirements to restore homeostasis. HRV recovery is essentially the reactivation of the parasympathetic nervous system. In the short term (within 90 minutes post-exercise), it is primarily driven by metaboreflex stimulations from muscles and blood acidosis. In the long term (more than 1-hour post-exercise), it is mainly influenced by baroreflex stimulation, primarily due to changes in plasma volume. (Stanley et al., 2013).

Endurance training interventions can accelerate post-exercise HRV recovery following endurance exercise by improving parasympathetic reactivation after submaximal exercise (Buchheit et al., 2008; Cipryan, 2018; D'Agosto et al., 2014; Seiler et al., 2007). However, post exercise HRV recovery following maximal efforts, such as sprints, is usually unaffected by training interventions (Cornelissen et al., 2010; Martinmäki & Rusko, 2008; Perini et al., 2002), or by aerobic fitness (Glaister et al., 2014). Post exercise HRV is an indicator of exercise intensity, with the anaerobic contribution significantly influencing the extent of parasympathetic reactivation (Buchheit et al., 2007). Consequently, regardless of training status, a maximal effort involving equal anaerobic contribution may lead to a comparable post exercise HRV state.

Cardiac parasympathetic reactivation measures the recovery from one angle, but it does not align with the recovery times of all systems, such as the neuromuscular system or energy stores. For example, a 20-minute maximal performance can be replicated in a similar manner after 3 hours of recovery, even though parasympathetic reactivation is still incomplete (Stuessi et al., 2005). Moreover, although HRV recovery after a maximum sprint exercise is typically unchanged, the recovery time of some systems can be accelerated through endurance training. Endurance training can improve recovery factors such as muscle reoxygenation rate (Buchheit & Ufland, 2011) and the rate of phosphocreatine resynthesis (McMahon & Jenkins, 2002). These contribute to improved repeated sprint performance (Buchheit & Ufland, 2011) by facilitating faster recovery between sprints and/or reducing fatigability during sprints.

2.5.4 Minimum intensity and volume for adaptations

There appears to be an intensity threshold for endurance adaptations. For example, in untrained adults with a VO_{2max} below 40 ml/kg/min, improvements in VO_{2max} have been observed with exercise intensity as low as 30% VO_{2max}. However, when the initial VO_{2max} is above 40 ml/kg/min, further improvement requires exercising at a minimum of 50% VO_{2max} intensity. (Swain & Franklin, 2002). For moderately trained individuals, the minimum intensity needed for VO_{2max} improvement has been reported to be in the range of 65–70% VO_{2max}, while well-trained athletes require at least 95% VO_{2max} intensity to sufficiently challenge the oxygen transport and utilization system for further enhancement (Midgley & McNaughton, 2006).

A similar phenomenon, that trained individuals require higher intensities, has been observed with lactate threshold adaptations (Londeree, 1997). Further, capillary density and capillary to fiber ratio develop less effectively in untrained individuals when training below 50% VO_{2max}, compared to training above 50% VO_{2max} intensity (Liu et al., 2022).

All in all, it appears that intensity around 50% VO_{2max} would be the minimum level required to induce positive endurance training adaptations, and trained individuals would require higher intensities for continued progress. Interestingly, the 50% VO_{2max} intensity recommendation aligns with the intensity below which EPOC does not accumulate (Laforgia et al., 2006). This suggests that adaptations may only occur when the body is subjected to a certain level of physiological strain during exercise. Finally, since the minimum effective intensities differ between untrained individuals and athletes, it follows that untrained and highly trained individuals are distinct populations that need to be studied separately (Laursen & Jenkins, 2002).

It appears that there is not only minimum intensity, but also a minimum duration that is needed for endurance adaptations. For example, exercising for 30 minutes continuously in the LIT zone has a greater impact on VO_{2max} adaptations than 3 x 10 minutes interval, even when the exercise intensity and weekly volume were matched (DeBusk et al., 1990). Further, 30 minutes at the LIT zone weekly was not enough to improve VO_{2max}, while 60 minutes was (Foulds et al., 2014).

2.5.5 Chronic adaptations to prolonged low intensity exercises

The acute responses following LIT and the exercise dose of LIT change with increasing duration, as have been described in section 2.2. Although it is known that a single six-hour LIT session leads to endurance adaptations extending up to six days later, such as a 5% increase in plasma volume, a 30% reduction in exercise muscle lactate concentration, and a 14% increase in Monocarboxylate Transporter 1 and 4 activity (Green et al., 2002), surprisingly little research has compared the longer-term effects of the LIT sessions with different durations.

Although prolonged LIT sessions have not been extensively studied, the volume of LIT has been examined. With studies using a range of 90–300 weekly LIT minutes, the results are unclear. Some controlled high vs. low volume studies have reported high volume being associated to a better VO_{2max} improvement (Ross et al., 2015), while others reported no difference (Asikainen, 2002; Foulds et al., 2014; Lin et al., 2021). However, it may be that the higher weekly volume leads to a fewer number of low responders, despite the fact that improvement in VO_{2max} align with 150 and 300 weekly LIT minutes (Lin et al., 2021).

On the other hand, an excess amount of LIT, such as 6 h of daily skiing (Schantz et al., 1983) or 2 h of daily running (Dressendorfer et al., 1991) has not resulted in changed VO_{2max}, although peripheral adaptations occurred. In these excessive volume studies, adaptations may have been adversely affected by insufficient energy availability, as indicated by weight loss and reported insufficient energy intake.

2.5.6 Trainability of durability

Currently, there is a limited number of interventions focused on durability. Recalculated mean values from tables and figures indicate a VO_2 drift, ranging from 4% to 16% during 90–180 minutes of low to moderate intensity endurance exercise for recreationally active individuals. These VO_2 drifts have been reduced by 2–4% through endurance training alone, using a combination of LIT and MIT, or HIT. (Carter et al., 2001; Coggan et al., 1993; Hurley et al., 1986; Phillips et al., 1996). Combined strength and endurance training for athletes has been effective in reducing VO_2 drift (Rønnestad et al., 2011). However, pure LIT studies have not been reported.

In the aforementioned studies (Carter et al., 2001; Coggan et al., 1993; Hurley et al., 1986; Phillips et al., 1996; Rønnestad et al., 2011), HR drift, which initially was 10–20%, had been reduced by 3–9%. Endurance training alone has not shown the ability to reduce drifts among athletes (Hausswirth et al., 2010; Rønnestad et al., 2011). Observational studies suggest that there is an association between durability, as indicated by the preservation of power profiles in a fatigued state and the volume of LIT training (Spragg et al., 2023).

2.6 Individual adaptations to training

A consistent finding has been that, with the same training, some individuals improve significantly while others show minimal progress (Bouchard et al., 1999). This is of particular interest because researched would want to determine how to identify the most suitable training methods, intensities, volume, and load for each individual.

2.6.1 High and low responders

Individuals who show exceptionally large response to training interventions are classified as *high responders*, whereas *low responders* show exceptionally small responses[1] . Similar training leads to highly variable inter-individual adaptations. Improvements in VO_{2max} in a 20 week long intervention can range from 0 to over 1000 ml/min (Bouchard et al., 1999).

There are no universal non responders (Lundby et al., 2017; Montero & Lundby, 2017; Pickering & Kiely, 2019). Everyone has positive adaptations following training intervention, if there are enough variables in the analysis (Bouchard et al., 2012), or if the training dose is increased by prolonging the duration of intervention (Ross et al., 2015), by increasing the exercise intensity (Ross et al., 2015) or volume (Montero & Lundby, 2017).

2.6.2 Responding to different type of exercise

Not only do measured adaptations vary, but also mechanisms which produce the responses may vary. If VO_{2max} is changed similarly between two individuals, these individuals may have different sensitivities for pathways that launch these adaptations. One could benefit more from oxygen deficiency in a muscle, while another from increased calcium flux. (Kainulainen, 2009).

Different types of exercise provide different stimuli. For instance, HIT affects homeostasis through strong metabolic acidosis and peripheral neuromuscular fatigue, while LIT depletes carbohydrate stores, maximizes lipid oxidation capacity, and affects central neuromuscular fatigue. Thus, individuals who do not adapt to a certain type of exercise can be more responsive for different stimulations (Beaven et al., 2008; Bonafiglia et al., 2016). In theory, if HIT does not bring adaptations, LIT can be more effective and vice versa.

2.6.3 Predicting individual adaptations

When retrospectively examining the variables that best explains the observed changes in VO_{2max}, the factors include initial VO_{2max} (Sisson et al., 2009; Skovereng et al., 2018), gross efficiency (Skovereng et al., 2018), age, and sex

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[1] The exact definition of ”exceptional response” is ambiguous [64], and its further examination is out the scope of this literature review.

(Mann et al., 2014). However, overall these baseline values explain only a minimal amount of the change in VO_{2max} (Mann et al., 2014), while Bouchard et al. (Bouchard et al., 1999) argued that about 50% of training responses in VO_{2max} would be caused by genetics.

A more refined method to predict adaptations involves the use of cardiac autonomic function, measured by heart rate variables. High and low frequency powers have predicted whether HIT or LIT is individually more effective to improve VO_{2max} (Kiviniemi et al., 2015; Vesterinen et al., 2013; Vesterinen, Häkkinen, et al., 2016). Cardiac autonomic function is closely related to perceived stress, and total perceived stress has also been used successfully to predict the VO_{2max} improvement (Bartholomew et al., 2009; Otter et al., 2015; Ruuska et al., 2012).

In the context of running, individuals have been categorized as either aerial or terrestrial based on their running technique. Aerial runners report more positive feelings toward higher speed runs compared to terrestrial runners (Lussiana & Gindre, 2016). It has been speculated that the aerial runners would benefit more on the higher running speed in their training (Gindre et al., 2016), which they also tend to prefer initially.

The challenge in identifying predictive influencers for optimal exercise prescription lies in the fact that VO_{2max} is a complex high-level phenotype influenced by many independent factors (Mann et al., 2014). This is underscored by the fact that when the same training intervention is repeated after a washout period, despite a consistent change in gene expressions (Lindholm et al., 2016), the magnitude of VO_{2max} adaptation varies considerably (Del Giudice et al., 2020). Those who were high responders the first time, were no longer the second time. Therefore, external factors to training, such as nutrition, rest, and stress, play significant roles in adaptation processes.

2.7 Exercise enjoyment

An interesting question could be whether an individual can somehow "feel" if a chosen intervention is suitable for them — essentially, whether they are a high responder or low responder to the selected training approach. In this thesis, it was explored whether exercise enjoyment could serve as a predictor for aerobic power capacity adaptations.

2.7.1 Enjoyment and pleasure and exercise intensity

Enjoyability of HIT and LIT has two sides (FIGURE 6A). HIT is regarded more enjoyable *after* the exercise session (Oliveira et al., 2018). On the other hand, *during* the exercise HIT is felt more unpleasant than LIT, and unpleasantness increases as the exercise session progress (Ekkekakis et al., 2005b). To distinguish these two notions, here we understand *enjoyment* as a measurement after the exercise and *pleasure* during the exercise.

During the exercise, LIT is felt pleasant, as it poses no challenge to the homeostasis and it draws from an extensive source of energy reserves (Ekkekakis et al., 2005b). On the other hand, HIT is regarded more unpleasant than LIT, as it has been proposed to pose a threat to survival in a form of cardiovascular complications, risk of injury, and it can be continued only briefly, as it draws from suppressed source of energy reserves (Ekkekakis et al., 2005b).

The reason that HIT is on average regarded more enjoyable than LIT after the exercise (Oliveira et al., 2018), might be because the participants experience improved competence, sense of accomplishment, and pride (Niven et al., 2020) after the HIT session. Additional reason might be the possible release of endogenous opioids, such as β-endorphin, stimulated by metabolic acidosis from the HIT (Taylor et al., 1994), which further increases the feeling of happiness and reduces the sensation of pain (Dfarhud et al., 2014).

2.7.2 Enjoyment and pleasure as individual response

The hedonistic approach suggests that humans tend to sustain behavior if they feel it pleasurable and enjoyable (Murphy & Eaves, 2016; Teixeira et al., 2021). Relying on the hedonistic approach, if HIT would be pleasurable, people would emphasize it in their ordinary physical activity. However, it seems that HIT is a greatly avoided exercise mode by ordinary free-living individuals and consequently, HIT would not be pleasurable and enjoyable (Ekkekakis et al., 2023). This would make LIT the more attractive training form. Another reason for not using HIT could be that it is considered less familiar than LIT (Stork et al., 2020).

Some individuals are more sensitive to stimuli and would get aroused at lower intensity than others (Ekkekakis et al., 2005a). For example, pleasure increased for about half of the participants during 30 min of exercise at 60% VO_{2max} intensity, while for the others the pleasure decreased (Van Landuyt et al., 2000). In practice, individuals have a unique intensity after which their pleasure decreases during the exercise (FIGURE 6B).

The preference and tolerance to high intensity exercise is an individual trait. Individuals whose intensity trait involves a higher preference and tolerance toward high intensity exercise, also enjoyed high intensity exercises more than those with an intensity trait toward lower intensities (Box & Petruzzello, 2020; Ekkekakis et al., 2005a).

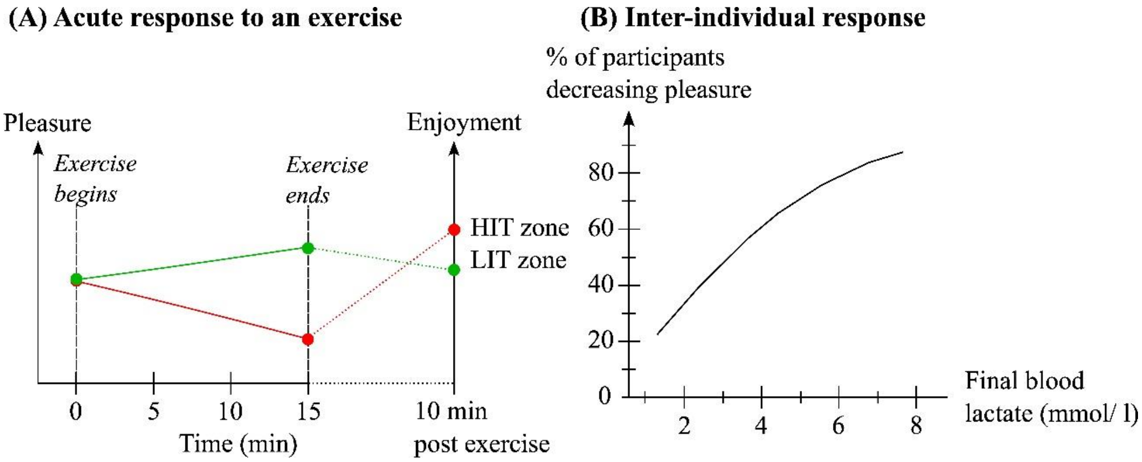


FIGURE 6. (A) A schematic illustration of exercise pleasure during the exercise (Ekkekakis et al., 2000, 2005b) and exercise enjoyment (Oliveira et al., 2018) after the LIT and HIT sessions. (B) Relation of final blood value immediately after an exercise session and percentage of participants reporting decrease in pleasurable during the exercise. Modified from (Ekkekakis et al., 2011). *LIT* Low intensity training; *HIT* High intensity training.

3 PURPOSE OF THE THESIS

The duration of a LIT session influences exercise induced acute responses. The purpose of this thesis was to investigate what are the endurance performance adaptations following an extensive volume LIT intervention, including prolonged LIT sessions, and compare them to adaptations following a HIT intervention.

The specific aims were to study:

1. How does the durability of untrained participants change after 10 weeks of LIT and HIT interventions? (Study I)
2. Can exercise intensity be compensated by utilizing high volume training, when examining the changes of low and high intensity performance in untrained participants during 10 weeks of LIT and HIT interventions? (Studies I, III)
3. Does exercise enjoyment predict aerobic improvements in aerobic capacity induced by the LIT and HIT interventions in untrained participants (Study II)?

4 METHODS

4.1 Participants

Totally 47 healthy sedentary or recreationally active (endurance exercise less than 6 h/wk) untrained adults aged 20–40 years were screened for this thesis. Thirty-five (74%) completely fulfilled the training intervention. The baseline characteristics are in TABLE 2. There were no differences at baseline between the groups for males, females, nor combined males and females. The flow chart is seen in FIGURE 7.

Exclusion criteria were hypertension, pregnancy or nursing, diagnosed upper respiratory infection or other acute illnesses within two-weeks before the first laboratory visit, age < 18 or > 40 y, abnormal resting electrocardiogram, and systematic endurance training. A total of 47 participants took part in the screening visit, which included assessments of body height, resting electrocardiogram, resting blood pressure, and health status. Forty four participants met the inclusion criteria and started the training intervention.

TABLE 2. Basic baseline characteristics (mean, SD) of the participants.

	Low intensity group			High intensity group		
	Female	Male	Combined	Female	Male	Combined
Number	9	7	16	10	9	19
Age (yrs.)	33 (5)	34 (6)	33 (5)	30 (5)	34 (5)	32 (5)
Height (cm)	168 (6)	178 (4)	173 (8)	164 (7)	180 (7)	172 (11)
Body mass (kg)	73.2 (15.2)	88.4 (9.7)	79.8 (14.9)	62.8 (9.0)	87.7 (9.8)	74.6 (15.7)
Fat percentage (%)	30.2 (6.9)	24.7 (7.9)	27.8 (7.6)	27.6 (5.9)	22.3 (6.0)	25.1 (6.4)
VO_{2max} (ml/kg/min)	35.1 (3.7)	40.9 (5.5)	37.6 (5.3)	37.6 (5.0)	37.2 (6.4)	37.4 (5.5)
VO_{2max} (l/min)	2.54 (0.12)	3.62 (0.14)	3.01 (0.66)	2.33 (0.04)	3.25 (0.13)	2.77 (0.55)
P_{max} (W)	188 (25)	272 (25)	225 (49)	176 (11)	251 (43)	212 (48)
LT_1 (W)	83 (14)	121 (24)	99 (27)	79 (14)	115 (30)	96 (29)
LT_1 (% VO_{2max})	56.0 (4.6)	51.7 (6.5)	54.1 (5.7)	56.0 (4.2)	55.7 (4.5)	55.9 (4.2)
LT_2 (W)	134 (23)	204 (23)	165 (42)	128 (11)	191 (38)	158 (42)
LT_2 (% VO_{2max})	76.9 (6.2)	78.4 (6.8)	77.6 (6.3)	77.0 (4.1)	81.3 (6.8)	79.1 (5.8)
15s sprint (W)	662 (145)	911 (89)	771 (175) (n = 14)	605 (88)	944 (124)	766 (202)
fat oxidation (mg/min) at low exercise	154 (41)	156 (78)	155 (58)	127 (55)	213 (137)	168 (109)
Maximal stroke volume (ml)	115 (19) (n = 5)	141 (7) (n = 6)	129 (19) (n = 11)	111 (17)	153 (43) (n = 7)	128 (36) (n = 17)

VO_{2max} Maximal oxygen uptake; *P_{max}* Power associated to VO_{2max}; *LT_1* The first lactate threshold; *LT_2* The second lactate threshold

4.2 Study design

The study compared adaptations of 10-week LIT and HIT interventions. Altogether, there were seven laboratory visits: three before the training intervention, one during intervention, and three after the intervention (see FIGURE 7). The three visits before the intervention included: 1) screening 2) combined sprint and VO_{2max} tests and 3) durability test. Anthropometric, sprint and VO_{2max}, and durability tests were also repeated after the intervention. A VO_{2max} test was also performed during week 6 of the intervention.

The weekly training dose was monitored by self-reported weekly perceived exertion (wRPE) using Borg RPE Scale® (Borg, 1982) by asking after each intervention week, “How much the training has strained your week on a scale 0–10?”. To measure enjoyment of the exercises, participants filled the physical activity enjoyment scale (Kendzierski & DeCarlo, 1991) questionnaire after each exercise session during the weeks 1 and 10 of the intervention.

After the first three visits, the participants were randomized into two training groups, LIT and HIT, by applying a minimization method (Hu & Hu, 2012) using EE drift and group size as variables with Mathematica 13 (Wolfram Research, USA). Randomization was done separately for females and males.

The primary variable for which the sample size was calculated was EE drift during the 3 h cycling test. Based on VO_2 drifts in interventions (Carter et al., 2001; Coggan et al., 1993), it was estimated that intervention would cause an average 3 percentage point reduction in EE drift in the HIT group, and 6 percentage point reduction in the LIT group with 3 percentage point standard deviation. Based on these findings, power calculations produced a group sample size of 16 ($\alpha = 0.05; \beta = 0.80$).

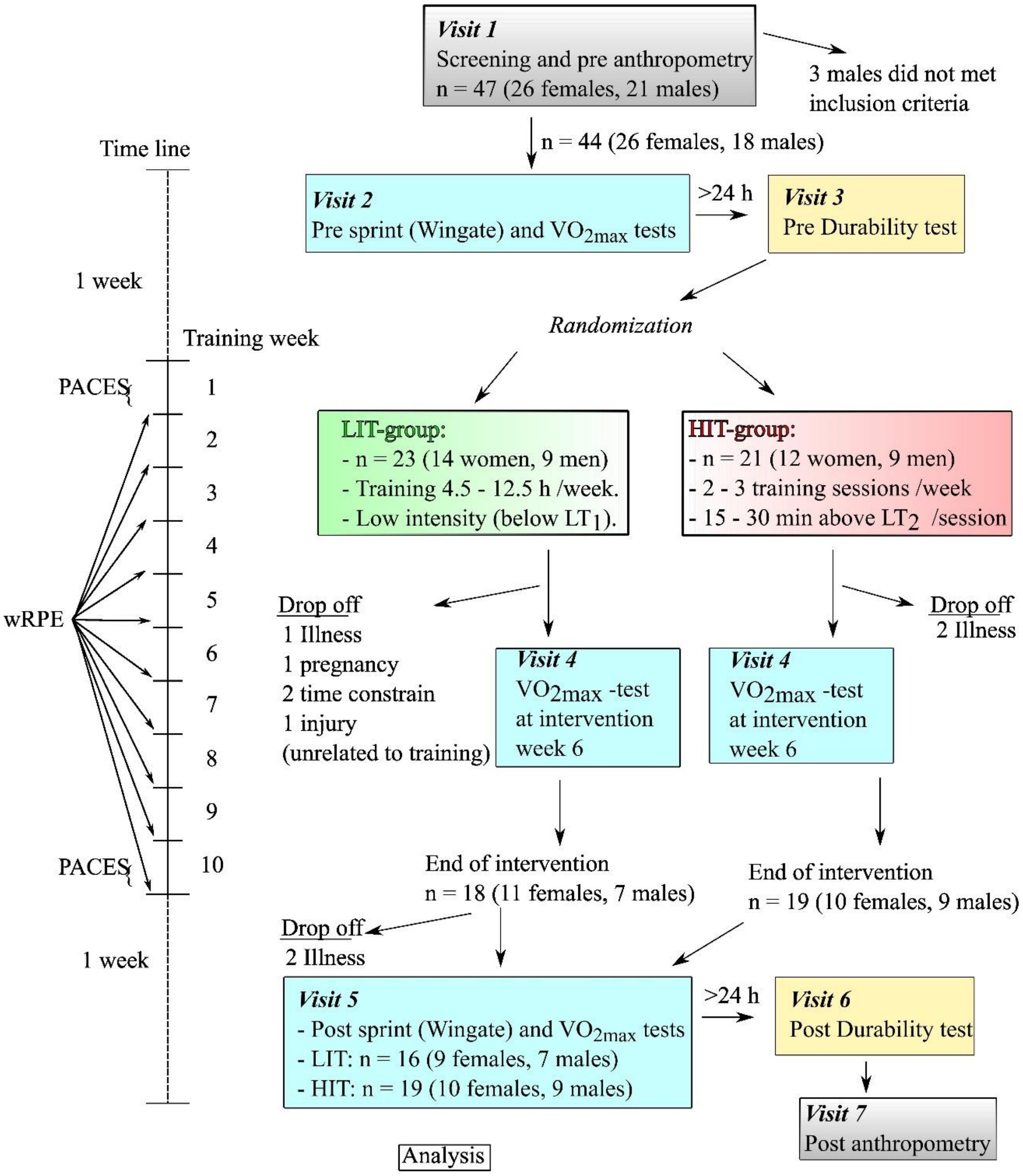
4.3 Measurements

4.3.1 Anthropometry

Body mass and fat percentage of the participants were measured by bioelectrical impedance (InBody 770, Biospace Ltd., Seoul, Korea) in the morning, after at least 8 h of fasting, and while wearing underwear clothes. The height to the nearest centimeter was also measured.

4.3.2 Physical activity

Daily physical activity was estimated by recording heart rate continuously from the wrist using the Garmin Forerunner 945 (Garmin Ltd., Taiwan) for 2-4 weeks before the intervention. This was done to estimate the baseline physical activity and endurance training before the training intervention.



Excluded:

- From cardiac impedance analysis (n=3) because over 50 % missing data points due to low quality
- From sprint analysis (n=5) because data were not acquired, test were not executed and test was clearly not maximal.
- From VO_{2max} analysis (n=2) because post test was not executed and data was not retrieved.

Excluded:

- From HRV (n=1) and cardiac impedance (n=3) analysis because over 50 % missing data points due to low quality
- From sprint analysis (n=2), because data was not retrieved and test was not executed.

FIGURE 7. Flow chart. *LIT* Low intensity training; *HIT* High intensity training; *wRPE* weekly rating of perceived exertion; VO_{2max} Maximal oxygen uptake; *PACES* Physical activity enjoyment scale questionnaire LT_1 First lactate threshold; LT_2 Second lactate threshold; *HRV* Heart rate variability;

4.3.3 Sprint and VO_{2max}

Wingate (visits 2 and 5) and VO_{2max} (visits 2, 4, and 5) tests were performed individually at the same time of the day (± 2 h), as time of day may influence the measured VO_{2max} value (Knaier et al., 2019). The participants were advised to refrain from caffeine and alcohol 24 h before the tests and to eat no later than 3 h prior the tests. To calculate VO_{2max} relative to body mass and to monitor weight during the durability test, body mass was recorded (seca 719, seca GmbH & Co. KG., Hamburg, Germany) with cycling clothes on and shoes removed (300 g was subtracted as the weight of clothes) before each performance test.

15 s Wingate test (sprinting ability) was done after a 10-minute warm up at 50 W, followed by a 10 second countdown phase to reach maximum pedaling rate with the load (7.5% of body mass), followed by 15 seconds of all out maximal cycling (Monark 894E, Monark Exercise AB, Vansbro, Sweden). Participants were heavily encouraged verbally by researchers. Participants were familiarized with the Wingate test during their screening visit.

Incremental VO_{2max} cycling test was started exactly 35 minutes after termination of the Wingate test except during visit 4 in which Wingate was not performed. Preceding supramaximal tests do not affect VO_{2max} (Pendergast et al., 1983). During the 35 minutes, participants remained seated for 10 minutes, after which they performed light physical activity (walking or cycling at 50 W). VO_{2max} test was a step-incremental cycling test (Monark LC4, Monark Exercise AB, Vansbro, Sweden). The initial power was 40 W for females and 50 W for males, with incremental increases (20 – 25 W for females and 30 W for males) every 3 minutes. Researchers verbally encouraged the participants during the last stages. Gas exchange was measured breath-by-breath (Jaeger Vyntus TM CPX, CareFusion Germany 234 GmbH, Hoechberg, Germany) and HR was monitored with a Garmin Forerunner 945 (Garmin Ltd., Taiwan) and Garmin dual or HRM-Pro heart belt (Garmin Ltd., Taiwan). Means from the last minute of every stage were used in analysis. During the last minute of each state, blood lactate was measured by fingertip sampling (EKF-diagnostic GmbH Ebendorfer Chaussee 3, Germany), and RPE (Borg Scale 0–10) was recorded. VO_{2max} was defined as the highest continuous 60 s mean oxygen consumption. Maximal aerobic power (P_{max}) was defined as the weighted mean of the last 3 min of the test: power of last completed stage (W) + [time (s) of unfinished state]/(180 s) × increment (W). The first lactate threshold was defined as the lowest value of the lactate/VO_2 -ratio and the second lactate threshold as a sudden and sustained increase in blood lactate concentration (Faude et al., 2009). Two researchers independently determined the thresholds. In case of disagreement, a third opinion was obtained.

4.3.4 Durability test

Durability tests (visits 3 and 6) were performed individually for each participant at the same time of day (± 2 h). The participants were advised to have a standard meal 2.5–3 h before the test. They were instructed to document the timing and contents of the meal, and to repeat it before the second durability test. Before the durability test, body mass was measured (seca 719), followed by sitting on the bench while being prepared for the noninvasive cardiac impedance (PhysioFlow PF-07 Enduro, Manatec Biomedical, Macheren, France) with PF50 PhysioFlow (Manatec Biomedical, Macheren, France) electrodes (Physioflow, 2016).

Thereafter, the participants cycled for 3 h (Monark LC4) with a predetermined power, 50% VO_{2max}, measured by the incremental test, but not more than 95 % LT_1 to ensure that each participant cycled at the LIT zone. In the pre-durability test, the realization of the power was 48 ± 4% VO_{2max} and 87 ± 8% LT_1. The intensity relative to VO_{2max} rather than LT_1 was chosen, because VO_{2max} was considered more stable, especially as graded test was conducted after a 15-second Wingate test. The same absolute power in the pre- and post-durability tests was used. Ten-minute measurement slots were repeated every 30 min. During the first 20 minutes, the participants chose their preferred position and cadence (over 60 rpm), which were recorded and maintained during the subsequent 10-minute measurement slots in both pre- and post-tests. Especially, fat oxidation was measured from the first 10-minute measurement interval using non-direct calorimetry based on breathing gases using the equation (Frayn, 1983): $1.67 \times \mathrm{VO_2(l/min)} - 1.67 \times \mathrm{VCO_2(l/min)}$. Between the 10-minute measurement slots, participants could adjust their position and cadence (> 60 rpm) freely. The 3 h cycling was followed immediately by a 15 second Wingate test. After the 3 h cycling + 15 second sprint, the participants sat on a chair for 15 minutes, during which their heart rate (Garmin HRM-Pro or Garmin dual heart belt, Forerunner 945) and breath-by-breath gas exchange (Jaeger Vyntus TM CPX) were measured. The recovery measurements were averaged in 3-minute intervals. Body mass was again measured after the recovery measurements. The sweat absorbed by clothing was not accounted for in the body mass measurements.

Hydration (0.3% NaCl solution) was available ad libitum. Water intake during 3 h tests was measured. In the LIT group, it was 1.2 (0.4) l and 1.1 (0.4) l in pre- and post-tests, respectively. In the HIT group, the respective values were 1.3 (0.4) l and 1.1 (0.4) l. During the test, carbohydrates were given as a 2:1:1 mixture containing maltodextrin, fructose, and glucose dissolved into 1 dl of 0.3% NaCl. The mixture of carbohydrates was used to avoid saturating a single carbohydrate transporter (Jeukendrup, 2011). NaCl was added as sodium stimulates the physiological drive to drink and the renal water reabsorption (Baker & Jeukendrup, 2014). Carbohydrate intake was individualized, and the amount was related to the cycling power, calculated to cover 50% of theoretical energy expenditure, where 18% gross efficiency was assumed (Ettema & Loras, 2009). A maximum of 75 g of carbohydrates was given per hour to minimize gastrointestinal problems (Jeukendrup, 2014). The carbohydrate intake was identical in the pre- and post-tests (mean ±SD: 51 ± 14 g /h).

Breath-by-breath gas exchange (Jaeger Vyntus TM CPX), heart rate (Garmin HRM-Pro or Garmin dual heart belt, Forerunner 945), and cardiac impedance (Physioflow) was measured during each 10-minute measurement slots, after which RPE (0–10) was recorded. From cardiac impedance, stroke volume was recorded, as it, together with heart rate, determines cardiac output. Additionally, left ventricular ejection time was recorded, as it is closely associated with the fluctuations in cardiac sympathetic activity. (Michael et al., 2017).

Blood was drawn from the fingertips at 0, 1, 2, and 3 h for analyzing blood lactate (EKF-diagnostic GmbH Ebendorfer Chaussee 3). The 15-s Wingate test was performed within the first minute after finishing the 3 h test. The progression of the durability test is shown in FIGURE 8.

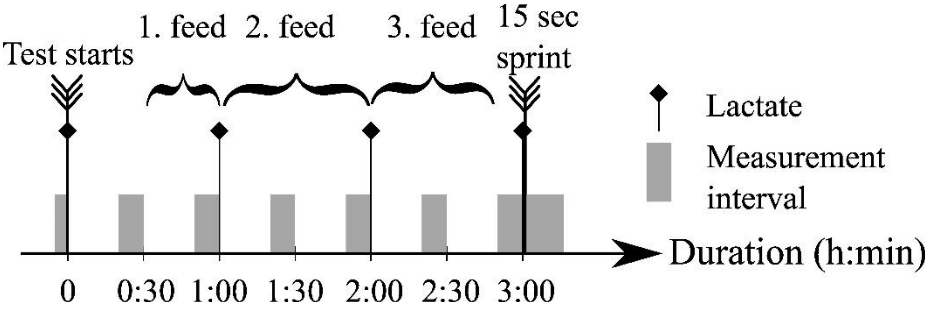


FIGURE 8. The progression of the durability test. During the measurement interval, gas exchange was measured. Nutrition was administered at a predetermined rate of grams per hour, with these three feeding intervals indicated in the figure.

4.3.5 Energy expenditure

Energy expenditure (EE) was calculated with the equation (Keskinen et al., 2004): $EE\ (\mathrm{kJ/min}) = (5.05 \times \mathrm{RER} + 16.1) \times \mathrm{VO_2 (l/min)}$, where RER is respiratory exchange ratio and $\mathrm{VO_2 (l/min)}$ absolute oxygen consumption.

4.3.6 Exercise Enjoyment

Exercise enjoyment was measured by the 18-item Physical Activity Enjoyment Scale *(PACES;* Kendzierski & DeCarlo (Kendzierski & DeCarlo, 1991)) in Finnish. Participants responded to "How do you feel at the moment about the physical activity you have been doing" on the 7-point bipolar scale (e.g. “1 = it is not very refreshing…. 7 = It is very refreshing” and “1 = it is not at all stimulating…. 7 = it is very stimulating”). The score was the summation of all the items, running between 18–126. Participants filled the PACES after each training session in the first and the last week of the intervention, after their exercise sessions, through a mobile phone application (AthleteMonitoring, FITSTATS Technologies, Inc., Moncton, Canada). Weekly mean values were used for the final exercise enjoyment scores. Cronbach’s α in the pre-tests for PACES was 0.95.

4.3.7 Heart rate variability

In the heart rate variability analysis, low frequency (0.04–0.15 Hz) and high frequency (0.15–1.1 Hz) bands were used. The higher than usual frequency limit of 1.1 Hz was chosen to include the respiratory frequency during exercise. HR and HRV data were collected with the Garmin HRM-Pro or HRM-dual belt, with 1000 Hz resolution frequency, and analyzed with Kubios HRV Premium (Version

3.5.0, Kubios Oy, Kuopio, Finland). Medium automatic quality detection with a 5% acceptance threshold and an automatic beat correction method were used. Low- and high-frequency spectrums were calculated by applying the Lomb-Scargle periodogram with a 0.02 Hz smoothing window. The HRV samples were 8-minute subintervals within 10-minute measurement intervals of the durability test, and 3-minute intervals at the recovery period after the durability test.

4.4 Measured variables

4.4.1 Durability

Durability was estimated as a pooled variable using three different approaches:

1) The *magnitude of physiological drifts*: Change in EE, HR, RPE, ventilation, imputed left ventricular ejection time, and imputed stroke volume between 30 min and 180 min in the 3 h durability test.
2) The *time of onset* of a drift: defined as the time when the value of the drift had first changed a predetermined amount. The thresholds were arbitrarily chosen, as in (Smyth et al., 2022), and they were +5% (HR, ventilation), +2.5% (EE), + 2 steps (RPE), and -1.5% (imputed left ventricular ejection time).
3) *The physiological strain*: defined as the absolute levels of HR, HRV, RPE, and blood lactate concentration from the durability test. The strain was used as a proxy for a "area under curve".

The *overall durability* calculated by pooling the all these three factors in a single p-value and effect size.

4.4.2 Low intensity performance variables

Low intensity performance variables were defined as factors that were measured at rest or the intensity corresponding to the first lactate threshold or below (including resting conditions). In this thesis, they included: intensity (absolute and relative to maximum) at LT_1, HRV recovery from the durability test, and fat oxidation at the durability test. Cycling gross efficiency was not chosen as a monitored variable, as its trainability is unclear and debataple (Hopker et al., 2013; Montero & Lundby, 2015; Swinnen et al., 2018).

4.4.3 High intensity performance variables

High intensity performance determinants were defined as factors that were measured at the intensity corresponding to the second lactate threshold or above. In this thesis, they included: intensity (absolute and relative to maximum) at LT_2, VO_{2max}, P_{max}, maximal stroke volume, and sprinting power.

4.5 Low and high intensity training intervention

4.5.1 Training intensity distribution and training dose

Training dose was calculated by distributing cycling power output to five zones [50]: Zone 1 (below LT_1 – 10 W); Zone 2 (LT_1 – 10 W to LT_1 + 10 W); Zone 3 (LT_1 + 10 W to LT_2 – 10 W); Zone 4 (LT_2 – 10 W to LT_2 + 10 W); Zone 5 (above LT_2 + 10 W). For each zone, a weighting factor was linked (in an ascending order: 1, 2, 3, 4, 7.5) and training dose was calculated by multiplying the factor by the time spent in the zone (Cejuela-Anta & Esteve-Lanao, 2011).

The target power for the LIT group was Zones 1 and 2, and for the HIT group Zones 4 and 5. Heart rate was divided into three zones (HRZones 1 – 3) separated by LT_1 and LT_2. In addition, for the LIT group, the number of times their 30 s -average power exceeded Zone 2 was calculated. For the use of baseline physical activity before the start of the training intervention, HRZone 0 was defined as a zone below halfway between resting HR and LT_1, and HRZone 1b above Zone 0 and below LT_1.

To achieve an estimation for balanced training doses for LIT and HIT training in the intervention, a straightforward linear HR-based training dose estimation method was employed. This method assigned weights of 1, (1+x)/2, and x to the three HR zones, and the training dose was calculated by multiplying these weights by the time spent in each zone. The same method was repeated to three power zones, separated by LT_1 and LT_2 powers. The objective was to find the numerical coefficient x that would balance training doses of the LIT and HIT groups in the intervention, when participants were able to affect the training progression themselves.

4.5.2 Training intervention

Participants were instructed to continue their previous physical activity habits, while all strenuous exercise in addition to LIT or HIT were not allowed.

LIT consisted of 5–6 weekly sessions of cycling below LT_1 -power. Sessions included long (1.5–4 h), medium (1–1.5 h), and short (45–60 min) exercises. Weekly exercise hours were initially 4.75 h, which progressed individually (see section 4.5.3) based on weekly perceived exertion (wRPE) up to the maximum of 12.5 h weekly. Participants exercised mostly outdoors with their own bicycles with Rally RK200 dual-sensing power meters (Garmin Ltd., Taiwan). A possibility for indoors cycling, with their own bicycle attached to a trainer, or theuse of a Wattbike Trainer (Wattbike Ltd., Nottingham, UK), was also given. Three (out from 16) participants chose to do their training completely indoors. The others cycled 3% of their exercises indoors.

In the HIT group, there were 2–3 weekly indoor exercise sessions with the Wattbike Trainer or an indoor trainer with their own bicycles attached with Rally RK200 dual-sensing power meters. Training consisted of 3–7 minutes of long high-intensity work intervals, separated by recovery periods ¾ of the work interval duration. Initially, the cumulative high-intensity time in a session was 15 minutes, and it progressed individually (see section 4.5.3) up to a maximum of 30 min. Each session included a 10 min warm-up and cool-down, which, together with recovery periods, was performed with power < 60 W, while high-intensity sections were initially 110% of LT_2 power (±15 W). The work interval intensity in the HIT group was increased by 10%, if all the weekly exercises had RPE ≤ 6 and HR did not rise above LT_2.

In both groups, HR (Garmin HRM-Pro heart belt, Forerunner 945) and RPE (0–10) were recorded from each session. In the LIT group, power data was recorded with power meters (Rally RK200), and in the HIT group, power data was collected from the Wattbike Trainer or power meters (Rally RK200). All data was transferred to AthleteMonitoring app, from which the training realization was monitored weekly. In the LIT group, the participants were actively given weekly feedback on whether training was at the prescribed level. Apart from the first HIT-session, all sessions were unsupervised. The target power was modified in both groups according to the VO_{2max} -test at intervention week 6.

4.5.3 Intervention progression

The training intervention lasted 10 weeks. To enhance recovery, weeks 3 and 7 were load reduction weeks. The progression of exercise sessions was individually linked to the weekly perceived exertion. After each intervention week (excluding load reduction weeks), participants were asked 'How much has the training strained your week on a scale of 0–10?'. The training dose was increased more for those with lower exertion, by increasing the volume the exercises. The training programs for the LIT and HIT groups and the individual progression plan are prescribed in detail in Supplemental Section 8 (TABLES 10 and 11).

4.6 Statistical analysis

Data is presented as the mean (standard deviation). Statistical tests were calculated by SPSS 26.0 and 28.0 (SPSS Inc, Chicago, IL, USA) and Mathematica 13.0 (Wolfram Research Inc., Champaign, Illinois, USA). Missing data on heart rate variability and cardiac impedance were handled by multiple imputation. In short, in this method missing data points from 3-h test were imputed multiple times by using existing data and incorporating randomization in the imputed values. The final value is the pooled estimate derived from all the imputed values. To be conservative, 50 imputations were used (Licht, 2010). Pooled p-values were calculated by applying z-method (Licht, 2010).

Before performing the final analysis, it was determined if the magnitude of change in variables differed between the sexes (Kruskal-Wallis test). Most of them were >95%. Thus, it was decided to analyze females and males in a combined group. The Shapiro-Wilk test was used to examine normality together with visual inspection of Q-Q plot.

If results were not normally distributed, or values were categorial (RPE, onset of drifts), the nonparametric Wilcoxon signed-rank -test was used for comparison between time points, and Mann-Whitney U -test for between-group comparison. When normality assumptions failed, but covariance matrices were homogenous by Box's test, Pillai's trace was utilized in ANOVA. Its effect size partial eta squared (η_p^2) was calculated (II). Small, moderate, and large effect size magnitudes for η_p^2 were categorized as 0.01, 0.06, and 0.14. If covariance assumptions were not met, Kruskal-Wallis test was used. To calculate the average drifts and their onsets, their weighted mean was calculated. In physiological strain, HRV responses were first averaged as a single variable. A harmonic mean p-value technique (I) was applied to estimate the combined change in durability from all examined factors (drifts, their onset, and physiological strain) given all parameters' weights were proportional to their sample size. Also, pooled p-values were calculated using the z-method (III). Post hoc correlations were done using Spearman correlations with RPE and Pearson correlations otherwise.

The effect size (ES) of differences for the main variables were calculated with a corrected effect size Hedge's g. Also, a non-central 95% confidence interval (CI) was calculated in study I [114]. Effect size for between-group differences was calculated by subtracting within-group effect sizes from each other (Morris & DeShon, 2002). After nonparametric tests, effect size was calculated by a formula $Z/\sqrt{n}$, where Z is the z-score, and n is the total number of participants on which Z is based. As this corresponds to point biserial r, an analytical conversion is made to represent it as d-family ES (McGrath & Meyer, 2006):

$$\frac{r}{\sqrt{(1-r^2)\frac{n_1 n_2}{(n_1+n_2)^2}}},$$

where n_1 and n_2 are the sizes of groups 1 and 2. A common language effect size (CLES) is also provided for the main variables (I). When normality assumptions were met, a continuous method was used. In other cases, a sign-test (within-group CLES) or Mann-Whitney U -test (between-group CLES) were utilized. [47]. The interpretation of CLES of X% is 'the probability of a randomly selected individual's variable increasing / being greater than the variable from randomly selected individuals from the other group after the training is X%.' Small, moderate, large, and very large effect size magnitudes for Hedge's g were categorized as 0.20, 0.50, 0.80, and 1.2, and 56%, 64%, 71%, and 80% for CLES, respectively. Weak, moderate, and large correlate magnitudes for correlation were categorized as 0.40, 0.60, and 0.80, respectively.

In figures, the statistical values of the durability test were pooled. P-values were changed to z-scores, which were averaged, similar to the methodology of multiple imputation (Licht, 2010). Effect sizes were pooled following the suggestion by [270]: Cohen d_i ES → Biseral r_i ES → Fisher Z_{ri} → Taking average $\bar{Z}_r = Mean(Z_{ri})$ → Averaged biseral $\bar{r}$ ES → Averaged $\bar{d}$ ES → Averaged Hedge's $\bar{g}$, where i is the different time points from which averages were taken. Correlations were averaged using the same procedure. Common language effect sizes were averaged in continuous cases by averaging all μ_D/σ_D values, where μ_D is the mean value of the observed difference and σ_D is standard deviation. In non-normal cases, CLES was averaged by taking the average over all CLES'.

4.7 Missing data

All the excluded data from studies I–III is presented in TABLE 3. In the durability test, all participants with more than 50 % of the data points missing during the 3 h cycling test were removed from the analysis. Included participants had 7.0 % of HRV and 13.2 % of cardiac impedance data missing. In the recovery period after the 3 h cycle + 15 s sprint, all participants with more than 25 % of data points missing were removed from the analysis. Included participants had 12.5% of HRV data missing. Multiple imputations were used to fill in these missing data. Drifts in imputed left ventricular ejection time and stroke volume were interpolated from regression lines.

During physical activity heart rate measurements, part of the data was dismissed, altogether 12 (±15)% of the gathered data, because heart rate was not adequately recorded from the wrist. No imputation was used to fill this data, and the analysis was adjusted relative to the included total amount. Further, if there were less than seven days of measurements, the participant was removed from the physical activity analysis.

4.8 Use of Artificial Intelligence in Proofreading

Artificial intelligence (ChatGPT 3.5, OpenAI, United States) has been used to aid the writing process of the thesis. It has been used solely for linguistic proofreading purposes to correct pre-existing original text.

4.9 Ethics statement

All participants provided written informed consent, and the study was approved by the Ethical Committee of the Central Finland Health Care District (8U/2020), complying with the Declaration of Helsinki.

TABLE 3. Data excluded from analyses in the LIT and HIT groups in studies I – III.

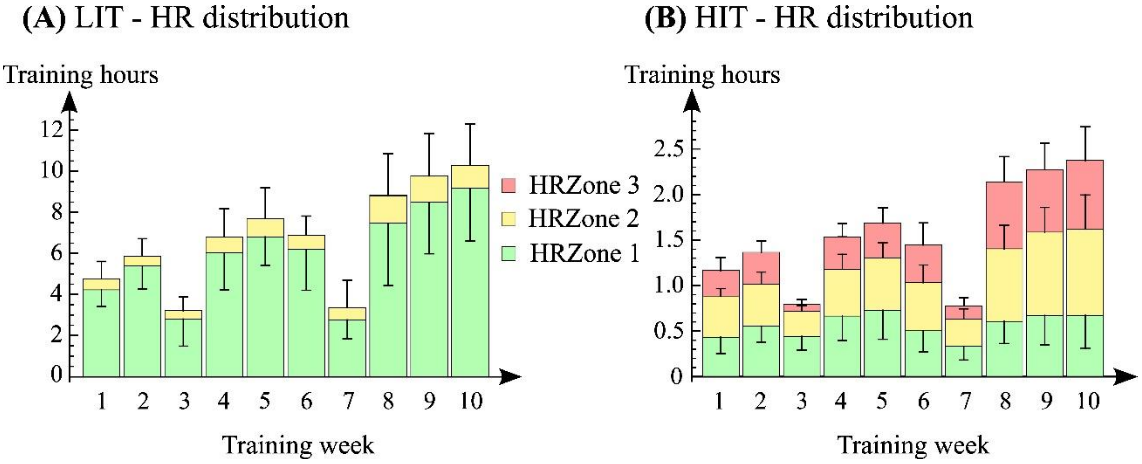
	Excluded from analysis	
	LIT group	HIT group
Study I LIT: n = 16 HIT: n = 19	- From cardiac impedance analysis during the 3 h cycling (n = 3), because over 50% data points were missing due to low quality. -From sprint analysis (n = 5), because data was not acquired or sprint was clearly not maximal. -From VO_{2max} analysis (n = 2), because post test was not executed or data was not retrieved.	- From HRV (n = 1) and cardiac impedance (n = 3), because over 50% of data points were missing due to low quality. - From sprint analysis (n = 2), because data was not retrieved or test was not executed. - From pre-intervention physical activity (n = 2), because there were too few activity days.
Study II LIT: n = 18 HIT: n = 19	-From wRPE at week 1 (n = 1) and week 10 (n = 4), because data was missing. -From VO_{2max} analysis (n = 4), because post test was not executed or data was not retrieved.	-From wRPE at week 1 (n = 3) and week 10 (n = 2), because data was missing.
Study III LIT: n = 16 HIT: n = 19	-From HRV (n = 8) and cardiac impedance (n = 8) analysis, because too low data quality -From sprint analysis (n = 2), because sprint was clearly not maximal -From VO_{2max} analysis (n = 2), because post test was not executed or data was not retrieved.	-From HRV (n =5) or cardiac impedance (n = 6) analysis, because data quality was too low.
Baseline physical activity LIT: n = 16 HIT: n = 19		-From baseline physical activity analysis (n = 2), because there was less than one week of data.

LIT Low intensity training; *HIT* High intensity training; *HRV* Heart rate variability; *VO_{2max}* Maximal oxygen uptake; *wRPE* Weekly ratings of perceived exertion

5 RESULTS

5.1 Training realization

For those who completed the entire intervention (n =35), adherence rate in training sessions was 98.4%. The weekly training HR intensity distribution is shown in FIGURE 9 and training realization in TABLE 4. Before the training intervention, there were no differences in HR intensity distribution between the groups during their physical activity (p > 0.28). The mean wRPE during the intervention was largely lower in the LIT group compared to the HIT group (p = 0.006, ES = 1.0). wRPE increased similarly (p = 0.58, ES = 0.2) in both groups (TABLE 5).


(A) LIT - HR distribution

(B) HIT - HR distribution

FIGURE 9. Mean (SD) weekly training HR distribution for (a) LIT, SD only for zones HRZone 1 and 2; (b) HIT. Notice the different y-axis in the figures. *LIT* Low intensity training; *HIT* High intensity training; LT_1 First lactate threshold. LT_2 Second lactate threshold; *HRZone 1* HR below LT_1; *HRZone2* HR between LT_1 to LT_2; *HRZone 3* HR above LT_2. Figure colored from article III, reproduced by Creative Commons Attribution License.

TABLE 4. Mean (SD) training realization in the LIT and HIT groups during 10-week intervention.

	LIT (n = 16)	HIT (n = 19)
Physical activity before the intervention		
Monitored physical activity days (d)	28 (12)	22 (13) (n = 17)
HR intensity distribution before intervention (min/d) Dismissed / HRZone 0 / HRZone 1b / HRZone 2 / HRZone 3	171 (193) / 1128 (184) / 107 (89) / 6 (7) / 0.5 (0.4)	169 (203) / 1091 (242) / 108 (76) / 6 (8) / 0.4 (0.2) (n = 17)
Training characteristics during the intervention		
Total training time (h)	68.2 (7.3)	15.6 (1.8)
Mean training volume (h / week)	6.8 (0.7)	1.6 (0.2)
Total number of ≥2 h exercises	12 (1)	*Not applicable*
Total number of ≥3 h exercises	6 (2)	*Not applicable*
Mean training frequency / week	4.8 (0.2)	2.4 (0.1)
Mean training HR (% HR_{max})	63.4 (4.3)	76.1 (4.3)
Mean power at work intervals (% power at LT_2)	*Not applicable*	117 (5)
Mean training power (% P_{max}) at exercises (LIT) and at work intervals (HIT)	36 (4)	86 (4)
Mean exercise session RPE	2.8 (1.4)	7.2 (1.9)
Mean weekly RPE	4.5 (1.6)	5.9 (1.0)
Time (% of total amount) at power Zones 1 & 2	96.6 (2.5)	54.1 (4.7)
Time (% of total amount) at power Zone 3	3.2 (2.4)	1.9 (2.4)
Time (% of total amount) at power Zones 4 & 5	0.2 (0.3)	44.0 (5.4)
Mean weekly amount of 30 s intervals with mean power above Zone 2	5.5 (7.8)	*Not applicable*

LIT Low intensity training group; *HIT* High intensity training group; *HR* Heart rate; *HR_{max}* Maximum heart rate; *RPE* Rating of perceived exertion; *Power Zone* 1 power below LT_1 – 10 W; *Zone 2* Power between LT_1 – 10 W to LT_1 + 10 W; *Zone 3* Power between (LT_1 + 10 W to LT_2 – 10 W; *Zone 4* Power between LT_2 – 10 W to LT2 + 10 W; *Zone 5* Power above LT_2 + 10 W; *LT_1* First lactate threshold; *LT_2* Second lactate threshold; For physical activity measurement: *Dismissed* HR data not available; *HRZone 0* HR below halfway between resting HR and LT_1; *HRZone 1b* HR between HRZone0 and LT_1; *HRZone 2* HR between LT_1 and LT_2; *HRZone 3* HR above LT_2.

TABLE 5. Mean (SD) weekly RPE development.

	LIT group	HIT group	Group difference
wRPE at week 1	3.5 (1.9) (n = 15)	4.8 (1.5) (n = 16)	p = 0.007 ES = 1.1
wRPE at week 10	5.2 (1.8) (n = 12)	6.9 (1.5) (n = 18)	p = 0.04 ES = 0.8
Change	1.8 (1.4) (n = 11)	2.0 (2.2) (n = 15)	p = 0.58 ES = 0.2
Time difference	p = 0.01 ES = 1.2	p = 0.007 ES = 1.1	

LIT Low intensity training; *HIT* High intensity training; *wRPE* weekly rating of perceived exertion.

5.2 Durability (study I)

The magnitude of drifts did not change differently between the groups (time x group difference harmonic p = 0.28), nor did onset of drifts (harmonic p = 0.44), or physiological strain (harmonic p = 0.73) as seen in TABLE 6. When pooled together, this means that there were no time x group differences in the change of overall durability between the LIT and HIT groups (harmonic p = 0.42). The overall durability was improved in both the LIT (harmonic p = 0.03, averaged ES = 0.60) and HIT (harmonic p = 0.01, averaged ES = 0.78) groups.

Especially, EE drift was decreased similarly (time x group p = 0.55, ES = 0.06) in both groups: in the LIT group from 6.4 (4.8) to4.0 (5.6)% (p = 0.03, ES = 0.45) and in the HIT group from 6.5 (6.8) to3.0 (6.7)% (p = 0.03, ES = 0.51). EE and HR drifts in the pre and post tests are shown in FIGURE 10.

TABLE 6. Mean (SD) change in pooled magnitude (HR, EE, RPE, Combined HRV, stroke volume, and left ventricular ejection time) and onset (HR, EE, RPE, Combined HRV, left ventricular ejection time) of drifts and physiological strain (HR, RPE, Combined HRV).

	LIT	HIT	Time x group difference
ΔMagnitude of drifts	7.7 (6.8) % → 6.3 (6.0) %	8.8 (7.9) % → 5.4 (6.7) %	
	Harmonic p = 0.09 Avg ES = 0.27 Avg CLES = 62%	Harmonic p = 0.03 Avg ES = 0.49 Avg CLES = 65%	Harmonic p = 0.28 Avg ES = 0.22
ΔOnset of drifts	106 (57) min → 131 (59) min	108 (54) min → 137 (57) min	
	Harmonic p = 0.08 Avg ES = 0.58 Avg CLES = 68%	Harmonic p = 0.03 Avg ES = 0.61 Avg CLES = 63%	Harmonic p = 0.44 Avg ES = 0.03
ΔPhysiological strain	Harmonic p = 0.01 Avg ES = 0.60 Avg CLES = 73%	Harmonic p = 0.005 Avg ES = 0.78 Avg CLES = 76%	Harmonic p = 0.73 Avg ES = 0.18
Overall change in durability (combined magnitude of drifts, onset of drifts, and strain)	Harmonic p = 0.03 Avg ES = 0.49 Avg CLES = 68%	Harmonic p = 0.01 Avg ES = 0.62 Avg CLES = 70%	Harmonic p = 0.42 Avg ES = 0.13

LIT Low intensity training group; *HIT* High intensity training group; *ES* Effect size; *CLES* Common language effect size.

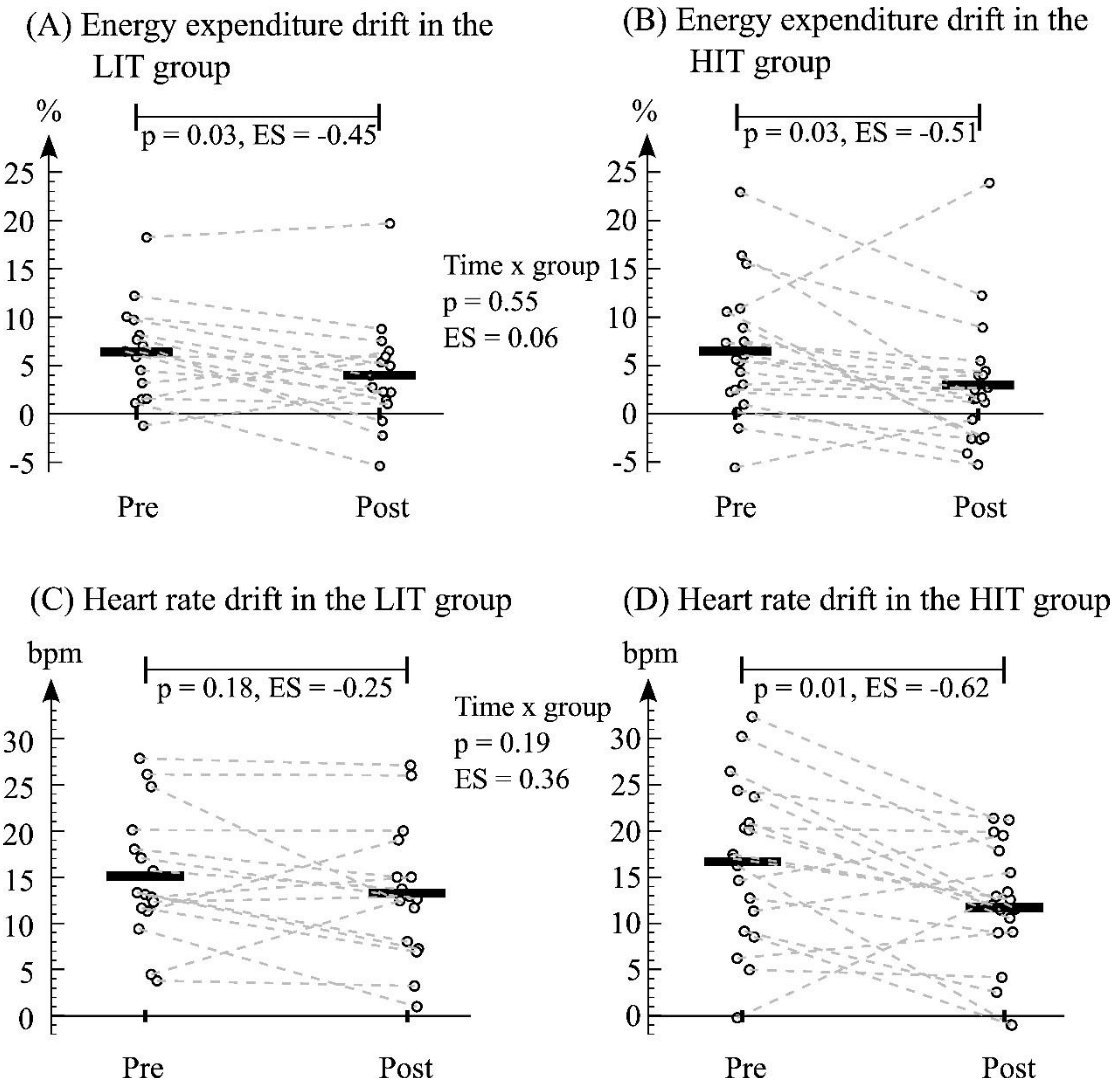


FIGURE 10. Energy expenditure drifts in the (A) LIT group, and (B) HIT group. Heart rate drifts in the (C) LIT group, and (D) HIT group. Time and time x group p value and ES are reported. In the figures, the mean values are represented by the black thick lines and individual values by circles. *LIT* Low intensity training group; *HIT* High intensity training group; *ES* Effect size; *p* p-value.

5.3 Low and high intensity performance (study III)

The LIT intervention enhanced pooled low intensity performance (TABLE 7), while the HIT intervention pooled high intensity performance (TABLE 8). There were no time x group differences in the low intensity performance (p = 0.62, ES = 0.19), but there were in the high intensity performance (p = 0.02, ES = 0.46). Specifically, VO_{2max} was increased only in the HIT but not in the LIT group.

TABLE 7. Mean (95% confidence interval) changes in low intensity performance.

	LIT (n = 16)	HIT (n = 19)	Time x group difference
Power (W) at LT$_1$. Pre value and change.	**Pre: 98 (84–112)** **Δ: +16 (8–25)** (n = 15)	**Pre: 96 (83–109)** **Δ: 15 (5–25)**	
	p < 0.001 ES = 0.60	p = 0.005 ES = 0.49	p = 0.93 ES = 0.11
VO$_2$ (%VO$_{2max}$) at LT$_1$. Pre value and change.	**Pre: 54.8 (51.7–57.8)** **Δ: +3.4 (0.2–6.5)** (n = 14)	**Pre: 55.9 (54.0–57.8)** **Δ: -0.1 (-2.8–2.6)**	
	p = 0.04 ES = 0.57	p = 0.93 ES =-0.02	p = 0.09 ES = 0.60
fat oxidation (mg/min) at low intensity exercise. Pre value and change	**Pre: 155 (127–184)** **Δ: +31 (-5–67)**	**Pre: 168 (119–217)** **Δ: +6 (-40–52)**	
	p = 0.06 ES = 0.42	p = 0.36 ES = 0.06	p = 0.86 ES = 0.36
ΔHRV recovery (pooled change in LnRMSSD and Ln Total power)	(n = 8) Pooled p = 0.27 Pooled ES = 0.26	(n = 14) Pooled p = 0.28 Pooled ES = 0.32	Pooled p = 0.87 Pooled ES = -0.06
ΔDurability	p = 0.03 ES = 0.49	p = 0.01 ES = 0.62	p = 0.42 ES = 0.13
Pooled change in low intensity performance	Pooled p = 0.01 Pooled ES = 0.49	Pooled p = 0.13 Pooled ES = 0.28	Pooled p = 0.62 Pooled ES = 0.19

LIT Low intensity training group; *HIT* High intensity training group; *ES* Effect size; *LT$_1$* First lactate threshold; *VO$_{2max}$* Maximal oxygen uptake; *HRV* Heart rate variability; *LnRMSSD* natural logarithm of the root mean square of successive differences of R-R intervals.

TABLE 8. Mean (95% confidence interval) changes in high intensity performance.

	LIT (n = 14)	HIT (n = 19)	Time x group difference
Power (W) at LT_2. Pre value and change.	**Pre: 162 (141–184)** **Δ: +6 (-1–13)**	**Pre: 158 (139–176)** **Δ: +21 (15–27)**	
	p = 0.14 ES = 0.14	$p < 0.001$ ES = 0.51	p = 0.007 ES = 0.37
VO_2 ($\%VO_{2max}$) at LT_2. Pre value and change.	**Pre: 77.6 (74.2–81.0)** **Δ: +0.1 (-3.4–3.6)**	**Pre: 79.1 (76.4–81.7)** **Δ: -0.2 (-2.9–2.6)**	
	p = 0.95 ES = 0.03	p = 0.90 ES = -0.03	p = 0.97 ES = -0.06
VO_{2max} (l/min). Pre value and change.	**Pre: 2.90 (2.58–3.23)** **Δ: +0.02 (-0.11–0.16)**	**Pre: 2.76 (2.52–3.01)** **Δ: +0.32 (0.22–0.42)**	
	p = 0.71 ES = 0.04	$p < 0.001$ ES = 1.55	$p < 0.001$ ES = 1.51
Pmax (W). Pre value and change	**Pre: 217 (192–241)** **Δ: +11 (3–19)**	**Pre: 212 (190–234)** **Δ: +27 (21–33)**	
	p = 0.008 ES = 0.23	$p < 0.001$ ES = 0.55	$p < 0.001$ ES = 0.32
Maximal stroke volume (ml). Pre value and change.	**Pre: 126 (111–141)** **Δ: -6 (-25–13)**	**Pre: 127 (105–149)** **Δ: +8 (-3 – 20)**	
	p = 0.50 ES = -0.22	p = 0.13 ES = 0.20	p = 0.14 ES = 0.42
15s sprint (W). Pre value and change.	**Pre: 650 (570–729)** **Δ: -3 (-13 – 7)**	**Pre: 635 (562–707)** **Δ: +21 (10–32)**	
	p = 0.57 ES = -0.02	$p < 0.001$ ES = 0.13	p = 0.003 ES = 0.14
Pooled change in high intensity performance	Pooled p = 0.34 Pooled ES = 0.05	Pooled p = 0.007 Pooled ES = 0.48	Pooled p = 0.02 Pooled ES = 0.46

LIT Low intensity training group; *HIT* High intensity training group; *ES* Effect size; *LT_2* Second lactate threshold; VO_{2max} Maximal oxygen uptake; *P_{max}* Maximal aerobic power.

5.4 Exercise enjoyment (study II)

Exercise enjoyment of the first week did not predict improvement of P_{max} (n = 32, $\beta = 0.02$, p = 0.93), nor the total training dose (n = 37, $\beta = -0.07$, p = 0.53) during the training intervention. Further, the change in exercise enjoyment was not associated with the change in P_{max} (n = 37, $\beta = 0.02$, p = 0.94), nor the change in weekly RPE (n = 37, $\beta = -0.27$, p = 0.26). The decrease in exercise enjoyment did not differ (p = 0.98) between the LIT and HIT groups during the intervention (TABLE 9).

TABLE 9. Mean (SD) exercise enjoyment development.

	Exercise enjoyment at week 1	Exercise enjoyment at week 10	Change	Time difference
LIT (n = 18)	90.4 (13.1)	83.5 (13.4)	-6.9 (12)	$p = 0.03$ ES = 0.51
HIT (n = 19)	97.6 (11.4)	90.6 (14.3)	-7.0 (14.0)	$p = 0.04$ ES = 0.53
Group difference	$p = 0.08$	$p = 0.13$	Time x group difference: $p = 0.98$ $\eta_p^2 = 0.00$	

LIT Low intensity training group; *HIT* High intensity training group.

5.5 Training dose balance (study IV)

The training dose (sum of the times in the three training zones multiplied by weighing factor of the zones) in the LIT group was greater than in the HIT group: 87.7 (13.5) vs. 55.0 (7.6) arbitrary units ($p < 0.001$, ES = 3.0), when using the predetermined coefficients. Using power zones, training doses of the LIT and HIT groups would coincide, when LIT, MIT, and HIT power zones would be assigned with weights 1, 8, and 15, respectively. Further, the training dose would be balanced in terms of HR if the weights for the LIT, MIT, and HIT HRzones were set at 1, 7.5, and 14, respectively.

6 DISCUSSION

This thesis examined the effects of a 10-week training intervention involving a very high volume (progressed from 4.8 to 10.3 ± 1.8 hours in week 10) at a very low intensity (36% P_{max} or 63% HR_{max} or 47% VO_{2max}) or high-intensity training (long intervals at 86% P_{max} or 117% LT_2 power). The main finding was that even a substantial overall volume and prolonged individual exercise sessions cannot fully substitute for the lack of intensity, even in untrained participants. LIT improved durability and low intensity performance, but did not enhance high intensity performance. On the other hand, HIT improved both low and high intensity performance at least as well as LIT. Consequently, a large training dose alone is not sufficient for comprehensive endurance performance development if it does not include high enough intensity. Furthermore, it was observed that exercise enjoyment was a distinct factor from perceived exertion and maximal aerobic power as enjoyment was not related to weekly perceived exertion and it did not predict change in aerobic power.

6.1 Durability

Durability increased equally in both the LIT and HIT groups. As VO_{2max} was not improved after LIT, it can be suggested that durability is not solely associated with VO_{2max}, a fact that is supported by literature (Jones, 2023).

6.1.1 Trainability of durability

In earlier studies, the VO_2 drift was reduced by endurance training alone or concurrent endurance and strength training by 2–4 percentage point (Carter et al., 2001; Coggan et al., 1993; Rønnestad et al., 2011), which is equal to a 3 percentage point decrease in the EE drift observed in this thesis study.

The present study found no significant difference in sprint performance between fatigued and fresh conditions. This suggests that neuromuscular fatigue may not be a relevant factor in the present study. Therefore, the reasons behind reduced drifts and their onset are speculated to be primarily physiological, rather than dependent on the fatigue of the neuromuscular system.

EE (or VO_2) drift occurs when glycogen stores in the slow-twitch muscle fibers of agonist muscles are depleted, requiring the body to engage less efficient co-agonist muscles and fast-twitch muscle fibers to sustain a constant power output [175]. Also elevated O_2 cost of fatigued muscle (Hopker et al., 2017; Vanhatalo et al., 2011) increases the EE drift and body temperature regulation (Kyröläinen et al., 2000). Body temperature combined with increased sympathetic activation (estimated by left ventricular ejection time in this study) are reported factors for HR drift (Coyle & González-Alonso, 2001). Consequently, the HR drift would largely occur because of increased physiological loading, and the stroke volume drift would be associated with that of HR. Furthermore, RPE is a general marker of perceived exertion, and its reduced drift would indicate an overall less taxing exercise. The body temperature drift is also associated with the ventilation drift (Kyröläinen et al., 2000), and increased ventilation may be another reason for increased energy expenditure.

All the measured drift variables are part of a comprehensive network, which is why they were also collectively reported as pooled variables. The pooled reduction in drifts, delayed in their onset, and reduction in physiological strain would indicate an overall improvement in the whole network's resistance to fatigue.

The intensity of the prolonged test in this study was initially below the first lactate threshold. However, there is a suggestion that the intensity of the first lactate threshold already decreases after 2 h of low intensity exercise, even for moderately trained athletes (Stevenson et al., 2022). Hence, in the present study the intensity of the participants may have slipped above the first lactate threshold during the prolonged test. This suggestion is supported by the fact that blood lactate concentration increased approximately 0.5 mmol/l during the durability test in both groups. Therefore, the detected slower drifts at the trained state may be partially explained by the improved LT_1 power: higher LT_1 power enables participants to cycle longer during the prolonged test in the LIT zone before LT_1 decreases below cycled intensity, forcing the participants to enter the MIT zone, where the drifts are more pronounced.

Lastly, the improvement in durability in the present study was not as clear and large as anticipated. Compared to VO_{2max}, which improved by an effect size of 1.5 in the HIT group, durability improved only by an effect size of ~0.5, even though the participants were untrained and followed a demanding training intervention. As a result, it may be stated that durability seems to be a factor that develops rather slowly, even among untrained individuals, at least when compared to maximum time trial performance (Rosenblat et al., 2021) or VO_{2max} (Wen et al., 2019). However, the testing power might have influenced the magnitude of change. Stronger drifts would be expected at higher intensity, such as in the MIT zone. Therefore, the training effect on them could have been more significant if the durability test had been conducted in the MIT zone. It is also possible that pooling the variables simultaneously truncates the effect size, as HIT intervention improved the overall high intensity performance by an effect size of ~0.5, although VO_{2max} was improved at a larger margin (ES ~1.5).

6.1.2 Future directions of durability research

The adaptations to LIT zone training are different among untrained and trained participants (Londeree, 1997; Midgley et al., 2006; Swain & Franklin, 2002). Therefore, more randomized controlled intervention trials on the effects of LIT and HIT on durability are needed for both untrained and athletic participants.

Previous studies have pointed out that aerobic fitness and durability would be associated (Billat et al., 2020; Hirakoba & Asano, 1983; Smyth et al., 2022). However, the present study suggests that VO_{2max} and durability are separate factors that could be improved separately. A similar connection is between time trial ability and VO_{2max}, which are closely related, but can be improved separately (Vollaard et al., 2009). Hence, exploring the connection between VO_{2max} and durability more deeply would be intriguing.

Carefully conducted laboratory studies are needed to deepen the understanding of durability in acute exercise bouts. For example, investigating the link between durability and endocrinal, body temperature, and muscle activity patterns drifts would be of interest.

Durability could be interpreted as the physical stress tolerance. It would be intriguing to study whether this concept extends beyond physical stressors. It is known that low work-related stress is associated with high VO_{2max} (Schilling et al., 2020; Teisala et al., 2014), indicating a link between physical fitness and mental stress tolerance. In general, mental stress reduces endurance performance, acting as a fatiguing stressor, similar to prolonged submaximal exercise (Marcora et al., 2009; Pageaux & Lepers, 2016). Further, endurance training increases mental stress tolerance (Filipas et al., 2020), suggesting that "mental durability" may have a strong physical dimension. Additionally, it might be that the correlation between VO_{2max} and mental stress tolerance is due to training that improves both durability and VO_{2max}. Thus, durability could be the mediating factor between low mental stress and high VO_{2max}. Further research should investigate whether durability would be a better explanatory factor for mental stress tolerance than VO_{2max}.

Metabolic fitness refers to the overall efficiency and health of metabolic processes in the body, including insulin response to an oral glucose tolerance test, fasting lipids, and fasting insulin (Laye et al., 2015). Despite matching participants based on VO_{2max}, active runners exhibited superior metabolic fitness compared to sedentary individuals (Laye et al., 2015). This suggests that VO_{2max} alone may not directly account for differences in metabolic fitness. Therefore, durability could be a candidate for mediating the benefits of training on metabolic fitness. It would be intriguing to hypothesize that durability and metabolic fitness could be interconnected, as both rely on the body's ability to efficiently manage, tolerate, and respond to stress. It would be of interest to study the potential significance of durability to metabolic fitness, if any.

6.2 Specificity of training

No group difference in low intensity performance (absolute and relative LT_1, durability, fat oxidation at low intensity exercise, and short term HRV recovery from durability test), while only HIT enhanced pooled high intensity performance (absolute and relative LT_2, maximal stroke volume, VO_{2max}, P_{max}, and sprint).

6.2.1 Pooled low intensity performance

Typically, both LIT and HIT have been shown to improve the low intensity performance in untrained participants; the first lactate threshold (Helgerud et al., 2007; O'Leary et al., 2017), shift from glycogen to lipid utilization during a submaximal exercise (Atakan et al., 2022; Conley et al., 2001; Holloszy & Coyle, 1984), and durability (Coggan et al., 1993; Phillips et al., 1996). These are, apart from durability, usually explained by peripheral factors, such as general oxidative capacity of a muscle, aerobic enzyme activity, fiber type, capillary density, and mitochondrial density (Burgomaster et al., 2005; Conley et al., 2001; Holloszy & Coyle, 1984; Ivy et al., 1980). In the present study, there were no group difference in the adaptations to low intensity performance.

In the present study, HRV recovery was not improved. HRV recovery after maximal effort, such as sprints in the present study, is typically uninfluenced by training interventions (Cornelissen et al., 2010; Martinmäki & Rusko, 2008). This can be explained by the fact that post exercise HRV is an indicator of exercise intensity, and maximal effort is always maximal. Hence, the short-term recovery would be unaffected by a few weeks of training. In contrast, HRV recovery from a submaximal exercise has been improved following endurance training by improving parasympathetic reactivation (Buchheit et al., 2008; Cipryan, 2018; D'Agosto et al., 2014; Seiler et al., 2007).

It has been suggested that training at an intensity close to that which maximizes fat oxidation would further enhance maximal fat oxidation (Jeukendrup & Achten, 2001). Although the graded test in the present study was not conducted in a fasted state, it can still provide an estimate of the intensity at which maximal fat oxidation occurs. The average non-zero training intensity of the LIT group was 12 ± 21 W higher than the intensity that maximized fat utilization in VO_{2max} test. This means that the LIT group trained close to the power that maximizes their fat oxidation. As a result, it was expected that the LIT group should experience an increase in fat oxidation capacity, which was the case.

6.2.2 Pooled high intensity performance

It was surprising that the training in this study did not result in improvements in high intensity performance in the LIT group. In the untrained population, both HIT and LIT resulted in improved VO_{2max} and P_{max} (Milanović et al., 2015), maximal stroke volume (Arbab-Zadeh et al., 2014), LT_2 (Londeree, 1997) and sprint performance (Foster et al., 2015). Especially when comparing studies with similar training intensities to the present one, untrained participants training weekly four hours at 48% VO_{2max} intensity (Ocel et al., 2003) or two hours per week at 65-70%HR_{max} (Poon et al., 2022), have shown similar increases in VO_{2max} as those undergoing high intensity training.

High intensity performance factors, such as maximal stroke volume, VO_{2max}, P_{max} and absolute LT_2, are highly associated with central factors, particularly maximal cardiac output (Bonne et al., 2014). This is primarily attributed to the expansion of blood volume, since structural and functional changes within the myocardium may require more time than just a few weeks (Arbab-Zadeh et al., 2014; Bonne et al., 2014; Montero et al., 2015). Endurance training has also resulted in improved sprinting performance in untrained participants, possibly due to increased muscle mass and strength (Farup et al., 2012), enhanced economy of movement (Barnes & Kilding, 2015; González-Mohíno et al., 2020), or improved buffering capacity of a muscle (Edge et al., 2006). However, it is unlikely because of improved glycolytic enzyme, as it is only minimally affected after a HIT intervention (Kubukeli et al., 2002).

Although both thresholds are associated with the peripheral factors, only HIT intervention improved the second lactate threshold. A similar effect, with HIT emphasizing LT_2 development over LIT, has been reported also previously (O'Leary et al., 2017). The differing responses between the HIT and LIT groups may be due to their different patterns of muscle fiber activation. LT_2 marks the intensity where nearly all fast twitch fibers are recruited (Gollnick et al., 1974). Although extended LIT sessions can also activate fast twitch fibers (Gollnick et al., 1974), the LIT group likely targeted slow-twitch fibers predominantly, while the HIT group activated a wider range of muscle fibers in each session.

As the LIT group did not improve pooled high intensity performance, it is reasonable to speculate that the low intensity training in this study may not have been adequate to induce a significant increase in central factors. It was also not adequate to enhance muscle strength or economy of movement to improve sprint performance. Relatively moderate stimulus from low intensity exercise could be counterbalanced by extending the duration of the exercise (Hofmann & Tschakert, 2017; Kraus et al., 2002; Sisson et al., 2009). However, this was not the case in the present study, and the reason may be that the training in the LIT group did not reach a critical threshold above which high intensity performance is developed. Another possible reason is that the training of the LIT group was too taxing. Evidence suggests that an excessively high training dose can negatively impact P_{max} (Jeukendrup et al., 1992). While overtraining studies typically involve high-intensity training, it should be considered whether the ~10 weekly hours of LIT in the final weeks of my study might have been excessive for untrained individuals. However, this is unlikely, as wRPE was only moderate in the LIT group and lower compared to the HIT group, even in the final week. It would indicate that the participants in the LIT group did not find the training overly demanding.

One reason for the lack of improvement in LIT group might be that the training of the LIT group was outdoors. In outdoor conditions, the thermal stress is lower, and consequently the maximal aerobic power and threshold powers are typically 4–8% higher compared to indoors power (Lipski et al., 2022). Because of this, the actual training intensity in the LIT group might have been even lower than the estimated 36% P_{max}. Further, outdoor power production fluctuates continuously, lacking the consistent "steady effort" found indoors (Jeffries et al., 2019). Such fluctuations could lead to different adaptations in outdoor cycling compared to indoor cycling at the same mean power output.

Finally, in the LIT group, it would be anticipated that below 50% VO_{2max}, training would not lead to a further increase in VO_{2max}. The baseline VO_{2max} was slightly greater than 40 ml/kg/min for males, which is considered a threshold indicating that training below 50% VO_{2max} would not lead to VO_{2max} development (Swain & Franklin, 2002).

6.2.3 Minimum intensity for endurance adaptations

Adequate intensity is a crucial factor for endurance adaptations. My study supports the idea proposed by Swain & Franklin (Swain & Franklin, 2002) that untrained but physically active individuals appear to require a minimum intensity threshold (~50% VO_{2max}), below which the exercise stimulus is not sufficient to improve VO_{2max}, sprint performance, or overall high intensity performance. Even the substantial volume applied in this study was not sufficient to induce an adequate stimulus, although exercise duration generally has significant effects on training dose and acute responses. Hence, high intensity is required for overall development of high intensity performance. This conclusion is consistent also with detraining studies, in which reduced training strategies limit the loss of endurance performance, as long as training intensity is maintained (Mujika & Padilla, 2000).

However, it seems that the required minimum intensity to elicit a sufficient stimulus depends on the specific system under consideration; The low intensity used in this study resulted in positive adaptations to low intensity performance, primarily related to peripheral factors, although it was inadequate to enhance high intensity performance. Hence, the minimum intensity for positive adaptations to low intensity performance was lower than the minimum intensity for high intensity performance adaptations (FIGURE 11).

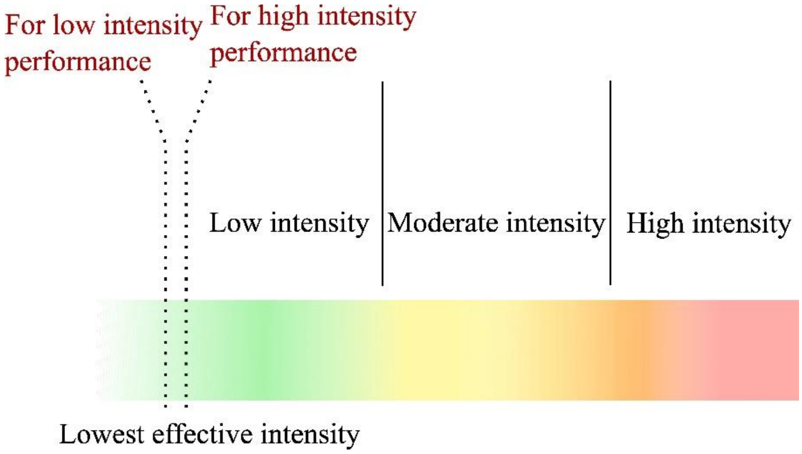


FIGURE 11. A schematic figure showing how the lowest effective intensity might depend on the desired variable to improve.

6.2.4 Training volume in the low intensity training group

The present study included prolonged exercise sessions for the LIT group with a high total volume. There were on average 6 sessions of at least 3 h of training, mostly performed in the last three intervention weeks. Although mean volume was 6.5 weekly hours, because of the heavy progression, the last three weeks had an average weekly volume of 9.6 ±1.6 h. There are not many studies using prolonged exercises in untrained participants. For instance, in a meta-analysis (Milanović et al., 2015), only two out of 21 studies contained 2 h long sessions and none had average weekly volume over 5 h.

In the study of Schantz et al. (Schantz et al., 1983), trained participants skied 6 h daily at 45% of VO_{2max} for 8 weeks. This resulted in peripheral changes in the muscle: increased citrate synthase and malate dehydrogenase enzyme activity, as well as increased capillary density. However, no improvement in VO_{2max} was detected. Similar results have been seen in studies examining expeditions to the Arctic areas, where untrained participants skied 6 h daily for 42 days (Boushel et al., 2014). Thus, these results are in line with the current study: low intensity performance improved without simultaneous improvement in high intensity performance due to high volume LIT with prolonged exercise sessions.

6.2.5 Future directions of specificity of training

The potential effect of prolonged LIT interventions on fat oxidation capacity, mitochondrial mass, and other typical endurance training adaptations are surprisingly scarce. Increasing the duration of the LIT exercise significantly alters the nature of an exercise session. Specifically, beyond 2 hours, there is a shift in the source of fat utilization, from intramuscular triacylglycerides to plasma-derived free fatty acids and glycerol (Watt et al., 2002). The fast-twitch muscle fibers are increasingly recruited as the glycogen stores in the slow-twitch fibers become depleted (Gollnick et al., 1974), and plasma catecholamine concentration is continuously increasing (Galbo et al., 1976; Zouhal et al., 2008). Therefore, more comparative studies investigating the effects of training interventions with sessions lasting over 2 hours are needed to reveal the chronic influence of prolonged exercise.

6.3 Training dose

Although the training scheduling table was equalized by training dose calculation presented in [50], the realization of training dose of the LIT group was much larger than that of the HIT group ($p < 0.001$, $g = 3.0$). However, the true equalization was done via perceived exertion of the week. All in all, participants in the LIT group felt training was easier, thus the weekly RPE based individualized progression was faster for them than for participants in the HIT group.

6.3.1 Training dose and endurance adaptations

Although the calculated training dose in the LIT group was substantially greater than that of the HIT group, the endurance adaptations observed in the LIT group were not greater than those in the HIT group. This implies that simply increasing the (calculated) training dose does not guarantee endurance adaptations, although there are models predicting endurance performance from training dose (Mitchell et al., 2020). Therefore, when assessing the dose-response relationship, intensity plays a crucial role, making it challenging to directly compare training doses of different intensities.

This contrasts with the findings from cross-sectional studies (Doherty et al., 2020) and dose-response studies (Busso, 2003), where higher training doses consistently induce greater maximal performance. However, this apparent discrepancy can be explained by the low intensity used in the present study. Higher training doses may lead to greater performance adaptations when comparing individuals' training with similar intensity distribution, or when the training intensity exceeds the threshold of a certain required minimal intensity.

Another factor to consider is that the quantification of very low-intensity training may have been inaccurate. This would mean that the actual training dose for the LIT group could have been lower than that of the HIT group, but our calculation methods are insufficient to determine this. If this would be the case, it might be that doubling or tripling the training volume of the LIT group might be necessary to achieve comparable training adaptations to those of the HIT group.

6.3.2 Balancing low and high intensity training doses

In the present study, the training intervention for the LIT and HIT groups (Supplement TABLE 11 and 12) were initially balanced using the training dose metric presented in (Cejuela-Anta & Esteve-Lanao, 2011), which gives the ratio

1:7.5 for a balanced HIT:LIT ratio. However, when the training dose was further adjusted based on weekly RPE, the ratio was doubled to 1:14–15.

This highlights the fact that calculated training doses vary greatly, depending on the system they measure. When energetically balanced, the ratio of durations of the HIT and LIT exercises can be calculated to be approximately 1:2; acute session RPE method would be ~1:4 (Hydren & Cohen, 2015); lactate curve-based metrics, would be 1:5 (Manzi et al., 2009); and finally impairment of performance and EPOC would suggest 1:9–11 (Fullerton et al., 2021; Larsen et al., 2014). However, these typical methods are based on acute responses to a single exercise bout. In the present study, weekly RPE suggests that a chronic perception method would offer a higher ratio than traditional balancing methods based solely on acute responses.

Further studies investigating how training dose metrics could be based on chronic responses would be beneficial. The weekly RPE method from the present study could attempt to be refined, for example, by including larger progression possibilities, and eliminating references to acute exercise doses. Additionally, recovery questionnaires could be a suitable base for a chronic training dose method.

6.4 Exercise enjoyment is a separate component of training

As humans are a psychophysical entity, it is reasonable to comprehensively elucidate the connections between psychology and physiology. In the present study, it was concluded that exercise enjoyment from the first week did not predict improvement in P_{max} and it was not related to weekly RPE. In other words, exercise enjoyment could not be used to predict who will be high and low responders to high and low intensity training.

6.4.1 Exercise enjoyment not predicting aerobic capacity improvement

The conclusion of this study, that P_{max} improvement cannot be predict by enjoyment alone, is supported by scarce literature. Exercise enjoyment did not predict the change in walking performance in a general weight loss intervention study (Berger et al., 2023). In the case of aerial and terrestrial runners, aerial runners had reported more positive feelings toward higher intensity training (Lussiana & Gindre, 2016). However, the more positive feelings toward more powerful training were not associated to a more beneficial explosive strength training compared to maximal strength training when done in addition to an endurance training (Patoz et al., 2021). P_{max} was chosen as a predictive variable over VO_{2max}, as it better quantifies the participants' performance capacity.

Some individuals prefer and enjoy higher intensity exercise and tolerate it better than others (Ekkekakis et al., 2005a). It would have been anticipated that individual progression would have allowed individuals with high tolerability and enjoyment to progress faster and gain greater improvement in P_{max} in a dose-response manner (Doherty et al., 2020). However, this did not occur in the present study. It may be that the sample size was too small to include enough high and low responders. This could lead to a too homogenous sample for final conclusions. Alternatively, the process of aerobic fitness adaptation may be too complex to be predicted solely by enjoyment or tolerance, even if they may play a role.

Not everyone experiences enjoyment from exercise (Aaltonen et al., 2014). In this perspective question of predicting fitness change based on exercise enjoyment might be narrow and would indicate that these people would not benefit from training.

Participants might also attribute factors other than those related to exercise to the exercise enjoyment scale measured in the present study. For example, anticipation might have an impact. It is known that a training intervention, coupled with an anticipation of improved psychological well-being, can lead to a more positive self-esteem change than from a training intervention alone (Desharnais et al., 1993). In the present study, during the first week, exercise enjoyment could be influenced by the anticipations of the upcoming intervention as well as the knowledge of being part of a research study. Likewise, in the final week, experiences from the completed nine weeks of the intervention, as well as the anticipation of its conclusion, might affect the measured exercise enjoyment scale.

6.4.2 Exercise enjoyment not linked to weekly RPE

While exercise enjoyment has been shown to predict physical activity (Ramer et al., 2021; Williams et al., 2006) and is correlated with exercise motivation (Klompstra et al., 2022), it did not correlate with the participants' overall weekly RPE in the present study. Acutely, this phenomenon has been observed in numerous studies, where participants reported greater exercise enjoyment after HIT sessions compared to LIT, even though the HIT sessions were perceived as more exerting (Malik et al., 2017; Oliveira et al., 2018). Interestingly, findings of this study suggest that this pattern is also applicable when considering the chronic context.

6.4.3 Future directions of enjoyment and endurance training

As was seen in Figure 6A, exercise enjoyment measured *after* the exercise differs considerably from the measured exercise pleasure felt *during* the exercise (Ekkekakis et al., 2000, 2005b). It is possible that exercise enjoyment is not the right indicator, and pleasure during the exercise might be better for defining individuals who find exercise likeable. Therefore, it might be of interest to study whether pleasure could be used to predict the training adaptations.

It would be a naïve starting point to assume that either LIT or HIT alone would the most suitable to someone to improve VO_{2max}. As has been highlighted in periodization intervention studies, programs which combine both LIT and HIT are usually superior to isolated LIT, MIT or HIT programs (Stöggl & Sperlich, 2014). Thus, it seems that the most important factor in individualization is not whether one should perform LIT or HIT, but *when* one should perform LIT or HIT. It could be of interest to study whether anticipated enjoyment or pleasure of an upcoming exercise session could be used to as part of a timing method for HIT exercises to guide endurance training, similarly to HRV (Kiviniemi et al., 2007; Nuuttila et al., 2017; Vesterinen et al., 2016) or sum of HRV, perceived recovery, and heart rate running speed index (Nuuttila et al., 2022).

Another subject for future research could be the self-selected training doses. In the present study, exercise enjoyment did not appear to influence training progression. However, it may be interesting to investigate, especially with more refined research questions, whether pleasure could have an effect on self-selected training progression.

6.5 The meaning of excess volume in low intensity training

As was the case also in the present study, low and high intensity endurance training interventions are often compared against each other. In reality, for untrained individuals, both interventions have similar endurance adaptations, although HIT often appears slightly more advantageous (Liu et al., 2022; Milanović et al., 2015; Ramos et al., 2015). Furthermore, among athletes, often studies which include severe high intense training have led to increased VO_{2max} (Midgley & McNaughton, 2006).

On the other hand, based on observational studies, athletes do not maximize the amount of HIT, but rather the amount of LIT (Haugen et al., 2022). If we assume that sports training has evolved through evolutionary processes towards optimal training programming, it raises a question of what the independent purpose of LIT training is when considering optimal endurance training. Below is a collection of hypotheses for the meaning of LIT for programming endurance training. Following these, the results of this study are presented in this context.

6.5.1 Hypothesis 1: low intensity training develops performance without cumulating stress

The role of LIT might be to enhance the development or maintenance of endurance performance, while allowing for recovery from the HIT sessions. Recovery from HIT sessions might takes two days (Stanley et al., 2013), limiting individuals to 2–3 weekly HIT sessions. This allows for 4–5 days a week to be allocated to LIT, as the recovery from a typical LIT session occurs in less than 24 hours (Stanley et al., 2013), sometimes even within hours (Seiler et al., 2007).

6.5.2 Hypothesis 2: Low intensity training is an alternative method for adaptations

LIT might introduce variability into the training, and variability is one of the foundations of functional endurance periodization (Kiely, 2012). At a muscle level, some endurance adaptations, for example mitochondrial biogenesis, are thought to be provoked through PGC-1α (Hoppeler, 2016). The endurance adaptations following LIT or HIT are quite similar, but are initiated through different pathways. Typically HIT activates metabolic pathways, while LIT affects fatty acid and Ca^{2+} -routes (Hoppeler, 2016).

6.5.3 Hypothesis 3: Low intensity training enables structural remodeling

In training interventions, the typical monitoring time is less than four months. However, cross-sectional studies have revealed that more than five years of active training induces greater adaptations compared to shorter durations of less than two years (Buzza, 2018). It might be that the extensive volume of low-intensity training is the factor that allows the following structural remodeling processes to occur over the course of several years: changes in the structure of the heart (Abergel et al., 2004) and enlarging of pericardium (Esch et al., 2007), angiogenesis (Hoppeler, 2016), muscle fiber transformation toward more economical and durable slow twitch fibers (Schiaffino & Reggiani, 2011), and increased mitochondrial mass (Bishop et al., 2014).

6.5.4 Hypothesis 4: Low intensity training affects something which has not been examined extensively

Durability is a newly reinvented term meaning fatigue resistance during prolonged effort (Maunder et al., 2021). Recovery is another surprisingly overlooked variable. It is known that well-trained athletes recover faster than recreationally active individuals (D'Agosto et al., 2014; Seiler et al., 2007). However, it is unclear which type of training optimally affects durability or recovery ability. LIT could be a potential candidate for this.

6.5.5 Hypothesis 5: Low and high intensity training have different emphases

Meta-analyses on variables related to low intensity performance have not been extensively conducted. It is known that running economy can be improved slightly more with LIT rather than HIT (González-Mohíno et al., 2020), and the opposite could be true with fat oxidation capacity (Atakan et al., 2022). It is possible that LIT may specifically affect certain low intensity performance variables.

6.5.6 Hypothesis 6: Low intensity training is needed psychologically

LIT might offer a sense of relief between HIT exercises. Acutely, LIT exercises improve mood better than HIT (Niven et al., 2020) while a LIT intervention decrease mental fatigue (Faude et al., 2009; Suzuki et al., 2004). However, the relationship between training distress and training intensity is not entirely clear. HIT interventions can increase distress (Halson et al., 2002), while some athletes experience reduced distress when their training periods include an appropriate amount of HIT (Milanez et al., 2014; Ouerghi et al., 2016).

6.5.7 Hypothesis 7: Low intensity training strengthens the high intensity training adaptations

Physical activity, in the form of LIT in endurance training, might help individuals "not to resist" exercise adaptations (Burton et al., 2021). It might be that physical activity, in the form of LIT and other low intensity activity, strengthen the effects of HIT (Hautala et al., 2012; Swift et al., 2021), although physical activity itself might not be sufficient to increase VO_{2max}.

6.5.8 Hypothesis 8: Low intensity training is futile

It is possible that the most effective endurance training interventions may not require LIT sessions. For example, the study conducted by Hickson et al. (Hickson et al., 1977), showed that six weekly HIT sessions led to a linear increase in VO_{2max} over 10 weeks. It may be that athletes tend to stick with what they have learned and they might be hesitant to abandon LIT, as they believe they need it.

6.5.9 Hypotheses for low intensity training: Reflections from this study

The results of this study support the notion that LIT can develop endurance performance with different emphases than HIT (Hypothesis 5). It was found that LIT specifically improved low intensity performance, while HIT improves both low and high intensity performance.

Moreover, the present study supports Hypotheses 1, 2, and 4 to some extent. LIT improved durability (Hypothesis 4) in a similar manner to HIT, but without a simultaneous increase in VO_{2max}. This means that the reasons for durability improvement may have been different for LIT and HIT (Hypothesis 2). Further, the weekly RPE was lower in the LIT group compared to the HIT group. From this, it can be concluded that while LIT may be time consuming, it did not accumulate physical stress to the same extent as HIT (Hypothesis 1). Even when the individualized progression aimed to reduce the difference in wRPE between the groups, this disparity persisted. Lastly, it should be noted that the present study cannot definitively dismiss the last option (Hypothesis 8), which suggests that LIT is futile. It should, however, be considered that the participants of the present study were untrained, so conclusions concerning trained people should be made with caution.

6.6 Practical recommendations

In the present study untrained participants cycled weekly either ~7 h at low intensity, or ~1.5 h at high intensity. The intensity of LIT was very low (63% HR_{max}), and it could be comparable with walking. On the other hand, intensity of HIT was high, and for some participants exercises were almost maximum performances, based on both weekly and session RPE. Hence, if we consider the perception of intensity, LIT and HIT were on opposite ends of the spectrum. On average, HIT was more effective, as it produced at least the same adaptations as LIT. At the same time, HIT was not less enjoyable than LIT. Thus, a straightforward recommendation would be to favor 1.5 weekly hours of HIT over ~7 h of LIT.

However, it might be that neither of the presented training interventions is practical for untrained individuals. In the LIT group, the time commitment was substantial and it did not even lead to an overall increase in high intensity performance. On the other hand, in the HIT group, the high intensity exercises might have been excessively long for beginners. Indeed, just 12 minutes of high-intensity exercise per week has been sufficient for improvements at a similar intensity to that used in this thesis (Tjønna et al., 2013). Therefore, the minimum of 15 minutes of high intensity time per session, at least twice a week, in my study might be an excessively high volume. Especially for untrained people, who tend to avoid HIT during free living condition (Ekkekakis et al., 2023).

The recommendations for untrained individuals from my thesis are thus more conceptual. First, it seems that too low intensity endurance training is not sufficient for overall endurance performance adaptations, even when the training volume is very high. Therefore, it would be beneficial to include higher intensity activities than 63% HR_{max} in the weekly routine.

Second, although LIT in the present study appeared less effective than HIT, it still had positive effects on some of the measured performance variables. Thus overall, it could be considered that even very low intensity endurance training, while not optimal, is still beneficial and better than nothing.

Third, it seems that exercise enjoyment cannot be used to predict aerobic capacity adaptation. Thus, whether an exercise feels “terrible” or “enjoyable” is not an indicator of its effectiveness.

6.7 Limitations and strengths

6.7.1 Limitations

The sample size was calculated based only on the primary variable of the EE drift. This meant that sample size may have been inadequate in studies II–III. Also, there were no control group, which could have helped to clarify the development of measured outcomes. There were further reductions in the sample size, particularly for HRV and cardiac impedance analyses, due to missing data (data quality issues). By utilizing the multiple imputation method, some of the reduction in sample size was salvaged.

Although many studies have used and measured physiological drifts during submaximal endurance exercise (Carter et al., 2001; Coyle & González-Alonso, 2001; Ekelund, 1967; Mullins et al., 2015; Phillips et al., 1996; Rønnestad et al., 2011; Smyth et al., 2022; Wills et al., 2019), it seems that test-retest reliability measures have not taken into account the magnitude of drifts. Hence, it is not known how sensitive the drifts are to changes in environment and preparation.

Nerve and muscle-level measurements were not used. Therefore, in the present study, direct access to peripheral changes through EMG data or muscle biopsies was not possible.

Diet was not controlled, although it is known that diet could have an impact on potential endurance adaptations, especially fat oxidation (Burke, 2021). However, participants were encouraged to keep the eating habits unaltered and to have adequate amounts of energy to meet the potentially increased energy demands caused by the training. Conducting 3 h of LIT exercise without fasting may have contributed to the fat oxidation results, and nutrient intake during the durability test may have also dampened the magnitude of drifts (Nieman, 1998; Utter et al., 1999). However, the previous meal was standardized, which slightly attenuated the lack of fasting. Further, as fat oxidation represents only one aspect in the pooled inspection of results, its influence alone cannot alter the observed results.

Change in plasma volume during the 3 h durability test was not monitored. However, the body mass was not reduced, indicating that dehydration likely did not occur. Further, the plasma volume reduction in prolonged low intensity exercise at intensity lower than 50% VO_{2max} is typically minimal (Grant et al., 1997). Therefore, it could be assumed that acute plasma volume change during the 3 h test likely had a small effect on the outcomes.

Only enjoyment after the exercise session was measured. As pleasure during the exercise differs from enjoyment measured after the exercise, there is still a possibility that pleasure felt during the exercise could serve as a predictive marker for the increase in aerobic power.

There are sex differences, for example in fat oxidation (Purdom et al., 2018) and in maximal oxygen uptake. Unfortunately, the sample size was not planned to assess possible sex differences in the studied variables. Additionally, menstrual cycle was not controlled, but ingesting carbohydrates during the 3 h test attenuated its effect (Campbell et al., 2001) on that particular test.

6.7.2 Strengths

Some individuals are exhausted after 3 h LIT exercise, while for others, it can be only a midpoint before exhaustion (Black et al., 2017). This individual tolerance to exercise and training dose was considered in this study in a unique way by enabling personalized training progression through an increase in training volume using weekly RPE. Previously mixed LIT and HIT training have been personalized by HRV (Kiviniemi et al., 2007; Nuuttila et al., 2017; Vesterinen et al., 2016) or a mixture of recovery and training status (Nuuttila et al., 2022).

Exercise sessions were monitored weekly, and active feedback was given weekly to the participants of their success to follow the training plan. This had two consequences. First, the active communication between the researcher and participants promoted a high adherence rate, as participants were engaged in intervention. Second, because of active feedback, the training realization was closely matched with the prescription, which is a crucial factor for the success of an intervention study (Mujika, 2013).

Methodologically, the results were not examined through individual variables but as a combination of several pooled variables. By doing so, one acquires a holistic view of the intervention's impact on a single pooled variable. Most often, VO_{2max} has been the single reported fitness number. However, performance includes much more, such as lactate thresholds, economy of movement, and fat utilization. The idea of the present study, that low and high-level performances could be combined into one pooled variable, could be useful for future studies. In this way, one variable would still represent changes in performance, but now in a manner that encompasses a broader spectrum of performance.

The training in the LIT group included prolonged exercise sessions lasting over 3 h. It is rare for untrained individuals to engage in such lengthy sessions. Additionally, achieving a mean weekly training volume of 6.5 hours or above is surprisingly uncommon in training interventions.

7 PRIMARY FINDINGS AND CONCLUSIONS

The intervention in this thesis aimed to reveal differences between very high volume of low intensity training and typical high intensity training. The main findings were:

1) Both low and high intensity training improved durability similarly for untrained participants. As durability was improved after LIT, without simultaneous increase in VO_{2max}, it was concluded that durability and VO_{2max} are at least partly affected by different processes. (Study I)

2) Excess volume of training was not enough to compensate for the lack of intensity, even for untrained participants. High intensity performance was not improved by excess volume of low intensity training. However, as low intensity performance was improved, a conclusion was made that the minimum intensity for endurance performance adaptations is lower for low intensity performance, compared to high intensity performance. Additionally, LIT and HIT may have intensity specific areas of improvement. (Study III)

3) Exercise enjoyment could not predict the individual improvement in maximal aerobic power. This means that it is not recommended to use exercise enjoyment to form individual training programs with the aim to optimize aerobic power improvement. (Study II)

4) A narrative review compared different rationales to balance the doses of low and high intensity exercises. It was shown that depending on method, one HIT minute could be equal to anything from 1.5 to 14+ LIT minutes. This means that 'exercise dose' is an elusive concept and may vary depending on the specific objectives of researchers and practitioners. Those engaged in endurance exercise research or athlete monitoring should carefully consider which exercise dose measurement would best suit their needs. (Study IV)

5) LIT was perceived as easier than HIT, shown by the lower weekly rating of perceived exertion. This supports the idea that one can perform large volumes of LIT within a week without accumulating substantial strain. Further, calculated training dose from LIT may be dramatically greater than the dose of HIT, and still the weekly perceived exertion can be lower. Lastly, a calculated training dose itself without a sufficiently high intensity is not sufficient to ensure high intensity endurance adaptations.

In conclusion, the present study stresses that a holistic view should be taken when comparing low and high intensity training. First, there is not a single unique way to assess whether training was successful. Even when VO_{2max} does not improve, low intensity performance may enhance, and vice versa. Second, exercise enjoyment is not associated with performance improvement, nor is the rating of perceived exertion of exercise. Hence, the psychological dimension of exercise enjoyment seems to be out of the reach, if not particularly measured. Lastly, calculated training dose alone is not a guarantee of endurance performance improvement. Attention should also be paid to how the training dose is achieved.

YHTEENVETO (SUMMARY IN FINNISH)

Kestävyysharjoittelun kuormitus on vahvasti liitoksissa saavutettavien adaptaatioiden kanssa. Kestävyyssuorituskyky paranee, jos harjoittelulla saavutetaan viikkotasolla riittävän suuri kuormitusaste. Kuormitusta voi kasvattaa joko kasvattamalla harjoitteluvolyymia tai -intensiteettiä. Tästä huolimatta tutkimukset keskittyvät paljolti intensiteetin vaikutuksiin, eikä suuren matalatehoisen harjoittelun vaikutuksia olla juuri selvitetty.

Tämän väitöskirjan tarkoitus oli tutkia miten todella suuri matalatehoinen harjoittelumäärä vaikuttaa harjoittelemattomilla ihmisillä verrattuna ”normaaliin” korkeatehoisen intervalliharjoitteluun. Tarkemmin, matalatehoinen ryhmä (PK-ryhmä) pyöräili 10 viikon ajan matalalla peruskestävyysteholla alle ensimmäisen laktaattikynnyksen keskimäärin 6,8 tuntia viikossa intensiteetin ollessa todella matala: 63% maksimisykkeestä eli 47% maksimaalisesta hapenottokyvystä. Määrä kasvoi voimakkaasti ollen viimeisellä kolmella viikolla keskimäärin 9,6 tuntia viikossa. Harjoituksia oli 4–6 kertaa viikossa pituuden vaihdellessa 45–240 minuutin välillä. Vastaavasti korkeatehoinen ryhmä (MK-ryhmä) pyöräili 2–3 kertaa viikossa pitkiä (>3 min) maksimikestävyysintervalleja siten, että yhdessä harjoitussessiossa kumuloitui yhteensä vähintään 15 minuutin verran korkeatehoista aikaa. Korkeatehoisen ryhmän harjoittelutunnit olivat keskimäärin 1,6 tuntia viikossa työpätkien intensiteetin ollessa 117% toisesta laktaattikynnyksestä. Ryhmien harjoittelumäärä lisääntyi yksilöllisesti perustuen heidän kokemaansa viikoittaiseen kuormitustuntemukseen; mitä helpommalta viikko tuntui, sitä enemmän seuraavalle viikolle nostettiin harjoitteluminuutteja.

Ensimmäisessä osatyössä keskityttiin kestävyyssuorituksen väsymisensietoon. Väsymisensiedon mittarina käytettiin yhdistelmää kolmesta seuraavasta tavasta: (1) mitattujen fysiologisten muuttujien kasvu 3 tunnin matalatehoisen polkemisen aikana, intensiteetiltään 48% maksimaalisesta hapenottokyvystä; (2) näiden muuttujien kasvamisvaihe 3 h pyöräilyn aikana; sekä (3) keskimääräiset fysiologiset tasot 3 h suorituksen aikana. Jotta laaja kokonaisvaltainen kuva kehon eri toiminnoista saataisiin, muuttujina kohdissa (1) ja (2) käytettiin energiankulutusta, sykettä, iskutilavuutta, koettua kuormitustuntemusta, ventilaatiota sekä vasemman kammion tyhjentymisaika. Kohdassa (3) käytettiin muuttujina sykettä, sykevälivaihtelua, veren laktaattikonsentraatiota sekä koettua kuormitustuntemusta.

Ensimmäisen osatutkimuksen päätulos oli, että sekä PK- että MK-ryhmän väsymisensieto parani yhtä hyvin.

Toisessa osatutkimuksessa tarkasteltiin harjoittelun yksilöllisyyttä. Tutkimuksissa pyritään löytämään markkereita, joilla voisi ennustaa onko valittu harjoittelutapa yksilöllisesti hyvä vai huono kyseiselle henkilölle. Usein tällaiset ennustemuuttujat ovat fysiologisia, kuten sykevälivaihtelu tai maksimaalinen hapenottokyky. Toisessa osatyössä tutkittiin voiko harjoituksen miellyttävyydestä ennustaa harjoitusjakson harjoitettavuushyötyä. Sitä varten sekä PKettä MK-ryhmäläisiltä kerättiin kyselylomakkeella ensimmäisen ja viimeisen viikon harjoitusten jälkeen harjoitusten miellyttävyys.

Päätuloksena toisessa osatyössä huomattiin, että harjoituksen miellyttävyydellä ei voitu ennustaa aerobisen tehon kasvua harjoitusjakson aikana. Lisäksi miellyttävyys ei ollut yhteydessä siihen kuinka kuormittavaksi tutkittavat arvioivat harjoitteluviikot.

Kolmannessa osatyössä jaoteltiin kestävyyssuorituksen osatekijät matalan- ja korkeatehoisiin suorituskykymuuttujiin. Matalatehoiset suorituskykymuuttujat olivat ne, jotka mitattiin korkeintaan ensimmäisellä laktaattikynnyksellä ja ne olivat: ensimmäisen laktaattikynnyksen intensiteetti, rasvankäytön aste 48% maksimaalisen hapenottokyvyn kuormituksessa, sekä sykevälivaihtelupalautuminen 3 h + 15 s sprintti -testistä. Korkeatehoiset suorituskykymuuttujat olivat: maksimaalinen hapenottokyky, maksimiteho kynnystestissä, toisen laktaattikynnyksen intensiteetti, 15 sekunnin sprinttiteho sekä maksimaalinen iskutilavuus.

Kolmannen osatutkimuksen päätulos oli se, että sekä PK- että MK-ryhmä paransivat yhtä hyvin matalantehon suorituskykyä, mutta vain MK-ryhmä paransi korkeantehon suorituskykyä.

Neljäs osatutkimus oli koontitutkimus, jossa verrattiin 10 eri kuormituslaskentamallin antamia ennusteita matalatehoisen ja korkeatehoisen harjoittelun kuormitusten balanssille. Toisin sanoen, laskettiin montako matalatehoista minuuttia vastaa yhtä korkeatehoista minuuttia eri kuormituslaskentamalleilla. Kun harjoitukset tasattiin energiankulutuksellisesti, matalatehoisia minuutteja tarvitaan noin 2, koetun kuormitustuntemuksen kanssa noin 4, laktaattikäyrään perustuvissa menetelmissä 5. Harjoituksen jälkeisen ylimääräisen hapenkulutuksen perusteella matalatehoisia minuutteja tarvittaisiin noin 10 yhtä korkeatehoista minuuttia kohti. Myös suorituskyvyn laskun perusteella matalatehoisia minuutteja tarvittaisiin noin 10. Tässä väitöskirjassatutkimuksessa PK- ja MK-ryhmien harjoittelua tasapainotettiin viikoittaisen kuormitustuntemuksen avulla. Tämä yksilöllinen harjoittelumäärän nostaminen johti siihen, että noin 15 matalatehoista minuuttia vastasi yhtä korkeatehoista minuuttia.

Tämän osatyön päätulos oli, että matala- ja korkeatehoista harjoittelua ei voi tasapainottaa kaikkien kuormitusmittarien mukaan samanaikaisesti; on valittava minkä systeemin mukaan haluaisi tasapainotuksen tehdä. Lisäksi, koska PK-ryhmä ei kehittynyt yhtä hyvin kuin MK-ryhmä, voidaan päätellä, että laskennallinen kuormitus itsessään ei takaa kehitystä, vaan mukana on oltava riittävän korkeatehoista harjoittelua.

Ensimmäinen johtopäätös oli, että harjoittelemattomilla sekä PK- että MK-harjoittelu parantaa väsymisensietoa kolmituntisessa matalatehoisessa työskentelyssä. Mekanismi todennäköisesti oli vain eri. MK-harjoittelun jälkeen tutkittavien maksimiteho oli kasvanut, jolloin he polkivat kolme tuntia matalammalla teholla suhteessa maksimiin, mikä edesauttoi pienempään väsymisensietoon. PK-ryhmällä taas ensimmäinen laktaattikynnys suhteessa maksimiin nousi, jolloin myös heille kolmituntinen oli helpompi, mutta suhteessa ensimmäiseen laktaattikynnykseen.

Toinen johtopäätös oli, että määräharjoittelulla ei voi kokonaisuudessaan korvata intensiteetin puutetta edes harjoittelemattomilla ihmisillä. Vaikka viikossa harjoittelisi kymmenisenkin tuntia, korkeatehoinen kestävyyssuorituskyky ei kehity, jos harjoitteluintensiteetti on liian matala.

Kolmantena johtopäätöksenä oli matalimman kannattavan intensiteetin kysymys. Nähtiin, että vaikka PK-harjoittelu ei kehittänyt korkeantehon suorituskykyä, se nosti kyllä matalantehon suorituskykyä. Toisin sanoen matalatehoinen kestävyyssuorituskyky paranee pienemmällä intensiteetillä kuin korkeatehoinen suorituskyky. Tämän seurauksena ei ole olemassa yhtä ainoaa tapaa arvioida, oliko harjoittelu onnistunutta; maksimaalinen aika-ajokyky ei välttämättä kerro matalatehoisen harjoittelun onnistumisesta.

Neljäntenä johtopäätöksenä harjoittelun psykologinen miellyttävyys -ulottuvuudesta ei saa edes toissijaisesti tietoa, ellei sitä mitata erikseen. Tämä johtuu siitä, että harjoittelun miellyttävyys oli irrallinen komponentti harjoittelun tuomaan viikoittaiseen kuormitukseen eikä miellyttävyydellä voitu ennustaa harjoittelun vaikutusta aerobiseen maksimitehoon.

Viimeisenä, harjoittelu laskettu kuormitus ei yksinään ole riittävä tae harjoittelun kokonaisvaltaisesta kehittymisestä. Olennaista on millä keinoin harjoittelukuormitus on saavutettu.

8 SUPPLEMENTS: TRAINING PROGRAMS

The training intervention lasted 10 weeks. Participants followed a pre-scheduled 22-line progression table for training, as detailed in TABLE 11 for LIT and TABLE 12 for HIT. These tables were designed with equal ascending calculated training doses (FIGURE 12). Each participant began with progression line 1 (TABLES 11 and 12). After each training week, excluding load reduction recovery weeks, participants were asked 'How much the training has strained your week on a scale of 0–10?' using a 10-scale RPE table. Based on their feedback, they progressed to the next line on the table, as outlined in TABLE 10.

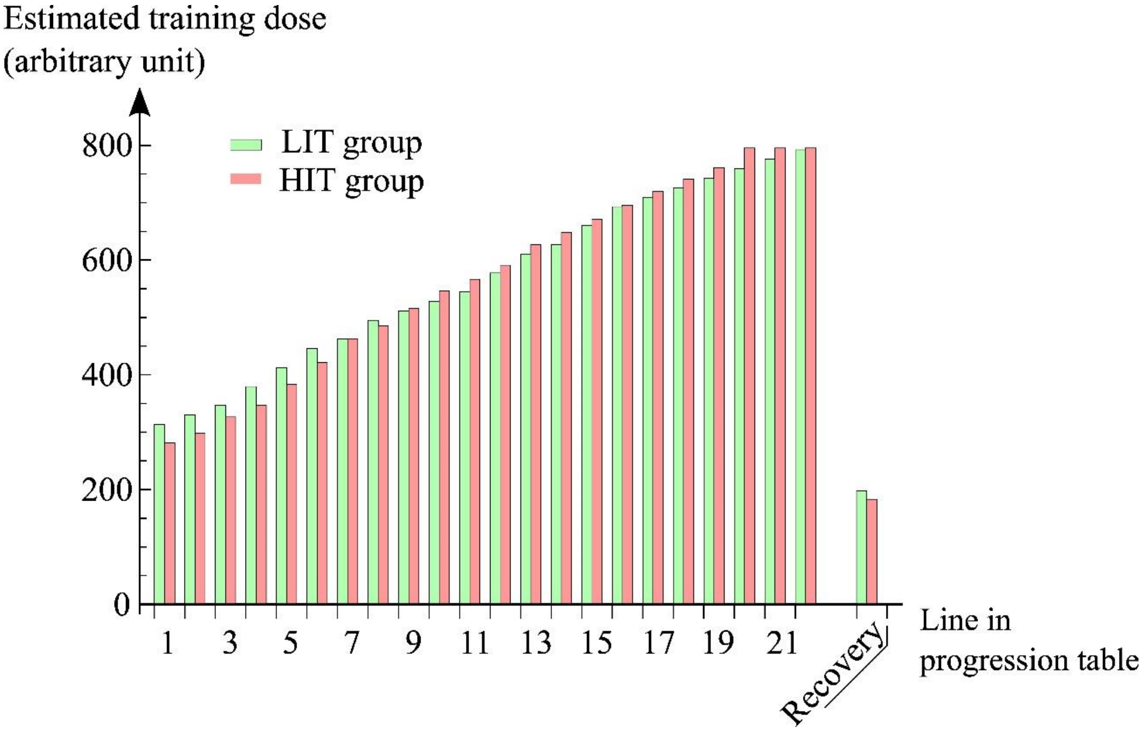


FIGURE 12. Calculated training doses of the progression tables for training of LIT and HIT groups using metric from (Cejuela-Anta & Esteve-Lanao, 2011). *LIT* Low intensity training. *HIT* high intensity training.

TABLE 10. Weekly rating of perceived effort and its influence on the training progression.

Weekly perceived exertion	Progression
9–10	0 (the same week was repeated)
7–8	+ 1
5–6	+ 2
3–4	+ 3
0–2	+ 4

8.1 Training program in the low intensity training group

The training progression line table for the LIT group is shown in TABLE 11. During training week 6, a follow-up VO_{2max} -test was conducted, replacing a "moderately long" training ride (1–1,75 h). Five (out of 16) participants progressed to the last progression line 22.

TABLE 11. Progression line table for the LIT group. The target power intensity in the sessions were Zone 1 and 2. During the training weeks participants were free to do the exercises in the order they preferred.

Progression line	Long exercise	Moderately long exercise	Short exercise	Amount of exercises (/ week)	Cumulative training time (h)
1	1 x 1.5 h	1 x 1 h	3 x 45 min	5	4.75
2	1 x 1.5 h	2 x 1 h	2 x 45 min	5	5
3	1 x 1.75 h	2 x 1 h	2 x 45 min	5	5.25
4	1 x 2 h	1 x 1.25 h 1 x 1 h	2 x 45 min	5	5.75
5	1 x 2.5 h	1 x 1.25 h 1 x 1 h	2 x 45 min	5	6.25
6	1 x 2.5 h	1 x 1.75 h 1 x 1 h	2 x 45 min	5	6.75
7	1 x 2.5 h 1 x 2 h	1 x 1 h	2 x 45 min	5	7
8	1 x 3 h 1 x 2 h	1 x 1 h	2 x 45 min	5	7.5
9	1 x 3 h 1 x 2 h	2 x 1 h	1 x 45 min	5	7.75
10	1 x 3 h 1 x 1.5 h	2 x 1 h	2 x 45 min	6	8
11	1 x 3 h 1 x 2 h	1 x 1 h	3 x 45 min	6	8.25
12	1 x 3 h 1 x 2.5 h	1 x 1 h	3 x 45 min	6	8.75
13	1 x 3 h 1 x 2.5 h	1 x 1.25 h 1 x 1 h	2 x 45 min	6	9.25
14	1 x 3 h 1 x 2.5 h	2 x 1.25 h	2 x 45 min	6	9.5
15	2 x 3 h	2 x 1.25 h	2 x 45 min	6	10
16	1 x 3.5 h 1 x 2.5 h	2 x 1.5 h	2 x 45 min	6	10.5
17	1 x 3.5 h 1 x 3 h	1 x 1.5 h 1 x 1.25 h	2 x 45 min	6	10.75
18	2 x 3 h	2 x 1 h 2 x 1.5 h		6	11
19	1 x 3.5 h 2 x 2 h	1 x 1.5 h 1 x 1.25 h 1 x 1 h		6	11.25
20	1 x 3.5 h 3 x 2 h	2 x 1 h		6	11.5
21	1 x 4 h 1 x 3 h	2 x 1.5 h 1 x 1 h	1 x 45 min	6	11.75
22	1 x 4 h 1 x 3.5 h	3 x 1 h 1 x 1.5 h		6	12
Load reduction recovery week	1 x 1.5 h		2 x 45 min	3	3

8.2 Training program in the high intensity training group

The training progression line table for the HIT group is shown in TABLE 12. During training week 6, a follow-up VO_{2max} -test was conducted, replacing the interval exercise originally planned for that week with the lowest training dose. Eight (out of 19) participants progressed to at least progression line 15, and none further than 19.

TABLE 12. Progression line table for the HIT group. Each session started with a 10 min warm up and ended with a 10 min cool down. Recovery between work intervals were ¾ of the work interval length. Target power intensity in the work intervals were 110% LT_2. In the exercises marked in red, the work intensity was "maximal sustainable average effort". Target power intensity at the warmup, recovery, and cool down was < 60 W. During the training weeks participants were free to do the exercises in the order they preferred

Progression line	Exercise type 1	Exercise type 2	Exercises / week	Cumulative HIT time (min/week)	Cumulative LIT time (min / week)
1	2 exercises: 5 x 3 min @ HIT		2	30	56
2	2 exercises: 4 x 4 min @ HIT		2	32	58
3	2 exercises: 5x3.5 min @ HIT		2	35	64
4	1 exercise: 3 x 6 min @ HIT	1 exercise: 5 x 4 min @ HIT	2	38	62
5	1 exercise: 5 x 4 min @ HIT	1 exercise: 5x4.5 min @ HIT	2	42.5	64
6	3 exercises: 3 x 5 min @ HIT		3	45	84
7	1 exercise: 5 x 4 min @ HIT	2 exercises: 3 x 5 min @ HIT	3	50	88
8	1 exercise: 5 x 4 min @ HIT	2 exercises: 3x5.5 min @ HIT	3	53	88
9	2 exercises: 5 x 4 min @ HIT	1 exercise: 3x5.5 min @ HIT	3	56.5	92
10	3 exercises: 4 x 5 min @ HIT		3	60	96
11	1 exercise: 3 x 7 min @ HIT	2 exercises: 7 x 3 min @ HIT	3	63	94
12	3 exercises: 4 x 5.5 min @ HIT		3	66	96
13	2 exercises: 6 x 4 min @ HIT	1 exercise: 4x5.5 min @ HIT	3	70	102
14	2 exercises:	1 exercise:	3	72.5	104

	5 x 5 min @ HIT	5x4.5 min @ HIT			
15	3 exercises: 5 x 5 min @ HIT		3	75	108
16	1 exercise: 7 x 4 min @ HIT	2 exercises: 5 x 5 min @ HIT	3	78	110
17	2 exercises: 7 x 4 min @ HIT	1 exercise: 5 x 5 min @ HIT	3	81	112
18	1 exercise: 4 x 7 min @ HIT	2 exercises: 7 x 4 min @ HIT	3	84	111
19	1 exercise: 6 x 5 min @ HIT	2 exercises: 7 x 4 min @ HIT	3	86	116
20	3 exercises: 6 x 5 min @ HIT		3	90	120
21	3 exercises: 5 x 6 min @ HIT		3	90	120
22	3 exercises: 5 x 6 min @ HIT		3	90	120
Load reduction recovery week	2 exercises: 3 x 3 min @ HIT		2	18	38

LIT Low intensity training (zone); *HIT* High intensity training (zone)

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ORIGINAL PUBLICATIONS

I

DURABILITY IS IMPROVED BY BOTH LOW AND HIGH INTENSITY ENDURANCE TRAINING

by

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EDITED BY
Danilo Iannetta,
The University of Utah, United States

REVIEWED BY
Hugo A. Kerhervé,
University of Rennes 2—Upper Brittany,
France
Rafael de Almeida Azevedo,
University of São Paulo, Brazil

*CORRESPONDENCE
Pekka Matomäki,
pmatomaki@gmail.com

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Durability is improved by both low and high intensity endurance training

Pekka Matomäki[1,2]*, Olli J. Heinonen[2], Ari Nummela[3], Jari Laukkanen[4,5], Eero-Pekka Auvinen[1], Leena Pirkola[1] and Heikki Kyröläinen[1]

[1]Faculty of Sport and Health Sciences, University of Jyväskylä, Jyväskylä, Finland, [2]Paavo Nurmi Centre & Unit for Health and Physical Activity, University of Turku, Turku, Finland, [3]Finnish Institute of High Performance Sport KIHU, Jyväskylä, Finland, [4]Central Finland Healthcare District, Department of Medicine, Jyväskylä, Finland, [5]Department of Medicine, Institute of Clinical Medicine, University of Eastern Finland, Kuopio, Finland

Introduction: This is one of the first intervention studies to examine how low- (LIT) and high-intensity endurance training (HIT) affect durability, defined as 'time of onset and magnitude of deterioration in physiological-profiling characteristics over time during prolonged exercise'.

Methods: Sedentary and recreationally active men (n = 16) and women (n = 19) completed either LIT (average weekly training time 6.8 ± 0.7 h) or HIT (1.6 ± 0.2 h) cycling for 10 weeks. Durability was analyzed before and after the training period from three factors during 3-h cycling at 48% of pretraining maximal oxygen uptake (VO_{2max}): 1) by the magnitude and 2) onset of drifts (i.e. gradual change in energy expenditure, heart rate, rate of perceived exertion, ventilation, left ventricular ejection time, and stroke volume), 3) by the 'physiological strain', defined to be the absolute responses of heart rate and its variability, lactate, and rate of perceived exertion.

Results: When all three factors were averaged the durability was improved similarly (time x group $p = 0.42$) in both groups (LIT: $p = 0.03$, g = 0.49; HIT: $p = 0.01$, g = 0.62). In the LIT group, magnitude of average of drifts and their onset did not reach statistically significance level of $p < 0.05$ (magnitude: 7.7 ± 6.8% vs. 6.3 ± 6.0%, $p = 0.09$, g = 0.27; onset: 106 ± 57 min vs. 131 ± 59 min, $p = 0.08$, g = 0.58), while averaged physiological strain improved ($p = 0.01$, g = 0.60). In HIT, both magnitude and onset decreased (magnitude: 8.8 ± 7.9% vs. 5.4 ± 6.7%, $p = 0.03$, g = 0.49; onset: 108 ± 54 min vs. 137 ± 57 min, $p = 0.03$, g = 0.61), and physiological strain improved ($p = 0.005$, g = 0.78). VO_{2max} increased only after HIT (time x group $p < 0.001$, g = 1.51).

Conclusion: Durability improved similarly by both LIT and HIT based on reduced physiological drifts, their postponed onsets, and changes in physiological strain. Despite durability enhanced among untrained people, a 10-week intervention did not alter drifts and their onsets in a large amount, even though it attenuated physiological strain.

KEYWORDS

durability, low intensity training, high intensity training, perceived exertion, cardiovascular drift

1 Introduction

Recently, the term *durability* has been defined as 'time of onset and magnitude of deterioration in physiological-profiling characteristics during prolonged exercise' (Maunder et al., 2021). Durability can be seen as a form of fatigue resistance. However, fatigue resistance is usually connected to neuromuscular fatigue during maximal and short performances. Durability, on the other hand, is usually linked to gradual fatiguing process in *prolonged* (i.e. several hours) *submaximal* exercise with usually physiological or psychological origin. Durability may be estimated directly by evaluating the magnitudes and onsets of *drifts*, defined as gradual changes in key physiological variables during prolonged submaximal exercise (Smyth et al., 2022). Durability may also be assessed by measuring a maximal performance capacity immediately after prolonged exercise (Maunder et al., 2021; Van Erp et al., 2021). Decreased absolute physiological responses, e.g. lactate and heart rate level, during submaximal exercise after a training period may also represent attenuated physiological responses and thus improved durability.

Many physiological drifts occur during prolonged low-intensity exercise, e.g. increased energy expenditure (EE) (Rønnestad et al., 2011; Hopker et al., 2017), which is coupled with upward drifts of ventilation (VE) (Ekelund, 1967; Martin et al., 1981; Hopker et al., 2017), rate of perceived exertion (RPE) (Rønnestad et al., 2011; Hopker et al., 2017; Wills et al., 2019), and heart rate (HR) (Ekelund, 1967; Rønnestad et al., 2011; Mullins et al., 2015). HR drift is the most widely used drift when studying durability (Maunder et al., 2021; Smyth et al., 2022), and it is also related to neuromuscular fatigue (Coyle and González-Alonso, 2001). Inversely, stroke volume (SV) (Ekelund, 1967) and linear heart rate variability (HRV) indices (Moreno et al., 2013) form downward drifts.

High durability, i.e., ability to resist physiological changes, has clear advantages. For example, a marathoner with high durability can resist the inevitable performance deteriorating changes and maintain performance capacity for prolonged periods of time. In line with this, lower HR drift in marathon running is associated with prolonged onset of drift and faster relative speed (Smyth et al., 2022) and greater HR drift is associated with decrease in running speed at the later stage of the race (Billat et al., 2020) as well as worse total time (Billat et al., 2020; Smyth et al., 2022). Larger HR drift predicts also decreased maximal oxygen uptake (VO_{2max}) at fatigued state (Wingo et al., 2005). EE drift has been strongly associated with a decrease in 5 min maximum performance in fatigued state (Passfield and Doust, 2000). Lately, it has been demonstrated that power profile does not decline after exhausting exercise (1500–2000 kJ) as much in successful professional cyclists compared to lesser successful ones (Van Erp et al., 2021). In addition, durability is a required feature in military training, because physical and mental functionality of soldiers should be maintained at high levels also in a fatigued state (Rudzki, 1989; Wills et al., 2019).

The most effective training methods to improve durability are not known. In some studies, strenuous (Hurley et al., 1986; Coggan et al., 1993) and high-volume moderate-intensity (Phillips et al., 1996; Carter et al., 2001) endurance training has led to reduced physiological drifts during prolonged exercise among untrained individuals. Well-trained athletes have not increased durability with endurance training alone (Hausswirth et al., 2010; Rønnestad et al., 2011), although the amount of low-intensity training (LIT) may be linked to increased durability (Spragg et al., 2022). Concurrent strength and endurance training has had a positive effect among athletes (Rønnestad et al., 2011).

There are no reports on intervention studies focusing on durability. Therefore, we wanted to understand how much and in which methods durability can be improved. Our main aim was to study durability before and after high- (HIT) and low-intensity endurance training of 10 weeks in recreationally active participants.

2 Materials and methods

2.1 Study design and protocol

Based on VO_2 drifts in interventions (Coggan et al., 1993; Carter et al., 2001) and our pilot studies, we estimated that intervention would cause an average 3 p. p. (percentage point) reduction in EE drift in the HIT group, and 6 p. p. reduction in the LIT group with 3 p. p. standard deviation. Based on these findings, power calculations give group sample size of 16 ($\alpha = 0.05; \beta = 0.80$).

The study included 6 visits to the laboratory (Figure 1): three before the training intervention, one during intervention, and two after intervention. All subjects provided written informed consent, and the study was approved by the Ethical Committee of the Central Finland Healthcare District (8U/2020), complying with the Declaration of Helsinki.

2.2 Subjects

Healthy sedentary or recreationally active (endurance exercise less than 6 h/wk) adults aged 18–40 years were recruited through social and print media announcements. Additionally, participants were not included if they had hypertension, pregnancy, or were nursing, or they had been diagnosed an upper respiratory infection or other acute illnesses within 2-weeks before the first laboratory visit. A total of 47 subjects were invited to the screening visit which included assessments of body height, resting ECG, blood pressure, health status, and medication (Figure 1: flow chart). Body mass and fat free mass were measured by bioelectrical impedance (InBody 770, Biospace Ltd., Seoul, Korea) in the morning after at least 8 h fasting. Forty-four subjects met the inclusion criteria and started the training intervention. Finally, 35 subjects (basic characteristics in Table 1) finished the entire study.

2.3 Laboratory tests and analyses

Visit 2, 4, & 5: The sprint (Wingate) and VO_{2max} were performed individually at the same time of the day (±2 h). Visit 4 included only the VO_{2max}-test. The subjects were advised to refrain from caffeine and alcohol 24 h before the tests and eating 3 h prior. Before each performance test, body mass was recorded (seca 719, seca GmbH & Co. KG., Hamburg, Germany) with cycling clothes on and shoes removed, then 300 g were subtracted as the weight of clothes.

15 s *Wingate test (sprinting ability)* was used to measure a fatigue of the neuromuscular system after a durability test. A 10-min warming up at 50 W followed by 10 s countdown phase to reach maximum

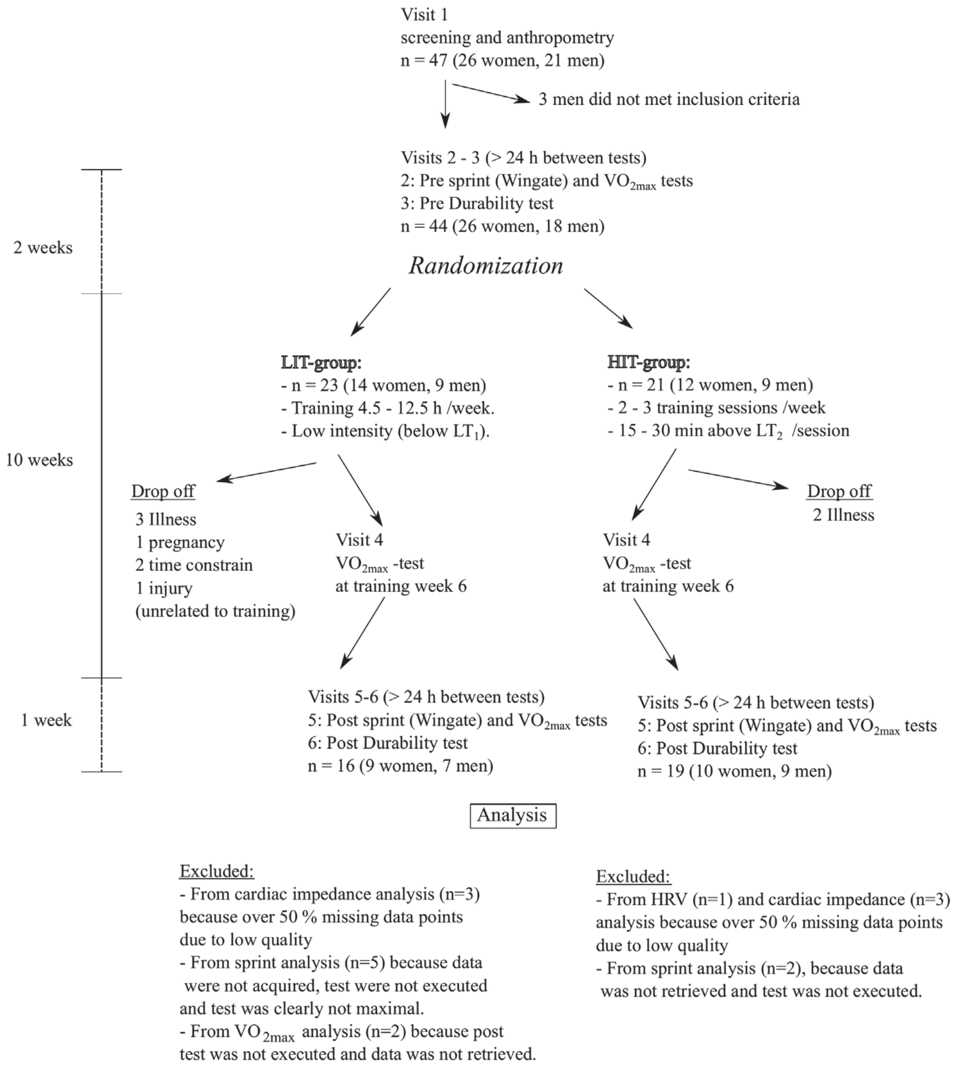

FIGURE 1
Flow chart and study design. Performance tests included VO_{2max} and sprint tests, and durability. *LIT* Low intensity training. *HIT* High intensity training. *HRV* heart rate variability. *VO_{2max}* maximal oxygen uptake. *LT_1* First lactate threshold. *LT_2* Second lactate threshold.

TABLE 1 Basic characteristics (mean, SD) at the beginning of the study.

		Body mass (kg)	Height (cm)	Fat percent (%)	Age (y)	VO_{2max} (l/min)	P_{max} (W)	P_{LT1} (W)	P_{LT2} (W)	Sprinting fatigue ratio (%)
LIT	women (n = 9)	73.2 (15.2)	168 (6)	30.2 (6.9)	33 (5)	2.54 (0.12)	188 (9)	83 (5)	134 (8)	-3.0 (3.7) (n = 7)
	men (n = 7)	88.4 (9.7)	178 (4)	24.7 (7.9)	34 (6)	3.62 (0.14)	272 (9)	121 (9)	204 (9)	-1.4 (6.0) (n = 4)
HIT	women (n = 10)	62.8 (9.0)	164 (7)	27.6 (5.9)	30 (5)	2.33 (0.04)	176 (3.4)	79 (4)	128 (4)	-0.1 (3.0) (n = 9)
	men (n = 9)	87.7 (9.8)	180 (7)	22.3 (6.0)	34 (5)	3.25 (0.13)	251 (14)	115 (10)	191 (13)	-1.5 (7.9) (n = 8)

LIT low intensity training group; *HIT* High Intensity Training group. *VO_{2max}* Maximal oxygen uptake. *P_{max}* Maximum aerobic power. *P_{LT1}* Power at the first lactate threshold. *P_{LT2}* Power at the second lactate threshold. *Sprinting fatigue ratio* Ratio of (15 s sprint after durability test - 15 s sprint rest)/(15 s sprint rest).

pedaling rate with the load (7.5% of body weight) followed by 15 s all out maximal cycling (Monark 894E, Monark Exercise AB, Sweden). Subjects were verbally encouraged by researchers. Subjects were familiarized with the Wingate test on a separate day before the test.

Incremental VO_{2max} cycling test. After the Wingate test, subjects remained sitting for 10 min, followed by a 25-min active recovery (walking around or 50 W cycling). Exactly 35 min after termination of the Wingate test, a step-incremental cycling test (Monark LC4, Monark Exercise AB, Sweden) was initiated. Initial power was 40 W for women and 50 W for men with increments of 20—25 W (women) and 30 W (men) at 3-min intervals. Subjects were verbally encouraged during the last stages by researchers. The ergometer (Monark LC4) was calibrated at the beginning of the study. Calibration was checked weekly with a 4000 g weight, following instructions by the manufacturer. Gas exchange was measured breath-by-breath (Jaeger Vyntus TM CPX, CareFusion Germany 234 GmbH, Hoechberg, Germany) and HR was monitored with a Garmin Forerunner 945 (Garmin Ltd., Taiwan). Means from the last minute of every stage were used in analysis. In the last minute of each state, blood lactate was measured by fingertip sampling (EKF-diagnostic GmbH Ebendorfer Chaussee 3, Germany) and RPE (Borg Scale 0–10) was recorded. VO_{2max} was defined as the highest continuous 60 s mean oxygen consumption. Maximal aerobic power (P_{max}) was defined as the weighted mean of the last 3 min of the test: power of last completed stage (W) + [time (s) of unfinished state]/(180 s) × increment (W). The first lactate threshold (LT_1) was defined as the lowest value of the lactate/ VO_2 -ratio, and the second lactate threshold (LT_2) as a sudden and sustained increase in blood lactate concentration (Faude et al., 2009). Two researchers independently determined the thresholds. In case of disagreement, a third opinion was obtained.

Durability is defined as 'time of onset and magnitude of deterioration in physiological-profiling characteristics over time during prolonged exercise' (Maunder et al., 2021). In this study, the original definition of durability was interpreted through three different factors:

1) The *magnitude of physiological drifts* (defined as a gradual change in physiological variables during exercise): Change in EE, HR, RPE, VE, imputed left ventricular ejection time (LVET), and imputed stroke volume (SV) between 30 min and 180 min in the durability test.
2) The *time of onset* of a drift, which was defined to be the time when the value of the drift has risen (or fallen) a predetermined amount. The thresholds were arbitrarily chosen, as in (Smyth et al., 2022), and they were +5% (HR, VE), +2.5% (EE), +2 steps (RPE), and -1.5% (imputed LVET).
3) *The physiological strain*, which was defined as the absolute levels of HR, HRV, RPE, and blood lactate from the durability test. The effect of prolonged exercise on sprinting performance was done by inspecting the sprinting fatigue ratio: Δ sprint = $(sprint_{fatigue}—sprint_{rest})/sprint_{rest}$, where $sprint_{fatigue}$ was the mean of 15-s Wingate power after the durability test and $sprint_{rest}$ at rested state.

To get a wider overall picture, durability was not understood as a single variable, but rather as a phenomenon which is illustrated by all these three different factors together.

Visit 3 and 6: Durability tests were performed individually for each subject at the same time of the day (±2 h). The subjects were advised to have a standard meal 2.5–3 h before entering the laboratory. They were instructed to document the timing and contents of the meal, and to repeat it before the second durability test. Before the durability test, body mass was measured (Seca 719), then followed by a rest period on bench while being prepared for the non-invasive impedance cardiography (Physioflow, 2016) (PhysioFlow PF-07 Enduro, Manatec Biomedical, France) with PF50 PhysioFlow electrodes to measure SV and LVET.

Thereafter, the subjects cycled for 3 h (Monark LC4) with a predetermined power, 50% VO_{2max}, measured on incremental test, but not more than 95% LT_1 to ensure that each participant cycled at low intensity zone. In pre-test the realization was 48 ± 4% VO_{2max} and 87 ± 8% LT_1. The same absolute power in pre- and post-tests was used. Ten-minute measurement slots were repeated every 30 min. During the first 20 min, the subjects chose their preferred position and cadence (over 60 rpm), which were recorded and maintained during the subsequent 10-min measurement slots in both pre- and post-tests. Between the 10-min measurement slots, subjects could adjust position and cadence (>60 rpm) freely. Gas exchange was measured breath-by-breath during each 10-min measurement slots (Jaeger Vyntus TM CPX), after which RPE (0–10) was recorded. Blood was drawn from fingertips at 0, 1, 2, and 3 h for analyzing blood lactate. The 15-s Wingate test was performed within the first minute after finishing the 3 h test.

Hydration (0.3% NaCl solution) was available *ad libitum*. Water intake during 3 h tests was measured and in the LIT group, it was 1.2 (0.4) l and 1.1 (0.4) l in pre- and post-tests, respectively. In the HIT group, the respective values were 1.3 (0.4) l and 1.1 (0.4) l. During the test, carbohydrates were given as a 2:1:1 mixture containing maltodextrin, fructose, and glucose dissolved into 1 dl of 0.3% NaCl. Carbohydrate intake was individualized, and the amount was related to the cycling power, calculated to cover 50% of theoretical energy expenditure where 18% gross efficiency was assumed (Ettema and Loras, 2009). A maximum of 75 g of carbohydrates were given per hour to minimize gastrointestinal problems (Jeukendrup, 2014). The carbohydrate intake was identical in pre- and post-tests (mean ± SD: 51 ± 14 g/h).

Energy expenditure (EE) was calculated using equation $EE\ (kJ/\min) = (5.05 \times RER + 16.1) \times VO_2\ (l/\min)$ (Keskinen et al., 2004), where RER is respiratory exchange ratio.

Heart rate variability (HRV), cardiac impedance, and multiple imputations. In the HRV analysis, low frequency (0.04–0.15 Hz) and high frequency (0.15–1.1 Hz) bands were used. The higher than usual frequency limit of 1.1 Hz was chosen to include the respiratory frequency during exercise. HR and HRV data were collected with Garmin HRM-Pro or HRM-dual belt (Garmin Ltd., Taiwan), with 1000 Hz resolution frequency, and analyzed with Kubios HRV Premium (Version 3.5.0, Kubios Oy, Kuopio, Finland). Medium automatic quality detection with a 5% acceptance threshold and an automatic beat correction method were used. Low- and high-frequency spectrums were calculated applying Lomb-Scargle periodogram with 0.02 Hz smoothing window. The HRV samples were 8-min subintervals within 10-min measurement intervals of the durability test. Only data points with effective data length at least 95% were included in the final analysis.

In the analysis, after removing all subjects with more than 50% missing data points (six from cardiac impedance measurements and one from HRV), 7.0% of HRV and 13.2% of cardiac impedance data were missing. Multiple imputations were used to fill in missing data. Drifts in imputed LVET and SV were interpolated from regression lines.

2.4 LIT and HIT training

Subjects were randomized into two training groups, applying minimization method (Hu and Hu, 2012) after the first three visits to laboratory. Training zones were determined based on lactate thresholds. The subjects were instructed to continue their daily physical activities (commuting, non-physical hobbies, etc.), but all strenuous exercise in addition to LIT or HIT was not allowed. The exact training programs are given in Supplementary Material 1.

LIT consisted of cycling under LT_1-power. The weekly 5–6 training days included long (1.5–4 h), medium (1–1.5 h), and short (45–60 min) exercises. Weekly training hours progressed individually (see Progression-paragraph below) based on perceived exertion from 4.5 up to maximum 12.5 h. Subjects did their training mostly outdoors with their own bicycles with Rally RK200 dual-sensing power meters (Garmin Ltd., Taiwan). A possibility for indoors cycling with trainer or Wattbike Trainer (Wattbike Ltd., Nottingham, UK) was given. Three (out from 16) subjects did their training completely indoors, and the others did 3% of their training indoors.

HIT consisted of 2—3 weekly indoor training sessions with Wattbike Trainers, or indoor trainer with their own bicycles with Rally RK200 dual-sensing power meters. Training consisted of high-intensity work intervals 3–7 min long with recovery periods ¾ of the work interval duration. In the first training week, there were 15 min of cumulative high-intensity time in a training session, and it progressed individually (see Progression-paragraph below) up to 30 min per session. Each session included 10 min warm up and cool down. These, as well as recovery periods, were done with power <60 W, and high-intensity segments were initially 110% LT_2 power (± 15 W).

In both groups, RPE (0–10) was reported from each training session. HR from each session was recorded with the Garmin HRM-Pro heart belt. In the LIT group, power data were recorded with power meters (Rally RK200), and in the HIT group, power data were collected from the Wattbike Trainer or power meters (Rally RK200). All data was transferred after the session to AthleteMonitoring app (AthleteMonitoring, FITSTATS Technologies, Inc., Moncton, Canada), from which training realization was actively monitored weekly by the first author. In the HIT group, if all weekly training had RPE ≤ 6 and HR did not rise above LT_2-threshold, the power was increased by 10%. In the LIT group, the subjects were actively given feedback whether training was at the prescribed level. Apart from the first HIT-session, all sessions were unsupervised. Training power was modified in both groups according to VO_{2max} -test (visit 4) at training week 6.

Daily physical activity was gathered by measuring heart rate from wrist continuously by Garmin Forerunner 945 for two to 4 weeks before the start of the intervention. This was done to estimate the baseline endurance training before training intervention.

Training zones and load. Training was monitored by distributing cycling power output to five zones (Cejuela-Anta and Esteve-Lanao, 2011): Z1 (below LT_1—10 W); Z2 (LT_1—10 W to LT_1 + 10 W); Z3 (LT_1 + 10 W to LT_2—10 W); Z4 (LT_2—10 W to LT_2 + 10 W); Z5 (above LT_2 + 10 W). For each zone, a weighting factor was linked (in an ascending order: 1, 2, 3, 4, 7.5) and training load was calculated by multiplying the factor by the time spent in the zone (Cejuela-Anta and Esteve-Lanao, 2011).

Targeted power of LIT was designed to be at Z1 and Z2, and HIT at Z4 and Z5. Heart rate was divided into three zones (HR Zones 1—3) separated by LT_1 and LT_2. In addition, for the LIT group, it was calculated how many times their 30 s -average power exceeded Z2 -zone. For baseline physical activity before the start of the training intervention, Z0 was defined to be a zone below halfway between resting HR and LT_1, and Z1b above Z0 and below LT_1. During physical activity heart rate measurement part of the data was dismissed, 12 ± 15% of the gathered data, because of heart rate was not adequately recorded from wrist.

Training progression. Both groups had 10 training weeks. Weeks 3 and 7 were load reduction weeks for enhancing recovery. Subjects' training progression was linked to the perceived exertion. After each training week (excluding load reduction weeks), subjects were asked 'How much the training has strained your week on a scale of 0–10?', and the training time was increased more with lower exertion (see Supplementary Digital Content 1). For those finishing the study, adherence rate in training sessions was 98.4%. The weekly training intensity distribution is shown in Figure 2 and training realization in Table 2.

2.5 Statistical analyses

Data are presented as mean (standard deviation). Statistical tests were calculated by SPSS 26.0 (SPSS Inc, Chicago, IL, United States) and Mathematica 13.0 (Wolfram Research, United States). Missing data on heart rate variability and cardiac impedance were handled by multiple imputation. To be conservative, 50 imputations were used (Licht, 2010). Pooled p-values were calculated applying z-method previously suggested (Licht, 2010).

Before performing the final analysis, it was determined if the magnitude of change in variables differed between the sexes (Kruskal-Wallis test) in 3 h test. Of all drifts and their onsets and physiological strains (88 tests), the only differences were detected in the RPE onset ($p = 0.03$) and lactate at 60 min time point ($p = 0.04$) in the HIT. As they were the only exceptions, it was decided to analyze females and males in a combined group. The Shapiro-Wilk test was used to examine normality.

If results were not normally distributed, group size was small (n < 10), or values were categorial (i.e. RPE, onset of drifts), the non-parametric Wilcoxon signed-rank-test was used for comparison between time points, and Mann-Whitney U-test for between-group comparison. When normality assumptions failed, but covariance matrices were homogenous by Box's test, Pillai's trace was utilized in ANOVA. If covariance assumption was not met, Kruskal-Wallis test was used. To calculate the average drifts and their onsets their weighted mean was calculated. In physiological strain, HRV responses were first averaged as a single variable. A harmonic mean p-value technique was applied to estimate the combined change in durability from all examined factors (drifts, their onset, and physiological strain) given all parameters weights proportional to their sample size. Post hoc correlations were done using Spearman correlations with RPE and Pearson correlations otherwise.

The effect size (ES) of differences for the main variables were calculated with a corrected effect size Hedge's g, for which a non-central 95% confidence interval (CI) was calculated (Goulet-Pelletier and Cousineau, 2018). Effect size for between-group differences was calculated by subtracting within-group effect sizes from each other (Morris and DeShon, 2002). After non-parametric tests, effect size was calculated by a formula $Z/\sqrt{n}$, where Z is the z-score, and n is the total number of subjects on which Z is based. As this corresponds to point biserial r, an analytical conversion is made to represent it as d-family ES (McGrath and Meyer, 2006):

$$\frac{r}{\sqrt{(1-r^2)\frac{n_1 n_2}{(n_1+n_2)^2}}},$$

where n_1 and n_2 are the sizes of groups 1 and 2. A common language effect size (CLES) is also provided for main variables. When normality assumptions were met, a continuous method was used. In other cases, a sign-test (within-group CLES) or Mann-Whitney U-test (between-

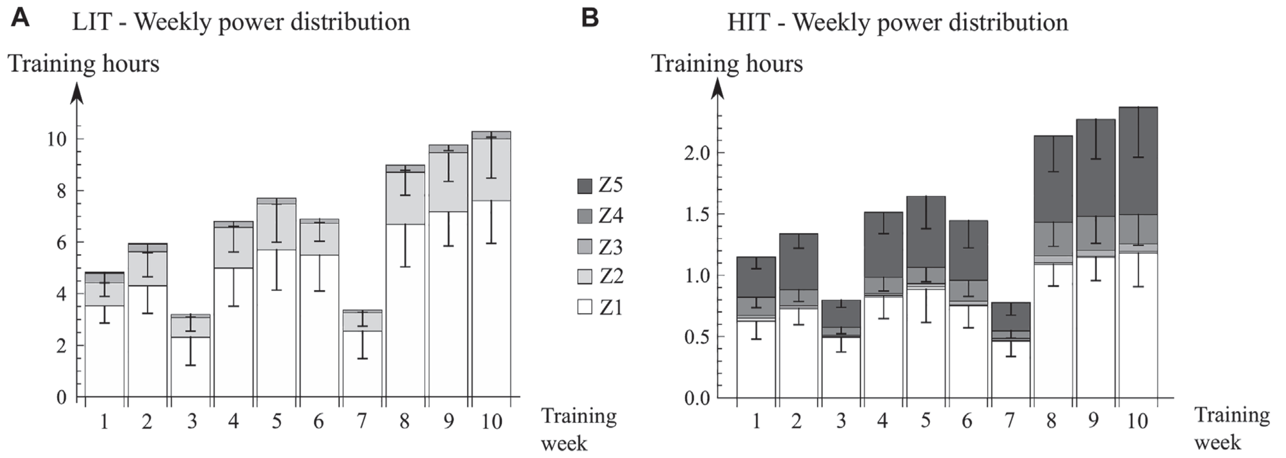

FIGURE 2
Mean weekly training power distribution for **(A)** LIT, SD for zones Z1, Z2, Z3; **(B)** HIT, SD for zones Z1, Z4, and Z5. Observe the different y-axis in figures **(A)** and **(B)**. The small reduction in hours in week 6 was caused by replacing one session by VO_{2max}-test. Mean weekly training hours in the LIT group was 4.4 (range 4.0—4.8) times than that of the HIT group (excluding load reduction weeks). *LIT* Low intensity training. *HIT* High intensity training. *Power zones* Z1 (below LT_1—10 W); Z2 (between LT_1—10 W to LT_1 + 10 W); Z3 (between LT_1 + 10 W to LT_2—10 W); Z4 (between LT_2—10 W to LT_2 + 10 W); Z5 (above LT_2 + 10 W). *LT_1* First lactate threshold. *LT_2* Second lactate threshold.

TABLE 2 Training realization, mean (SD), in LIT and HIT groups during 10- week training. Before training intervention there were no differences between the groups in HR distribution (p > 0.28).

	LIT (n = 16)	HIT (n = 19)
Before training		
Monitored days (d)	28 (12)	22 (13) (n = 17)
Physical activity (min/vrk) HR intensity distribution Dismissed/Zone 0/Zone 1b/Zone 2/Zone 3	171 (193)/1128 (184)/107 (89)/6 (7)/0.5 (0.4)	169 (203)/1091 (242)/108 (76)/6 (8)/0.4 (0.2) (n = 17)
Training charateristics		
Total training time (h)	68.2 (7.3)	15.6 (1.8)
Mean training volume (h/week)	6.8 (0.7)	1.6 (0.2)
Mean training frequency/week	4.8 (0.2)	2.4 (0.1)
Mean HR (% HR_{max})	63.4 (4.3)	76.1 (4.3)
Mean training session RPE	2.8 (1.4)	7.2 (1.9)
HR Zone 1 (%)/Power Zones Z1 & Z2 (%)	87.6 (17.5)/96.6 (2.5)	36.2 (10.1)/54.1 (4.7)
HR Zone 2 (%)/Power Zone Z3 (%)	12.3 (17.4)/3.2 (2.4)	37.7 (8.2)/1.9 (2.4)
HR Zone 3 (%)/Power Zones Z4 & Z5 (%)	0.1 (0.2)/0.2 (0.3)	26.1 (10.8)/44.0 (5.4)
30 s intervals > Z2 power/week	5.5 (7.8)	

LIT low intensity training group; *HIT* High intensity training group; *HR* Heart rate; *HR_{max}* Maximum heart rate; *RPE* Rate of perceived exertion. *Power Zones* Z1 (below LT_1—10 W); Z2 (LT_1—10 W to LT_1 + 10 W); Z3 (LT_1 + 10 W to LT_2—10 W); Z4 (LT_2—10 W to LT_2 + 10 W); Z5 (above LT_2 + 10 W). *LT_1* First lactate threshold. *LT_2* Second lactate threshold. *HR Training Zones* Z1 (below LT_1); Z2 (between LT_1 and LT_2); Z3 (above LT_2). For physical activity measurement *Dismissed* (HR data not acquired); *Z0* (below halfway between resting HR and LT_1); *Z1b* (above Z0, below LT_1).

group CLES) were utilized (Caldwell and Vigotsky, 2020). The interpretation of CLES of X% is 'the probability of a randomly selected individual's variable increasing/being greater than the one from randomly selected individuals from the other group after the training is X%.' Small, moderate, large, and very large effect size magnitudes for Hedge's g were categorized as 0.20, 0.50, 0.80, and 1.2, and 56%, 64%, 71%, and 80% for CLES, respectively.

In figures, the statistical values of the durability test were pooled: *p*-values were changed to z-scores which were averaged, similar to the methodology of multiple imputation (Licht, 2010). Effect sizes were pooled following the suggestion by (Rosenthal and DiMatteo, 2001): Cohen d_i ES → Biseral r_i ES → Fisher Z_{ri} → Taking average $\bar{Z}_r = Mean(Z_{ri})$ → Averaged biseral $\bar{r}$ ES → Averaged $\bar{d}$ ES → Averaged Hedge's $\bar{g}$, where i is the different time points from which averages

TABLE 3 Mean (SD) magnitude of the drifts of physiological variables during 3 h durability test. Drifts of the imputed LVET and SV are extrapolated from regression lines.

		LIT	HIT	Between group change
				Time x group
EE drift (%)	Pre	**6.4 (4.8)**	**6.5 (6.8)**	
	Post	**4.0 (5.6)**	**3.0 (6.7)**	
	Change (p.p.)	**-2.4 (4.0)** p = 0.03	**-3.5 (6.4)** p = 0.03	p = 0.90
		ES = -0.45 (-0.89—-0.08)	ES = -0.51 (-1.00—-0.08)	ES = 0.06 (-0.62—0.76)
HR drift (bpm)	Pre	**15.1 (7.0)**	**16.7 (8.7)**	
	Post	**13.2 (7.3)**	**11.7 (6.9)**	
	Change (bpm)	**- 1.9 (5.4)** p = 0.18	**-4.9 (7.8)** p = 0.01	p = 0.19
		ES = -0.25 (-0.66–0.11)	ES = -0.62 (-1.13—-0.18)	ES = 0.36 (-0.31—1.08)
RPE drift	Pre	**3.3 (1.7)**	**3.5 (2.0)**	
	Post	**2.6 (1.9)**	**3.1 (1.3)**	
	Change	**-0.7 (1.6)** p = 0.10	**-0.4 (1.4)** p = 0.18	p = 0.26
		ES = -0.60 (-1.39–0.09)	ES = -0.44 (-1.10–0.22)	ES = 0.16 (-0.52—0.86)
VE drift (l/min)	Pre	**3.9 (2.9)**	**4.8 (4.8)**	
	Post	**2.9 (2.7)**	**2.3 (3.3)**	
	Change (l/min)	**-0.9 (2.2)** p = 0.11	**-2.5 (5.1)** p = 0.05	p = 0.39
		ES = -0.32 (-0.75–0.06)	ES = -0.59 (-1.2–0.04)	ES = 0.27 (-0.41—0.98)
Imputed LVET drift (ms)	Pre	**-8.3 (17.9) (n = 13)**	**-16.4 (11.7) (n = 16)**	
	Post	**-12.3 (16.3) (n = 13)**	**-8.8 (10.0) (n = 16)**	
	Change (ms)	**-4.0 (19.2)** p = 0.48	**+7.5 (15.7)** p = 0.10	p = 0.13
		ES = -0.23 (-0.89—0.39)	ES = 0.67 (-0.03—1.48)	ES = 0.9 (0.17—1.78)
Imputed SV drift (ml)	Pre	**-6.8 (9.1) (n = 13)**	**-3.2 (7.8) (n = 16)**	
	Post	**-5.7 (7.9) (n = 13)**	**-2.6 (5.7) (n = 16)**	
	Change (ml)	**+1.0 (11.1)** p = 0.75	**+0.6 (8.1)** p = 0.82	p = 0.72
		ES = 0.12 (-0.62—0.88)	ES = 0.08 (-0.51—0.68)	ES = 0.04 (-0.72—0.81)

LIT Low-intensity training group; *HIT* High-intensity training group; *EE* Energy expenditure; *HR* Heart rate; *RPE* Rate of perceived exertion; *VE* Ventilation; *LVET* Left ventricular ejection time; *SV* Stroke volume. *p. p.* percentage point. *Change* Absolute change between pre- and post-tests. Bold values are description values of the variables, *p* *p*-value. *ES* Hedge's g effect size (95% confidence interval).

were taken. Correlations were averaged using the same procedure. Common language effect sizes were averaged in continuous cases by averaging all μ_D/σ_D values, where μ_D is the mean value of the observed difference and σ_D its standard deviation. In non-normal cases, CLES was averaged by taking the average over all CLES'.

3 Results

All factors combined. When magnitude and onset of drifts and physiological strain were all averaged together, durability was improved in both LIT and HIT groups (LIT: combined harmonic $p = 0.03$, averaged Hedge's g ES = 0.49, CLES = 68%; HIT: $p = 0.01$, ES = 0.62, CLES = 70%) with no difference between groups (time x group combined harmonic $p = 0.42$).

Magnitudes of drifts. There was no time x group difference in magnitude of drifts (combined harmonic $p = 0.28$). The averaged drifts from pre-to post-tests decreased (Table 3) in HIT (8.8 ± 7.9% vs. 5.4 ± 6.7%, combined harmonic $p = 0.03$, averaged Hedge's g ES = 0.49, CLES = 65%), but did not reach statistically significance level of $p < 0.05$ in LIT (7.7 ± 6.8% vs. 6.3 ± 6.0%, $p = 0.09$, ES = 0.27, CLES = 62%).

Onset of drifts. There were no time x group difference onset of drifts (combined harmonic $p = 0.44$). The average onset of drifts from pre-to post-tests prolonged (Table 4) in HIT (108 ± 54 min vs. 137 ± 57 min, combined harmonic $p = 0.03$, averaged Hedge's g ES = 0.61, CLES = 63%), but did not reach statistically significance level of $p < 0.05$ in LIT (106 ± 57 min vs. 131 ± 59 min, $p = 0.08$, ES = 0.58, CLES = 68%).

Physiological strain. The averaged change in physiological strain (Figure 3; Figure 4) was large both in LIT ($p = 0.01$, ES = 0.60, CLES =

TABLE 4 Mean (SD) time of onset of the physiological drifts: EE (2.5% increase), HR (5% increase), RPE (2 steps), VE (5% increase), LVET (1.5% decrease).

		LIT	HIT	Between group change
				Time x group
Time of onset EE increase of 2.5% (min)	Pre	**98 (59)**	**111 (60)**	
	Post	**126 (69)**	**161 (65)**	
	Change (min)	**+28 (76)** $p = 0.14$	**+50 (63)** $p = 0.007$	$p = 0.62$
		ES = 0.53 (-0.05—1.19)	ES = 0.96 (0.49—1.54)	ES = 0.43 (-0.24—1.16)
Time of onset HR increase of 5% (min)	Pre	**96 (50)**	**101 (52)**	
	Post	**118 (55)**	**115 (59)**	
	Change (min)	**+23 (66)** $p = 0.17$	**+14 (59)** $p = 0.19$	$p = 0.56$
		ES = 0.49 (-0.12—1.18)	ES = 0.43 (-0.05—0.96)	ES = 0.06 (-0.62—0.76)
Time of onset of RPE increase of 2 steps (min)	Pre	**128 (52)**	**120 (50)**	
	Post	**153 (46)**	**129 (45)**	
	Change (min)	**+26 (51)** $p = 0.07$	**+9 (50)** $p = 0.42$	$p = 0.30$
		ES = 0.66 (0.15—1.26)	ES = 0.26 (-0.22—0.77)	ES = 0.40 (-0.27—1.13)
Time of onset of VE increase of 5% (min)	Pre	**101 (56)**	**101 (59)**	
	Post	**122 (58)**	**134 (62)**	
	Change (min)	**+21 (32)** $p = 0.03$	**+33 (76)** $p = 0.07$	$p = 0.72$
		ES = 0.75 (0.45—1.16)	ES = 0.60 (0.03—1.24)	ES = 0.15 (-0.53—0.86)
Time of onset of Imputed LVET decrease of 1.5 % (min)	Pre	**110 (66) (n = 13)**	**106 (43) (n = 16)**	
	Post	**136 (63) (n = 13)**	**147 (49) (n = 16)**	
	Change (min)	**+26 (70)** $p = 0.22$	**+42 (74)** $p = 0.04$	$p = 0.28$
		ES = 0.48 (-0.11—1.16)	ES = 0.76 (0.19—1.44)	ES = 0.28 (-0.39—1.00)

LIT low intensity training group; *HIT* High intensity training group; *EE* Energy expenditure; *HR* Heart rate; *RPE* Rate of perceived exertion; *VE* Ventilation; *LVET* Left ventricular ejection time. *Change* Absolute change between pre- and post-tests. Bold values are description values of the variables, *p* *p*-value. *ES* Hedge's g effect size (95% confidence interval).

73%) and HIT ($p = 0.005$, ES = 0.78, CLES = 76%) The responses were similar on both groups (harmonic time x group $p = 0.73$).

VO_{2max} and sprinting fatigue ratio. There was a large time x group difference [$p < 0.001$, ES = 1.51 (0.80—2.43), CLES = 83%] in VO_{2max}(l/min), which improved only in HIT (Table 5) [LIT: n = 14, Δ VO_{2max} = +0.02 (0.24) l/min, $p = 0.71$, ES = 0.04 (-0.15—0.24), CLES = 54%; HIT: Δ VO_{2max} = +0.32 (0.21) l/min, $p < 0.001$, ES = 1.55 (1.22—2.05); CLES = 100%].

There was no time x group difference [$p = 0.91$, ES = 0.33 (-0.44—1.16), CLES = 51%] in the sprinting fatigue ratio (Table 5). It increased in the HIT group, but no change was observed in the LIT group [LIT: n = 11, Δ sprinting fatigue ratio = +0.8 (8.6) p. p., $p = 0.18$, ES = 0.15 (-0.86—1.19), CLES = 73%; HIT: n = 17, Δ sprinting fatigue ratio = +2.4 (4.6) percentage points, $p = 0.05$, ES = 0.48 (0.06—0.98), CLES = 70%].

Post-hoc correlations. When both groups were studied together in terms of training induced changes between the drifts, VO_{2max}, and power at LT_1, the only noteworthy correlations were observed between Δ EE and Δ VE drift (r = 0.49, $p = 0.003$), and between Δ HR and Δ imputed LVET drift (r = -0.44, $p = 0.008$). The other correlations were small ($|r| < 0.22$, $p > 0.22$). Especially, change in VO_{2max} was not associated with change in any physiological drifts.

Description of durability test. RER did not change during 3 h durability test from 30 min to 180 min: from 0.93 (0.03) to 0.92 (0.02) during pre-test and from 0.92 (0.04) to 0.92 (0.02) during post-test (n = 35, both groups combined) with no differences between the groups. Body mass during the 3 h durability test was unchanged: +0.2 (0.6) kg in pre-test, and -0.1 (0.4) kg in post-test (n = 28, both groups combined) with no differences between the groups. Also, the water intake was similar in pre- and post-tests ($p = 0.07$, g = 0.59, groups combined). EE, VO_2, Imputed LVET and SV during durability test are shown in Supplementary Digital Content 2.

4 Discussion

Our main finding was that there was no difference between improvement in durability after 10 weeks of both LIT and HIT based on averaged value consisted of reduced magnitude of the physiological drifts (-1.2 and -2.4 p. p. on average), postponed time of onset (25 and 29 min on average) and attenuated physiological strain. No adverse effects, i.e. increased drifts, shortened onset of drifts

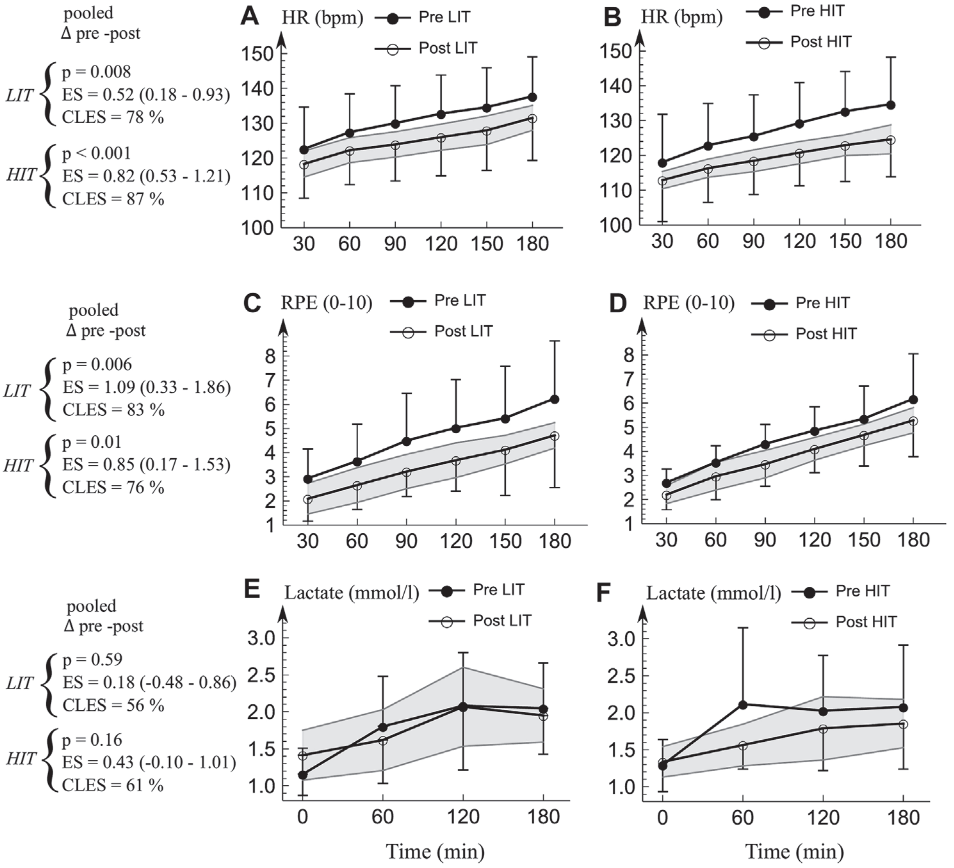

FIGURE 3
(A–B) Mean (SD) heart rate, **(C–D)** RPE, and **(E–F)** blood lactate concentration during durability test. Pooled *p*-values, ES (95% CI), and CLES were averaged from the time points of 30–180 min (60–180 min with lactate) to represent the average change. The gray area represents 95% confidence interval for the change in variable (i.e. if pre-value is outside gray area, the change in that time point is significant at $p = 0.05$ level). There were no time x group differences on average between the groups in HR, RPE, or lactate ($p > 0.25$). *LIT* Low intensity training group, *HIT* High intensity training group. *HR* Heart rate. *RPE* Rate of perceived exertion. *P p*-value. *ES* Effect size (Hedge's g). *CLES* Common language effect size.

or amplified physiological strain, were detected at the group level in any individual variable.

4.1 Results compared to literature

Our EE drift (6%) was consistent with earlier studies. Recalculated from average values from tables and figures, VO_2 drift between 4% and 7% has been reported during 90–180 min low-to moderate-intensity endurance exercise (Coggan et al., 1993; Carter et al., 2001; Rønnestad et al., 2011), but also values as high as 16% were reported (Hurley et al., 1986). In these studies, VO_2 drift was reduced by endurance alone or concurrent endurance and strength training by 2–4 p. p., which is equal to our 3 p. p. decrease in EE drift. In these same studies, initial HR drift of 10%—20% was reduced by 3 – 9 p. p. in endurance only or concurrent training. In our study, HR drift was initially 14%. HR drift was reduced by 4 p. p. in the HIT group, while it was not changed after LIT. It should be noted, however, that training does not necessarily lead to enhanced durability. Concurrent training did not affect durability (physiological drifts) during a 1 h load carriage task (Wills et al., 2019), and endurance training in well-trained athletes did not lead to enhanced durability (Hausswirth et al., 2010; Rønnestad et al., 2011), nor did concurrent training (Hausswirth et al., 2010).

4.2 Durability and relative reduction in intensity

Durability can usually be increased by endurance training in recreationally active subjects (Hurley et al., 1986; Coggan et al., 1993; Phillips et al., 1996; Carter et al., 2001). However, as training simultaneously increases VO_{2max}, the relative intensity during the prolonged tests in these studies were lower after the intervention. It is possible that after the intervention the first lactate threshold may have risen above tested intensity, thereby possibly moving the tested intensity to a different exercise zone. This provokes the question of whether durability itself is enhanced or the drifts are more restrained because of decreased relative intensity.

In our study, we assured that the intensity was in both test occasions initially at low intensity zone so that the origin of fatigue was similar at both times. Similar lactate concentrations in pre- and post-tests confirms the similar exercising zones. VO_{2max} increased

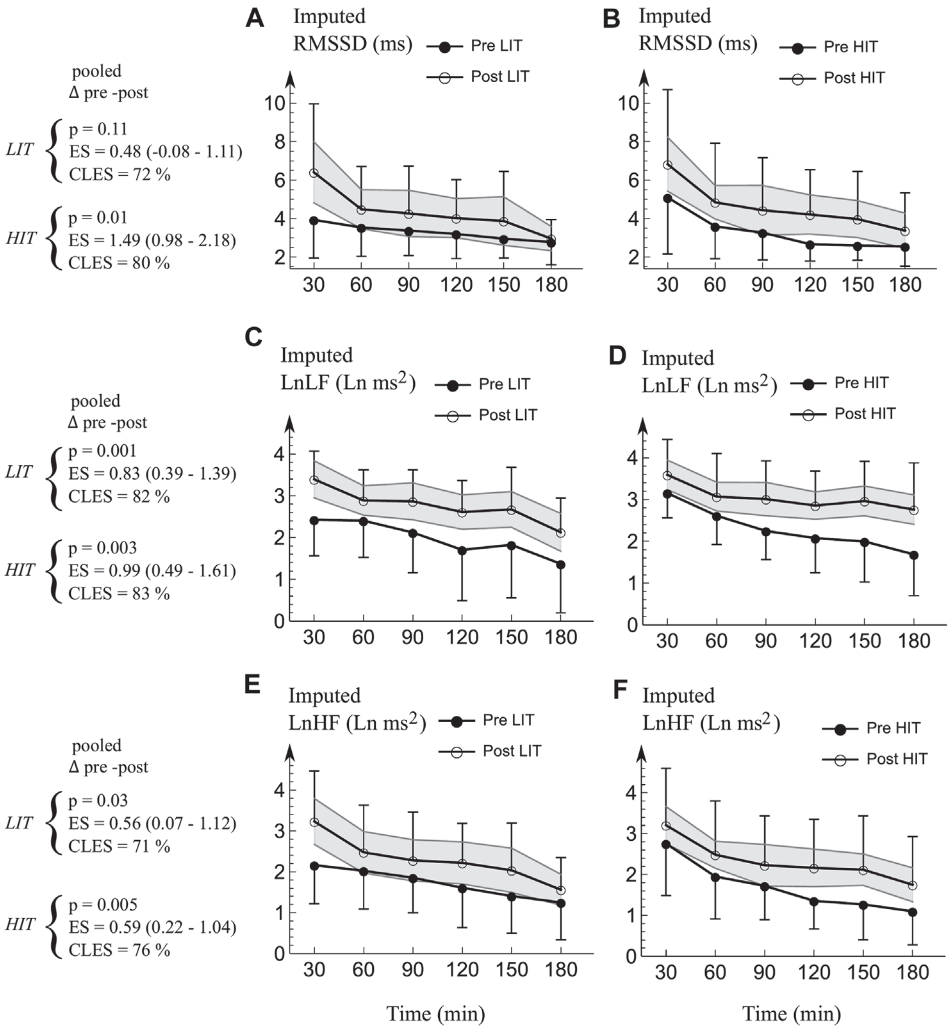

FIGURE 4
Mean (SD) imputed HRV responses to 3 h durability test. **(A,B)** RMSSD. **(C,D)** LnLF. **(E,F)** LnHF. Pooled *p*-values, ES (95% CI), and CLES were averaged from the time points of 30—180 min to represent the average change. The gray area represents 95% confidence interval for the change in variable (i.e. if pre-value is outside gray area, the change in that time point is significant at $p = 0.05$ level). ANOVA revealed no time x group differences ($p > 0.10$). *LIT* Low Intensity training group, *HIT* High Intensity training group. *HR* Heart rate. *RMSSD* Root mean square of successive RR interval differences. *LnLF* Natural logarithm of absolute power of the low-frequency band (0.04–0.15 Hz). *LnHF* Natural logarithm of absolute power of the high-frequency band (0.15–1.1 Hz). *p p*-value. *ES* Effect size (Hedge's g). *CLES* Common language effect size.

only in the HIT group and the relative intensity was -6 p. p. lower (49% vs. 43% VO_{2max}) in post-test compared to pre-test, while it remained unchanged in the LIT group. Hence, for the LIT group, durability was affected without increase in VO_{2max}. This supports the idea that factors affecting VO_{2max} and durability may be different, or that durability can be affected both by improving VO_{2max} as well as by improving submaximal metabolism.

In a previous study (Carter et al., 2001), subjects cycled both the same relative and absolute intensities after a high-volume training intervention. Based on the study (Carter et al., 2001), one can deduce (after recalculations) that physiological drifts and strain are diminished by reduced relative intensity alone, and that increased durability (2.4 p. p. reduction in VO_2 drift) might be possible when the same relative power is repeated. Further, concurrent endurance and heavy strength training has also shown that enhanced durability (reduced HR and VO_2 drifts from recalculations) is possible with only a small simultaneous increase (+3%) in VO_{2max} (Rønnestad et al., 2011). Finally, power profile in a fatigued state changes in competitive cyclists during the competition season (Spragg et al., 2022), with only minor changes in maximum exercise performance.

4.3 Decreased physiological strain

Formerly, the RPE response has been reduced after training during prolonged exercise (Rønnestad et al., 2011; Wills et al., 2019), which is consistent with the present findings. We observed that there was a decrease in submaximal exercise HR, which usually is reported to stem from increased plasma and total blood volume (Green et al., 1990). Structural or functional adaptations within the myocardium take longer and have not been found after a few weeks of endurance training (Bonne et al., 2014). Acute plasma volume expansion decreases HR considerably, up to 10–15 bpm (Green et al., 1990).

TABLE 5 Basic physiological characteristics before and after the training (mean, SD).

		VO_{2max}(l/min)	P_{max}(W)	PLT_1 (W)	PLT_2 (W)	Sprinting fatigue ratio(%)
LIT n = 16	Pre	2.90 (0.62) (n = 14)	217 (47)(n = 14)	98 (28) (n = 15)	162 (42) (n = 15)	-2.4 (4.4) (n = 11)
	Post	2.93 (0.51) (n = 14)	228 (45) (n = 14)	115 (26) (n = 15)	168 (39) (n = 15)	-1.6 (6.1) (n = 11)
	p-value	0.71	0.008	<0.001	0.14	0.18
HIT n = 19	Pre	2.77 (0.55)	212 (48)	96 (29)	158 (42)	-0.7 (5.7) (n = 17)
	Post	3.08 (0.59)	239 (47)	111 (32)	178 (37)	1.7 (4.0) (n = 17)
	p-value	<0.001	<0.001	0.005	<0.001	0.05
Between group change Time x group	*p*-value	<0.001	<0.002	0.85	0.004	0.53

LIT, low intensity training group; HIT, High Intensity Training group. VO2max, Maximal oxygen uptake. Pmax, Maximum aerobic power. PLT1, Power at the first lactate threshold; PLT2, Power at the second lactate threshold; Sprinting fatigue ratio Ratio of (15 s sprint after durability test - 15 s sprint rest)/(15 s sprint rest).

However, it does not alter, and hence explain changes in, HR drift (Green et al., 1990; Grant et al., 1997).

In creased HRV indices may also be a consequence of plasma expansion (Frank et al., 2001). Further, catecholamine responses to regular exercise in a stable trained state are reduced (Phillips et al., 1996; Carter et al., 2001). Hence, reduced sympathetic effect on the heart may lead to increased HRV, which indicates positive changes in balance of the autonomic nervous system.

4.4 Underlying mechanistic reasons to drifts

The six physiological drifts were investigated to gain a wide physiological drift profile. EE represents the overall physiological strain of exercise, and RPE represents perceived strain. HR is the most utilized marker of relative intensity during prolonged exercise, and with SV, they completely represent the circulating blood flow. LVET illustrates the sympathetic activity of the heart. VE, in addition to being strongly linked to CO_2 output, also portrays complex exercise hyperpnea.

EE drift is related to depletion of glycogen stores in slow-twitch muscle fibers of agonist muscles, after which the body needs to recruit less efficient co-agonists and fast-twitch fibers to maintain the constant power output (Krustrup et al., 2004). Also elevated O_2 cost of fatigued muscle (Hopker et al., 2017) is nominated to cause EE drift. Thus, it is presumable that at least one of these processes was slowed during our intervention. Glycogen content of a muscle is increased by endurance training (Murray and Rosenbloom, 2018), as well as fat oxidation capacity and efficiency (Phillips et al., 1996). Hence, after the training, the need to activate less efficient and highly fatigable fast-twitch fibers is postponed, leading to reduced EE drift. Additionally, endurance training alters type II fibers by augmenting fatigue-resistance to act more like the type I fibers (Seene et al., 2007), so their mechanical efficiency might not drop so considerably during prolonged exercise. As endurance training also enhances mitochondrial mass and function (Bishop et al., 2014), energy production can be spread through larger mass, inflicting smaller oxidative damage during prolonged cycling so that O_2 -cost is not elevated as greatly.

Due to the exercise intervention of the present study, HR drift was reduced in the HIT group. An increased sympathetic activation, core temperature, and fatigue of the neuromuscular system have been reported to be the reasons for HR drift (Coyle and González-Alonso, 2001). Core temperature was not measured in our study, and neuromuscular fatigue was negligible, as measured with 15 s maximum sprint. While HRV is a marker for autonomic nervous system balance, LVET and pre-ejection period can indicate chronotropic sympathetic activity (Thayer and Uijtdehaage, 2001). As the LVET drift was reduced in the HIT group in trained state, and its onset was postponed, it is possible that dampened sympathetic activity during durability tests may play a role in reducing HR drift. This observation is supported by the positive correlation between change in HR and LVET drifts. Increased HRV responses may further support our interpretation.

Durability can be seen as a form of fatigue resistance. However, the term ‘fatigue resistance’ has evolved greatly to different directions during its history. Its interpretations include, for example, an ability to resist fall in potentiated twitch force (Ducrocq et al., 2021) or in force during electrical stimulation (Morris et al., 2008), time to exhaustion (Lindsay et al., 1996), and a fraction of VO_{2max} used during a time trial (Hawley et al., 1997). Fatigue resistance is usually connected to neuromuscular fatigue during maximal and short performances. Durability, in turn, is a specifically defined way to study fatigue resistance associated to prolonged and submaximal performances using physiological variables.

4.5 Training induced changes

The groups had similar baseline physical activity habits consisting in mostly low intensity activity. Training intervention induced changes in measured responses in our study in both groups pointed toward improved durability, indicating improved durability with the exception of imputed LVET in the LIT group. Based on effect sizes, LIT and HIT did not seemed to increase drifts or their onset in large amount, despite that the subjects had not undertaken systematic endurance training and a majority of them had not engaged in 3 h exercise before. This is quite a contrast to other endurance capacity markers such as VO_{2max} (Wen et al., 2019) and time trial ability (Rosenblat et al., 2021), which are usually quite distinctly enhanced in untrained subjects. Indeed, VO_{2max} was also distinctly elevated in our HIT group with very large effect size.

Keeping power below LT_1 in the LIT group resulted in a mean HR of 63% HR_{max}. The sufficient exercise intensity to improve endurance capacity is at least 3 metabolic equivalents (Bull et al., 2020) which, in the case of the LIT group, corresponds to 58 (9)% HR_{max} in pre-test. As training did not induce changes in VO_{2max} in the LIT group, it is possible that the intensity was not high enough for these subjects (Swain and Franklin, 2002; Laursen, 2010), which leads to a conclusion that intensity to improve VO_{2max} could be higher than the intensity required for durability improvements.

It was surprising that high-volume LIT, which mimics very closely the durability test and challenges the same origins of fatigue (Black et al., 2017; Burnley and Jones, 2018), did not induce larger increases in durability. Earlier, 65% VO_{2max}-intensity training produced quite clear changes in the VO_2 drifts (Phillips et al., 1996; Carter et al., 2001), suggesting that durability may also be intensity dependent and one cannot simply compensate lower intensity with longer exercise bouts. Other reason might be that although the origins of fatigue are different in low and high intensity zones, high intensity zone could nevertheless stimulate similarly central neuromuscular function as can be deduced by similar M-wave decrease after low and high intensity exercise (Black et al., 2017) and they both deplete glycogen storages (Gollnick et al., 1974). Hence, they both could challenge similar abilities to resist fatigue at durability test. In our durability test constant energy intake was present, which prevented the influence of the possible enhanced fat oxidation capacity.

4.6 Limitations of our study

It seems that test-retest reliability measures have not been undertaken, although multiple studies have been conducted on physiological drifts in prolonged submaximal exercise (Ekelund, 1967; Phillips et al., 1996; Carter et al., 2001; Coyle and González-Alonso, 2001; Rønnestad et al., 2011; Mullins et al., 2015; Wills et al., 2019; Smyth et al., 2022). Hence, it is not known how sensitive physiological drifts are to changes in environment and preparation.

Nutrition was not controlled during the training, although the relevance of carbohydrate ingestion was stressed to participants during the training. Ingesting carbohydrates during the durability test reduced the importance of nutrition status, but it does not eliminate it completely (Tsintzas et al., 2001).

Change in plasma volume during 3 h durability test was not monitored. However, the body mass was not reduced, and the plasma volume reduction in prolonged low intensity exercise at lower than 50% VO_{2max} intensity is minimal (Grant et al., 1997). Therefore, it can be deduced that acute plasma volume change during 3 h test had minimal effect to the outcomes.

There are sex differences in physiological responses to exercise (e.g. fat oxidation) (Purdom et al., 2018). As such, it might be that there are sex-specific optimal training protocols to improve durability. Our sample size was not planned to assess possible sex differences in the studied variables. Menstrual cycle was not controlled, but ingesting carbohydrates during the durability test minimized its effect (Campbell et al., 2001).

Our sample size ($n = 35$) was quite favorable as compared to previous intervention studies ($n = 8–20$) (Coggan et al., 1993; Phillips et al., 1996; Carter et al., 2001; Frank et al., 2001; Hausswirth et al., 2010; Rønnestad et al., 2011; Bonne et al., 2014; Wills et al., 2019). Nevertheless, a higher number of subjects may have enabled us to observe differences between the study groups and/or training protocols.

4.7 Future directions

The existing research on durability has mostly been reported by observational studies using existing training databases (Van Erp et al., 2021; Smyth et al., 2022; Spragg et al., 2022). Although that allows one to reach a high number of subjects, carefully conducted laboratory studies are needed to deepen the understanding of durability, its links to other possible physiological sources (e.g. endocrinal, body temperature, and muscle activity patterns drifts), and adaptability to training.

5 Conclusion

Our study was one of the first interventions on focusing durability, and it showed that 10-week high- and low-intensity training programs increased durability among untrained subjects, and no differences between the training groups were noticed. Increased VO_{2max} facilitated 3 h cycling only in the high-intensity training group, although the change in VO_{2max} did not correlate with the change in durability. Hence, it seems that durability and VO_{2max} are not strongly related with each other and are driven by different physiological mechanisms. Despite durability enhanced among untrained people, a 10-week intervention did not alter drifts and their onsets in a large amount, even though it attenuated physiological strain.

Data availability statement

The raw data of this article is not yet available due to the agreement with the collaborative company and further papers will also be written from the same data. However, the corresponding author is willing to give further information in this regard.

Ethics statement

The studies involving human participants were reviewed and approved by Ethical Committee of the Central Finland Healthcare District. The patients/participants provided their written informed consent to participate in this study.

Author contributions

PM, OH, AN, and HK designed the study. PM, E-PA, and LP evaluated the practical implementation of the design and carried out the data collection. PM did the statistical analyses and initiated the writing. All authors revised the manuscript critically and approved the final version.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

Supplementary Material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fphys.2023.1128111/full#supplementary-material

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II

EXERCISE ENJOYMENT DOES NOT PREDICT CHANGE IN MAXIMAL AEROBIC POWER DURING A STRENUOUS 10-WEEK ENDURANCE EXERCISE INTERVENTION

by

Matomäki, P., Heinonen, O. J., Nummela, A., Kokkonen, M.,
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Exercise enjoyment does not predict change in maximal aerobic power during a strenuous 10-week endurance exercise intervention

Pekka Matomäki[1,2], **Olli J. Heinonen**[2], **Ari Nummela**[3], **Marja Kokkonen**[1], **Heikki Kyröläinen**[1]

[1] Faculty of Sport and Health Sciences, University of Jyväskylä, Finland; [2] Paavo Nurmi Centre & Unit for Health and Physical Activity, University of Turku, Finland; [3] Finnish Institute of High Performance Sport KIHU, Finland

Abstract

Study aim: Although exercise enjoyment is well studied in behavioral context, its associations to aerobic fitness adaptations during exercise interventions have received less attention.
Material and methods: Untrained participants (n = 37, 21 females), cycled either at low intensity (LIT) (n = 18, mean training time 6.7 ± 0.7 h/week) or high intensity (HIT) with 3–7 min working intervals (n = 19, 1.6 ± 0.2 h /week) for 10 weeks. Aerobic capacity, defined as the power associated with maximal oxygen uptake, was the performance outcome. Exercise enjoyment was measured after all exercise sessions during the first and the last week of the intervention.
Results: Exercise enjoyment did not predict the change of aerobic capacity ($p = 0.93$) and was not associated to the weekly perceived exertion ($p > 0.20$). Mean (95% CI) enjoyment decreased equally (time × group difference $p = 0.98$, $\eta_p^2 < 0.001$) in both groups [LIT: -7 (-13– -1); HIT: -7 (-14–0)].
Conclusions: Overall, enjoyment does not seem to be a suitable method to individualize training for improving aerobic capacity. Further, exercise enjoyment decreased during strenuous exercise intervention, and it is not a variable that affects how participants rate their overall weekly perceived exertion.

Keywords: Low intensity training – High intensity training – Exercise enjoyment – PACES – Responder

Introduction

Exercise enjoyment has been used to predict and explain exercise behavior, for example minutes of moderate to strenuous physical activity of children [42] and adults [56], adherence to physical activity [16], intention to continue to exercise [50], and buffering against the age-related decline in physical activity in youth [15]. While baseline exercise enjoyment as a predictive marker has been studied well in behavioral context, its ability to predict changes in physical performance has not received much attention. One of the rare occurrences is a study in which baseline exercise enjoyment at the beginning of the intervention did not predict walking performance in a general weight loss program [3]. Further, the change in exercise enjoyment during an intervention has been linked to an increased competence caused by change in aerobic capacity [17]. This suggests a link between improved aerobic capacity and increased exercise enjoyment of high intensity training (HIT), as has also been suggested elsewhere [18, 27]. However, even these studies do not address whether exercise enjoyment can predict future increases in aerobic capacity, even though they might change in parallel.

As adaptations to training are highly individual, some being high and some low responders [39], there is a growing interest in finding individualized optimal training programs. Typically, the predictive factors for increased aerobic fitness have been physiological ones, for example, cardiac autonomic function measured by heart rate variability [20] or genetic factors [26]. The use of psychological predictive factors, apart from stress [45], has been negligible.

Increased intensity also increases the exercise enjoyment, and HIT sessions are in many instances seen to be more enjoyable than low intensity (LIT) ones [37], although not always [8]. The reason might be that after a high intensity endurance exercise bout, one may experience

Author's address Pekka Matomäki, Faculty of Sport and Health Sciences, University of Jyväskylä, P.O. Box 35 (VIV), FIN-40014 Jyväskylä, Finland pmatomaki@gmail.com

competence, sense of accomplishment, and pride [36]. However, a number of variables influence the experienced enjoyment of a HIT session, as insufficiently active men report lower affective values during a long interval session compared to active ones [13], and the long duration of the work interval decreases the exercise enjoyment compared to short one [32].

Exercise enjoyment has typically improved or been unchanged during exercise intervention [1, 17, 18, 22, 27, 40, 41, 46, 48, 52, 53] with one exception [12] in which progressively declining enjoyment was reported in LIT and HIT across the course of the intervention. However, most of these studies used quite conservative total training loads both for LIT and HIT and short work interval lengths in their HIT group (<1 min). Further, these indoor conducted studies might be biased favoring HIT, as variable stimulus such as alternating high and low intensities as in interval training [19] increases enjoyability of an exercise.

This study has two aims. First, we tested a hypothesis that baseline exercise enjoyment at the beginning of the intervention would predict the change in maximal aerobic power and weekly rating of perceived exertion during strenuous 10-week HIT vs. LIT setting, where LIT was done outdoors. Second, possible changes in exercise enjoyment were studied, and it was hypothesized that outdoor LIT would be as effective to increase enjoyment as indoor HIT.

Materials and methods

A comprehensive description of the methods used in the research project can be found in our previously published study [34].

Participants

The study was done on healthy untrained 23–40-year-old adults (Table 1). Only participants who were sedentary or recreationally active were included. Totally 37 participants of 44 fulfilled the exercise intervention (Figure 1). Sixteen identified themselves as males, 21 as females, and none as other. All participants provided a written informed consent, and the study was approved by the Ethical Committee of the Central Finland Health Care District (8U/2020) compiled with the Declaration of Helsinki.

Exercise intervention

LIT and HIT exercises. Participants were randomly divided into LIT (n = 18) or HIT (n = 19) cycling groups for 10 weeks. Weekly training load progressed individually, emphasizing volume progression, based on self-reported weekly rating of perceived exertion (wRPE) using Borg RPE Scale® [4]. After each training week, participants were asked, in Finnish, ‘How much the training has strained your week in the scale 0–10?’. The prescribed training load progression was individualized based on wRPE, and progression was greater with lower wRPE. Training realization is shown in Table 2.

Endurance training in the LIT group was below the power corresponding the first lactate threshold (LT_1) with 3–6 weekly sessions, each lasting 45–240 min. Participants cycled with their own bikes mostly outdoors. They were given possibility to ride indoors. Three (out from 18) participants did their training completely indoors, and the others did 3% of their training indoors. The HIT group cycled 2–3 weekly indoor sessions. They had long work intervals (3–7 min) above the power corresponding the second lactate threshold (LT_2) with at least 15 min worth of cumulative work time in a session. Participants started intervention either in mid-

Table 1. Basic characteristics (mean and standard deviation) of the participants at the beginning of the study

		Aerobic capacity				
		Maximal oxygen uptake		Maximal aerobic power	Body mass index	Age
		[l/min]	[kg/min/min]	[W]	[kg/m^2]	[year]
Low intensity training group	Female (n = 11)	2.55 (0.12)	34.5 (3.8)	189 (23)	26.5 (4.4)	32.0 (5.4)
	Male (n = 7)	3.62 (0.14)	40.9 (5.5)	272 (25)	27.7 (2.8)	34.0 (6.2)
	Combined (n = 18)	2.97 (0.66)	36.7 (5.4)	221 (47)	27.0 (3.8)	32.8 (5.7)
High intensity training group	Female (n = 10)	2.33 (0.04)	37.6 (5.0)	176 (11)	23.5 (3.4)	29.8 (4.8)
	Male (n = 9)	3.25 (0.13)	37.2 (6.4)	251 (43)	27.0 (2.6)	34.2 (4.7)
	Combined (n = 19)	2.77 (0.55)	37.4 (5.5)	212 (48)	25.1 (3.5)	31.9 (5.2)

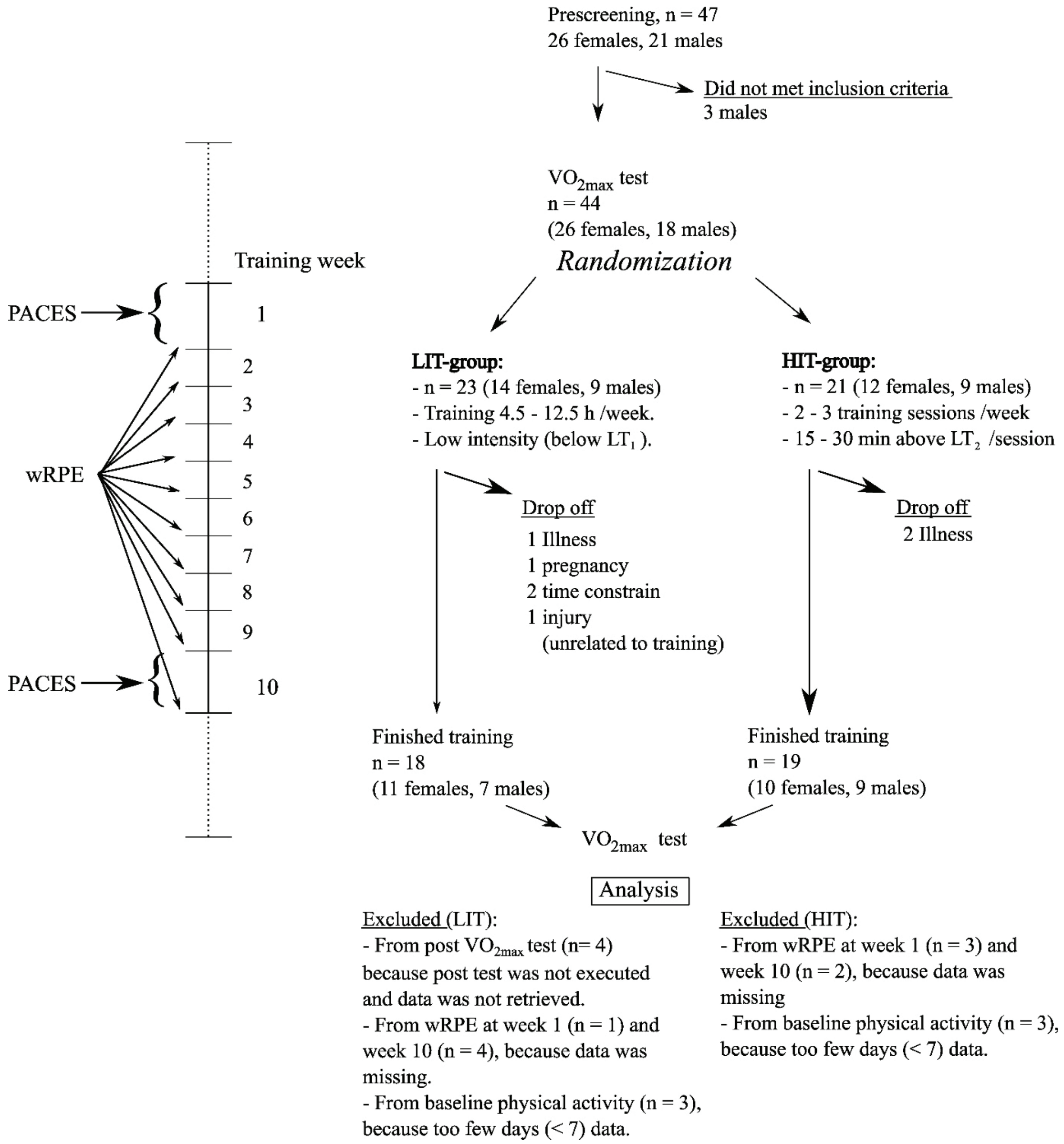

Figure 1. Flow chart of the study. *LIT* Low Intensity training group. *HIT* High Intensity Training group. *PACES* Physical activity enjoyment scale. VO_{2max} *test* Maximum oxygen uptake test. *wRPE* weekly rating of perceived exertion

Table 2. Total training realization (mean and standard deviation), in the LIT and HIT groups during 10-week exercise intervention

	Total training time [h]	Training volume [h/week]	Training frequency/week	Training session rating of perceived exertion	Time at power zones [%]					Total training load (a.u)
					Z1	Z2	Z3	Z4	Z5	
Low intensity training group (n = 18)	67.4 (7.6)	6.7 (0.8)	4.8 (0.3)	2.7 (1.3)	76 (12)	20 (12)	3 (2)	0 (0)	0 (0)	86 (13)
High intensity training group (n = 19)	15.6 (1.8)	1.6 (0.2)	2.4 (0.1)	7.2 (1.9)	53 (5)	1 (1)	2 (2)	11 (6)	33 (9)	55 (8)

Power Zones Z1 (below LT_1 – 10 W); Z2 (between LT_1 – 10 W to LT_1 + 10 W); Z3 (between LT_1 + 10 W to LT_2 – 10 W); Z4 (between LT_2 – 10 W to LT_2 + 10 W); Z5 (above LT_2 + 10 W). *LT_1* First lactate threshold. *LT_2* Second lactate threshold. *a.u.* arbitrary unit.

summer (June or July, 9 participants in the LIT and 12 in the HIT group), or in autumn (September or October, 9 in the LIT and 7 in the HIT group). A more detailed training description can be found elsewhere [34].

Measurements

Maximal oxygen uptake (VO_{2max}) was measured by maximal incremental cycling test with 3 min stages and 25–30 W increments in the week preceding the intervention and after the last training week. The measurements included breathing gases (Jaeger Vyntus TM CPX, CareFusion Germany 234 GmbH, Hoechberg, Germany) and blood lactate (analyzed with EKF-diagnostic GmbH, Ebendorfer Chaussee 3, Germany) from the last minute of each stage. LT_1 was defined as the lowest value of the lactate/VO_2 ratio, and LT_2 as a sudden and sustained increase in blood lactate concentration [11]. LT_1 and LT_2 were used to prescribe training, and maximal aerobic power (P_{max}) as the primary marker of aerobic capacity, calculated by the weighted mean of the last 3 min of the test: power of last completed stage (W) + [time (s) of unfinished state]/(180 s) × increment (W). Four participants from the LIT group did not execute post VO_{2max} test.

Training load. Training power output were distributed to five zones [6]: Z1 (below LT_1 – 10 W); Z2 (LT_1 – 10 W to LT_1 + 10 W); Z3 LT_1 + 10 W to LT_2 – 10 W); Z4 (LT_2 – 10 W to LT_2 + 10 W); Z5 (above LT_2 + 10 W). For each zone, a weighting factor was linked (in an ascending order: 1, 2, 3, 4, 7.5) and training load was calculated multiplying the factor by the time spend in the zone [6]. Realized weekly training loads are in Figure 2.

Exercise enjoyment was measured, in Finnish, by the 18-item Physical Activity Enjoyment Scale (PACES; Kendzierski & DeCarlo, 1991*).* Participants responded to "How do you feel at the moment about the physical activity you have been doing" on the 7-point bipolar scale (e.g. "1 = it is not very refreshing…. 7 = It is very refreshing" and "1 = it is not at all stimulating…. 7 = it is very stimulating"). The score was the summation of all the items, running between 18–126. Participants filled the PACES after each training session in the first and the last week of the intervention through mobile phone application (AthleteMonitoring, FITSTATS Technologies, Inc., Moncton, Canada). Weekly mean values were used for the final exercise enjoyment scores. In this study Cronbach's α for PACES was 0.95.

Physical activity. The participants were instructed to continue their daily physical activities (commuting, non-physical hobbies, etc.), but all strenuous exercise in addition to LIT or HIT was not allowed. To estimate baseline physical activity before the training intervention, daily heart rate from wrist was measured continuously (Garmin Forerunner 945, Garmin Ltd., Taiwan). Heart rate was divided into three zones using LT_1 and LT_2. Only participants with more than 7 days of data were considered. For a more comprehensive analysis of baseline physical activity, see [34].

Statistical analyses

Although the study question was included in the original study plan, the original sample size was calculated for the primary outcome of the study (increase in energy expenditure during prolonged cycling test) [34] making the current study more retrospective in nature. No sample size calculation was performed on the outcome measures of this study. Description data is presented as means and standard deviations (SD). Statistical tests were calculated by SPSS 26.0 and 28.0 (SPSS Inc, Chicago, IL, USA) and by Mathematica 13.0 (Wolfram Research, USA). The Shapiro-Wilk test was used to examine the normality together with visual inspection. Cronbach's α was calculated with all 44 participants taking part in the first exercise intervention week. Before performing the final analysis, it was determined if the magnitude of changes in the main variables differed between genders with Kruskal-Wallis test. No differences were detected in VO_{2max}, P_{max}, enjoyment, training load, or weekly rating of perceived exertion, and thus females and males were analyzed in combined groups.

Between-group differences were tested with 2 × 2 split plot ANOVA, and its effect size partial eta squared

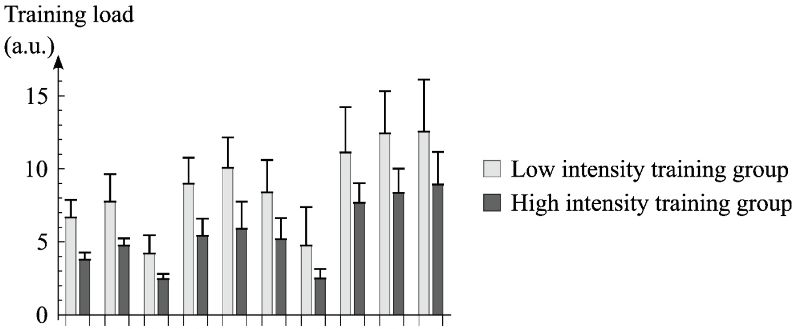

Figure 2. Mean (SD) training load during the intervention in the LIT and HIT groups. From the first to the last week of the training, the training load increased by a factor 1.9 ± 0.5 and 2.4 ± 0.9 in the LIT and HIT groups, respectively. In each week the load of the LIT group was higher than that of the HIT group ($p < 0.001$). *a.u.* arbitrary unit

(η_p^2) was calculated. Small, moderate, and large effect size magnitudes for η_p^2 were categorized as 0.01, 0.06, and 0.14 [44]. If sphericity assumption failed, Greenhouse-Geisser correction was used. In the paired comparison, 95% CI was calculated and t-test was used, except with physical activity in which Mann-Whitney was used. A hierarchical multiple linear regression was used to explore to which extent enjoyment predicted outcomes. In the first step of the model, age, gender, and group were entered as independent variables. The change in wRPE from the first to the last week was interpolated from a regression line. The analyses were run separately for summer and autumn participants, and the only difference was detected in the LIT group in change in VO_{2max} ($p = 0.04$), so it was decided to analyze summer and autumn participants in a combined group. Correlations were done using Spearman correlations.

Results

Prediction of the change in maximal aerobic power and training load by exercise enjoyment

Exercise enjoyment at week 1 did not predict the absolute change in P_{max} or the total training load (Table 3, Figure 3). Moreover, change in exercise enjoyment was not associated with the weekly rating of perceived exertion or absolute change in P_{max} (Table 3). The results were unaffected if the change in P_{max} was inspected in a relative rather than in an absolute value.

Development of exercise enjoyment

Exercise enjoyment at the first week was 90.4 (13.1) in the LIT and 97.6 (11.4) in the HIT group (between group $p = 0.08$) and at the end of the intervention 83.5 (13.4) in the LIT and 90.6 (14.3) in the HIT group (between group $p = 0.13$). Exercise enjoyment decreased in both training groups [LIT: –6.8 (-13.0–-0.8); HIT: –7.0 (-13.7–-0.2)] during the exercise intervention. ANOVA did not reveal time x group difference between the groups ($p = 0.98$, $\eta_p^2 < 0.001$).

Change in aerobic capacity

There were large time x group differences in improvement of P_{max} ($p < 0.001$, $\eta_p^2 = 0.28$) and VO_{2max} ($p = 0.003$, $\eta_p^2 = 0.26$). P_{max} improved in both groups [LIT: n = 14, ΔP_{max} = 11 W (3–19 W); HIT: ΔP_{max} = 27 W (21–33 W)], while VO_{2max} improved only after HIT [LIT: n = 14, ΔVO_{2max} = 0.4 ml/kg/min (-1.3–2.1 ml/kg/min); HIT: ΔVO_{2max} = 3.5 ml/kg/min (2.3–4.6 ml/kg/min)].

Table 3. Hierarchical multiple regression analyses on how much change in P_{max} and wRPE, and total training load were predicted by initial exercise enjoyment, and how much change in exercise enjoyment was associated with total training load and change in P_{max}

		Pre exercise enjoyment	Δ Exercise enjoyment
ΔP_{max} (n = 33)	Beta (p-value)	0.02 (p = 0.93)	0.02 (p = 0.94)
	Partial correlation	0.02	0.01
Total training load (n = 37)	Beta (p-value)	–0.07 (p = 0.53)	–0.40 (p = 0.20)
	Partial correlation	–0.11	–0.23
Δ Weekly rating of perceived exertion (n = 37)	Beta (p-value)	–0.21 (p = 0.26)	0.10 (p = 0.57)
	Partial correlation	–0.20	0.10

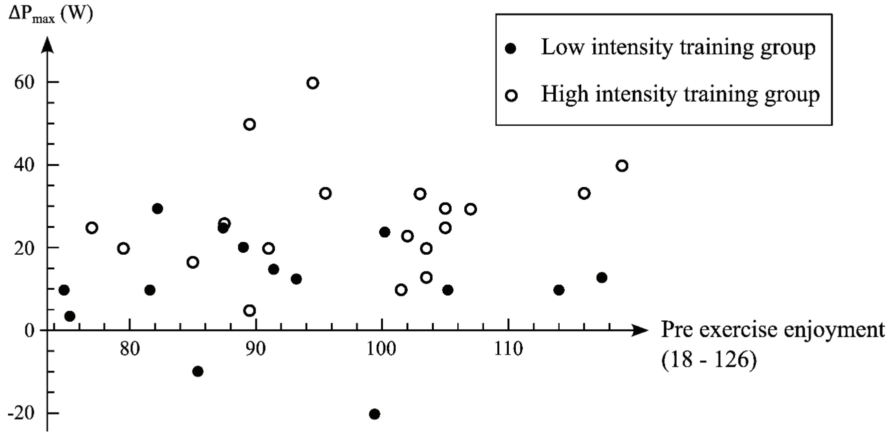

Figure 3. Scatterplot of pre exercise enjoyment scores and absolute change in P_{max} in the LIT and HIT groups

Associations of wRPE, enjoyment and training load

Exercise enjoyment did not correlate with wRPE at week 1 (LIT: $n = 17$, $\rho = 0.13$, $p = 0.62$; HIT: $n = 16$, $\rho = 0.34$, $p = 0.20$) nor at week 10 (LIT: $n = 13$, $\rho = 0.16$, $p = 0.61$; HIT: $n = 18$, $\rho = 0.09$, $p = 0.73$). Total training load correlated with average wRPE (LIT: $\rho = -0.55$, $p = 0.02$; HIT: $\rho = -0.65$, $p = 0.003$).

Physical activity

Daily minutes above the first lactate threshold at the baseline before the intervention were 6.6 (7.3) min in the LIT group and 6.2 (8.6) min in the HIT group with no difference between the groups ($p = 0.80$). The post-hoc correlations showed no differences between the time above LT_1 at the baseline and the baseline enjoyment in the LIT ($n = 15$, $\rho = -0.03$, $p = 0.93$) or the HIT ($n = 16$, $\rho = -0.22$, $p = 0.42$) group.

Discussion

The main findings of this study were that exercise enjoyment did not predict improvement in maximal aerobic power nor the individualized training load progression based on weekly rating of perceived exertion. Moreover, endurance exercise intervention with heavy load and progression decreased exercise enjoyment. Exercise enjoyment decreased even when participants were able to affect the progression themselves and train outdoors (LIT).

Exercise enjoyment predicting maximal aerobic power

There was no association between exercise enjoyment and changes in maximal aerobic power. Although exercise enjoyment may predict future physical activity [10, 42], it seems that there are not much studies on predicting change in fitness based on enjoyment.

Endurance runners have been divided into two global running patterns with different biomechanical parameters: aerial runners rely on stretch shortening cycle and return of elastic energy, while terrestrial runners minimize energy expenditure by reducing vertical oscillation [14]. Aerial runners had reported more positive feelings toward higher speed runs than terrestrial runners [28]. It has been speculated that aerial runners would benefit more from high-speed running training and explosive strength training [14]. Endurance coach practitioners have further suggested that, generally speaking, aerial runners would benefit from training intensity, and terrestrial runners from training volume [29], both of which they inherently already have positive feelings about [28]. In this study, we conceptualize this belief into a research question: Can enjoyment be used to predict the change in aerobic capacity?

However, this did not realize in our study, nor when aerial and terrestrial runners trained either explosive or maximal strength training in addition to an endurance training [38]. Further, in general weight loss program enjoyment did not predict change in walking performance [3]. Therefore, although some individuals prefer and enjoy higher intensity exercise and tolerate it better than others [9, 50], it seems that performance improvements cannot be predicted by positive feeling toward exercise alone.

There are confounding factors that may influence the conclusion. HIT has a small beneficial effect over LIT in enhancing VO_{2max} in untrained participants [35]. Combining greater enjoyment of HIT exercise [37] with its slightly beneficial effect on VO_{2max} could, at the group level, lead to a positive connection between baseline enjoyment and change in aerobic capacity. To specifically examine the individual responses without the above mentioned group level connection, we chose to use hierarchical regression, in which the group was added as an independent variable. Further, higher baseline physical activity has been associated with higher enjoyment at high intensity exercise [13], which might cause bias in the prediction of future change in aerobic capacity. However, in our study the amount of baseline physical activity above LT_1 was not associated with baseline exercise enjoyment in either group.

Exercise enjoyment and weekly exertion and total training load

Neither exercise enjoyment, nor its change were associated with the total training load or weekly rating of perceived exertion. Even though exercise enjoyment predicts physical activity [25, 42, 47, 56] and it is related to exercise motivation [21], it seems that exercise enjoyment is not a variable that affects how participants' valued overall weekly exertion or how their training load increased. Acutely, this has been reported in many studies in which enjoyment of HIT has been greater than LIT, despite HIT-session having greater perceived exertion [30, 37], but here we saw that this holds true also in larger picture.

Albeit training load was determined through weekly rating of perceived exertion, their correlation was not as high ($|\rho| = 0.55–0.65$) as one would have anticipated. That there was not a complete correlation might have emerged from interindividual difference in executing the training program. For example, that in the LIT group Z1 and Z2 zones had different emphasizes in participants' training.

Exercise enjoyment development during the intervention

Exercise enjoyment decreased during our 10-week intervention. In earlier studies, exercise enjoyment has typically improved or been unchanged [1, 17, 18, 22, 27, 40, 46, 48, 53] during an endurance exercise intervention, with one exception [12]. In our HIT group we used long intervals (>2 min) and reached at least 15 minutes of cumulative high intensity time per session as recommended for optimal aerobic fitness improvement [5, 55]. There is not much exercise enjoyment interventions using these recommendations, as only two exercise enjoyment interventions have exploited them [18, 27]. In those, enjoyment increased [27] and varied [18] during the intervention, while in our study exercise enjoyment decreased.

It seems plausible that increased training load caused our decreased enjoyment, as progression in our study was distinctively greater compared to other exercise enjoyment studies. Although not completely examined, it is possible that acutely the duration of an exercise can decrease enjoyment [1, 31]. In our study, the duration of training sessions and thus training load increased toward end of the intervention, which might have triggered decreased exercise enjoyment.

Surprisingly few studies have paid close attention to enjoyment development and factors affecting it in the long interventions [43]. After all, exercise enjoyment has been seen to change during weeks lasting interventions even when the sessions have been standardized throughout the intervention [12, 17, 18, 27, 41, 48]. Increased exercise enjoyment is often explained by increased aerobic capacity and the improved self-efficacy followed from increased fitness [17, 18, 27]. However, this cannot be the only affecting factor, as there are numerous studies in which the exercise enjoyment was unchanged [22, 52] or decreased [12] although aerobic capacity was improved. This was the case also in our study where the large change in P_{max} in the HIT group was accompanied by decreased exercise enjoyment. Other offered explanations to enjoyment development have included habituation to training [2, 48], need for an alternating stimulus [12], continuous exposure to exercise and exercise counselling [46], and fulfilled expectations of weight loss [27]. However, these factors were not measured in our study. It might be that quantitative methods alone are not adequate and more qualitative studies would be needed to reveal the whole complexity of exercise enjoyment development spectrum [49].

It seems that exercise enjoyment studies have exclusively compared the HIT and LIT exercises indoors. Indoor LIT has been reported to be felt monotonous [51] and boring [30] compared to HIT. Affective and exercise enjoyment may favorably be influenced by outdoor exercise in the presence of nature [23, 24], as well as autonomy of choosing how to implement the exercise session [33], both of which were present in our study design. We hypothesized that doing LIT outdoors would increase its enjoyment compared to indoor HIT. However, this was not realized even in the first week of the intervention, when the training load was still moderate. It seems that green exercise was not alone enough to lift enjoyment of the LIT compared to indoor HIT. Reasons why enjoyment was not uplifted in the LIT group might be changing weather, unaccustomed to outdoor cycling, and too restricted cycling power at exercises which might have limited the autonomy of choosing how to implement the session.

We acknowledge that the context of LIT and HIT was different, as solely LIT was conducted outdoors. However, this was a desired and intentional feature, and the research setting was equalized with the notion that both training modes encompass variation. HIT inherently includes variability through alternating intensities within a session, whereas variation in LIT needs to be introduced externally. In this study, it was achieved by transferring cycling to outdoor environments.

Limitations

One reason not to detect any associations between exercise enjoyment and maximal aerobic power change could be that due to small sample size, our participants were neither particularly high nor low responders [7]. If individual responding was minimal, a question of how well enjoyment predicts individual adaptation might become too challenging to get definite answer. Further, we did not have a control group, which could have helped to clarify the factors affecting development of exercise enjoyment.

When we studied whether the participants enjoy the type of exercise that is personally the most suitable for them, we understood improvement of maximal aerobic power to be the solely marker for "physiologically most suitable" exercise. However, it is well known that high responder to one variable is not that to another [54]. It follows that results may become different, if a different marker would have been chosen, for example, improvement in time trial performance, recovery ability, or more health related, such as blood pressure or arterial stiffness.

Although body mass index between the females in the LIT and HIT groups were not statistically significant (p = 0.09), difference of its mean (95% CI) of 3.0 (-0.6–6.7) indicate potential source of bias. However, it seems that obesity alone is not a substantial factor for exercise enjoyment and change in weight has been reported unclear connection to exercise enjoyment [2, 3].

Conclusions

Exercise enjoyment does not seem to be a suitable method to individualize training for increased maximal aerobic power. Moreover, exercise enjoyment is not a variable that affects how participants rated their overall weekly perceived exertion. Lastly, exercise enjoyment was decreasing during challenging endurance exercise intervention. The facts that participants had chance to affect the amount of progression and that the low intensity training was done outdoors were not enough to revert enjoyment deteriorated processes.

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Conflict of interest: Authors state no conflict of interest.

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III

ENDURANCE TRAINING VOLUME CANNOT ENTIRELY SUBSTITUTE FOR THE LACK OF INTENSITY

by

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RESEARCH ARTICLE

Endurance training volume cannot entirely substitute for the lack of intensity

Pekka Matomäki[1,2]*, **Olli J. Heinonen**[2], **Ari Nummela**[3], **Heikki Kyröläinen**[1]

1 Faculty of Sport and Health Sciences, University of Jyväskylä, Jyväskylä, Finland, **2** Paavo Nurmi Centre & Unit for Health and Physical Activity, University of Turku, Turku, Finland, **3** Finnish Institute of High Performance Sport KIHU, Jyväskylä, Finland

* pmatomaki@gmail.com

Abstract

Purpose

Very low intensity endurance training (LIT) does not seem to improve maximal oxygen uptake. The purpose of the present study was to investigate if very high volume of LIT could compensate the lack of intensity and is LIT affecting differently low and high intensity performances.

Methods

Recreationally active untrained participants (n = 35; 21 females) cycled either LIT (mean training time 6.7 ± 0.7 h / week at 63% of maximal heart rate, n = 16) or high intensity training (HIT) (1.6 ± 0.2 h /week, n = 19) for 10 weeks. Two categories of variables were measured: Low (first lactate threshold, fat oxidation at low intensity exercise, post-exercise recovery) and high (aerobic capacity, second lactate threshold, sprinting power, maximal stroke volume) intensity performance.

Results

Only LIT enhanced pooled low intensity performance (LIT: $p = 0.01$, ES = 0.49, HIT: $p = 0.20$, ES = 0.20) and HIT pooled high intensity performance (LIT: $p = 0.34$, ES = 0.05, HIT: $p = 0.007$, ES = 0.48).

Conclusions

Overall, very low endurance training intensity cannot fully be compensated by high training volume in adaptations to high intensity performance, but it nevertheless improved low intensity performance. Therefore, the intensity threshold for improving low intensity performance is lower than that for improving high intensity performance. Consequently, evaluating the effectiveness of LIT on endurance performance cannot be solely determined by high intensity performance tests.

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Introduction

According to the overload principle, training below a minimum intensity fails to provide sufficient stimulus for the body to elicit increases in physical fitness [1]. However, a clear definition of the minimum intensity required for positive endurance performance adaptations remains elusive. For instance, the minimum training intensity to induce improvements in maximal aerobic capacity (VO_{2max}) depends largely on the initial VO_{2max} level. Individuals with low initial capacity (<40 ml/kg/min) have no lower limit [2], while well-trained athletes are hypothesized to require training at a relatively high percentage, up to 95%, of their VO_{2max} to further enhance it [3]. A similar conclusion, suggesting that lower intensities are sufficient for improvement in individuals with lower initial values, has also been observed in lactate thresholds [4].

However, training intensity is not the sole factor governing adaptations in VO_{2max} as other factors including training frequency [5] and duration of exercise sessions [6] also impact the magnitude of these adaptations. Further, endurance performance is influenced by various variables, which are categorized in this study into low- and high intensity performance categories. *Low intensity performance category* encompasses all variables that impact endurance performance measured below the first lactate threshold (LT_1), such as fat oxidation capacity [7], durability [8], economy of movement [9] and post exercise recovery [10]. *High intensity performance category* refers to endurance performance related variables that are measured above LT_1, include variables such as VO_{2max}, second lactate threshold (LT_2) [9], maximal stroke volume and cardiac output [9] and maximal sprinting performance [11]. Despite athletes' preparation and competition periods usually having their own training emphases aiming to improve specific abilities [12], there is practically no scientific debate in the literature about how to periodize testing according to these emphases.

In general, improvements in untrained participants in all of these determinants have been observed with both low- and high intensity training: VO_{2max} [13], durability [8], fat oxidation capacity [14], lactate thresholds [4], cardiac output [15,16], economy of movement [17], and sprinting ability [18]. Although endurance training undoubtedly influences the modifications in these variables, a consensus regarding the impact of the frequency-duration-intensity triplet on these variables has not yet been reached.

The purpose of this study was to examine whether a lack of intensity could be compensated for by increasing volume, i.e., the duration and frequency of the exercises. Therefore, we compared the effects of a very high volume, very low intensity (LIT) cycling protocol with those of an intensive high intensity training (HIT). To gain a more comprehensive understanding of the impact of exercise intensity and volume, we examined the effects of HIT and LIT specifically on high intensity (sprint performance, second lactate threshold, aerobic capacity, maximal stroke volume) and low intensity (first lactate threshold, fat oxidation during exercise, acute recovery) performance categories.

Materials and methods

Participants

Recruitment started 1.6.2021 and ended 30.9.2021. Healthy sedentary or recreationally active untrained 18–40-year-old adults took part in the study, and their characteristics are in Table 1, with height and body mass (InBody 770, Biospace Ltd., Seoul, Korea) measured in the morning after at least 8 h fasting. Totally 35 (16 males, 19 females) of 44 implemented the exercise intervention (Fig 1). All participants provided a written informed consent. The study was approved by the Ethical Committee of the Central Finland Health Care District (8U/2020) compiled with the Declaration of Helsinki.

Table 1. Mean (SD) of the basic characteristics of the participants at the beginning of the study.

		Body mass index (kg/m^2)	Age (y)	VO$_2$max (ml/kg/min)
Low intensity training group	Female (n = 9)	25.9 (4.6)	32 (5)	35.1 (3.7)
	Male (n = 7)	27.7 (2.8)	34 (6)	40.9 (5.5)
	Combined (n = 16)	26.7 (3.9)	33 (6)	37.6 (5.3)
High intensity training group	Female (n = 10)	23.5 (3.4)	30 (5)	37.6 (5.0)
	Male (n = 9)	27.0 (2.6)	34 (5)	37.2 (6.4)
	Combined (n = 19)	25.1 (3.5)	32 (5)	37.4 (5.5)

VO_{2max} Maximal oxygen uptake.

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Training

A shortened description of training, tests and analysis is given, and a detailed one can be found elsewhere [8]. Participants were randomly divided into LIT (n = 16) or HIT (n = 19) cycling groups for 10 weeks. Weekly training load progressed individually, emphasizing volume progression. Progression was based on weekly ratio of perceived exertion (RPE); the easier the week was perceived, the greater the increase in volume. There were recovery weeks in the intervention weeks 3 and 7 to facilitate recovery. Using recovery weeks with lower training volume without alternating intensity maintains [19] or even enhance [20] endurance performance. From each exercise session, heart rate (Garmin Forerunner 945 and Garmin HRM-Pro belt, Garmin Ltd., Taiwan), power (Rally RK200, Garmin Ltd., Taiwan; or Wattbike Trainer, Wattbike Ltd., Nottingham, UK), and RPE was measured.

Training intensity distribution

Heart rates were distributed into the three zones: Z1 (below LT_1), Z2 (between LT_1 and LT_2); Z3 (above LT_2). Realized weekly training intensity distributions in the groups are shown in Fig 2. The total training HR intensity distribution in zones Z1–Z3 were 88 (18)% / 12 (17)% / 0 (0)% in the LIT group and 36 (10)% / 38 (2)% / 26 (11)% in the HIT group, respectively.

In the LIT group, the mean weekly training volume was 6.7 (0.8) h with a frequency of 4.8 (0.3) times. The mean RPE (0–10) was 2.7 (1.3) and the mean training intensity was 63 (4)% HR_{max}. In addition, it was calculated that on average participants in the LIT group exceeded LT_1 -power 21.0 (17.0) times weekly (30s average power). In the HIT group, the mean weekly training volume was 1.6 (0.2) h, frequency 2.4 (0.1) times, RPE 7.2 (1.9), and the training power in the work intervals was 117 (4)% of LT_2 power.

Training in the LIT group had 3–6 weekly sessions mostly outdoors (3 did all sessions indoors, others 3%) each lasting 45–240 min and target power was below the power of the first lactate threshold (LT_1). The mean realization of intensity during LIT was 63 (4)% HR_{max} or 87 (7)% HR_{LT1} or 47 (5)% VO_{2max} or 42 (5)% VO_2Reserve. The HIT group had 2–3 weekly indoor sessions. In each session, they did 10 min warm up and 10 min cool-down at the power level of below 60 W. As the main part, they cycled long work intervals (3–7 min) with target power 110% of the power of the second lactate threshold (LT_2) with at least 15 min worth of cumulative work time in a session.

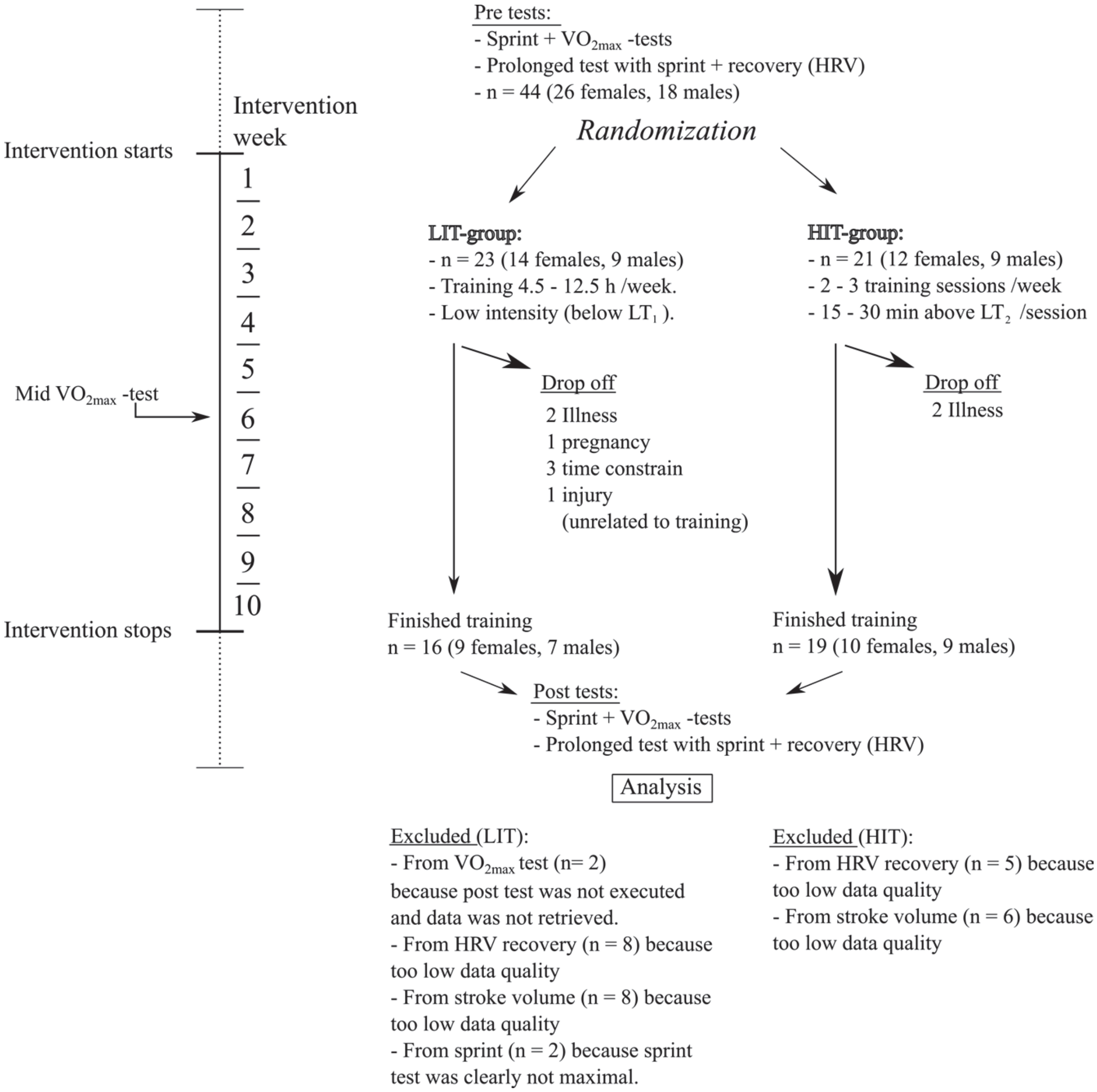

Fig 1. Flow chart of the study. *LIT* Low Intensity training group. *HIT* High Intensity Training group. *VO_{2max} test* Maximum oxygen uptake test. *HRV* Heart rate variability.

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Measured variables

Maximal graded test was done three times: preceding the intervention, at the intervention week 6, and after the intervention. VO_{2max}, LT_1, LT_2, and maximal aerobic power (P_{max}) associated with VO_{2max} were measured. LT_1 was defined as the lowest value of the lactate/VO_2 -ratio, and the second lactate threshold (LT_2) as a sudden and sustained increase in blood lactate concentration [21]. In addition, maximal stroke volume (SV_{max}) was measured during the

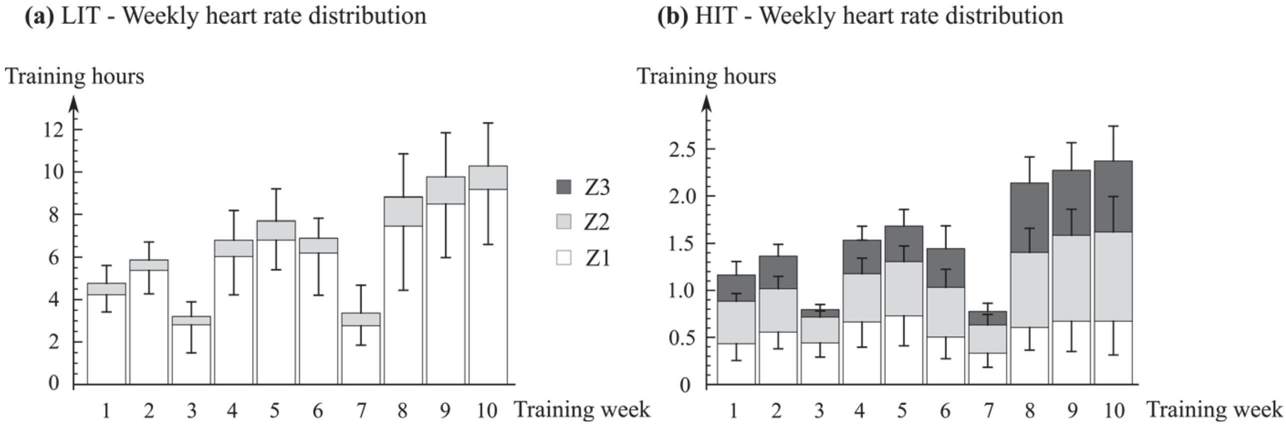

Fig 2. Mean (SD) weekly training heart rate distribution for (A) LIT, SD only for zones Z1 and Z2; (B) HIT. Notice the different y-axis in figures. *LIT* Low intensity training. *HIT* High intensity training. *Heart rate zones Z1* (below LT_1); *Z2* (between LT_1 to LT_2); *Z3* (above LT_2). *LT_1* First lactate threshold. *LT_2* Second lactate threshold.

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test by the noninvasive impedance cardiography (PhysioFlow PF-07 Enduro, Manatec Biomedical, France) with PF50 PhysioFlow electrodes. Other equipment included: ergometer (Monark LC4, Monark Exercise AB, Sweden), respiratory gas analyzer (Jaeger Vyntus TM CPX, CareFusion Germany 234 GmbH, Hoechberg, Germany), lactate analyzer (EKF-diagnostic GmbH Ebendorfer Chaussee 3, Germany), and HRM-pro or HRM-dual heart rate belt (Garmin Ltd., Taiwan).

Sprinting power was measured with 15 seconds Wingate -test (Monark 894E, Monark Exercise AB, Sweden), which is a reliable sprint test [22]. It was performed 35 minutes before the start of the graded test.

Prolonged test, lasting 3 h, was done preceding the intervention and again after the intervention. The participants were advised to have a standard meal 2.5–3 h before entering the laboratory. The absolute power was identical in the pre- and post-tests, and it was prescribed as 50% pre-VO_{2max}. The actual measured intensity in the pre-test was 48 (4)% VO_{2max}. Fat oxidation (g/min) was measured at 20–30 minutes into the test from gas exchange variables by the equation $1.67 \times VO_2(l/min) - 1.67 \times VCO_2(l/min)$ [23]. During the first 20 minutes, the participants chose their preferred position and cadence (over 60 rpm), which were recorded and maintained during the subsequent 10-minute measurement slot in both pre- and post-tests. After the 10-minute measurement slot, participants could adjust position and cadence (> 60 rpm) freely. During the test, carbohydrates were given to cover 50% of theoretical energy expenditure. As nutrition affects the fat oxidation measurement, carbohydrate intake was started after the first 30 minutes. Immediately after the 3-h prolonged test, the participants did 15 seconds Wingate -test, after which the participants sat quietly for 15 minutes on a chair to record recovery heart rate variability (HRV), and analyzed with Kubios HRV Premium (Version 3.5.0, Kubios Oy, Kuopio, Finland).

Heart rate variability (HRV)

In the HRV-analysis, low frequency (0.04–0.15 Hz) and high frequency (0.15–1.1 Hz) bands were combined into one total power band. The HRV samples were 3-minute subintervals during the recovery period at minutes 3, 6, 9, and 15. Only data points with effective data length of at least 90% were included in the final analysis. If participant had more than 2 missing data points of 8 possible ones, he/she was removed from final analysis. At total 8 in the LIT and 5 participants in the HIT group were removed. Of the rest, 12.5% of HRV data were missing. Multiple imputations were used to fill in missing data.

Performance categories

We separated low and high intensity performance categories and included all "traditional" endurance training performance variables that were measured during the study.

Low intensity performance category was encompassed variables measured at or below LT_1 -intensity: LT_1 described both as absolute power as well as VO_2-intensity relative to VO_{2max}, fat oxidation at the prolonged test, and HRV recovery followed from the prolonged cycling and sprint -tests.

High intensity performance category included variables measured above the first lactate threshold: LT_2 described both as absolute power as well as VO_2-intensity relative to VO_{2max}, VO_{2max}, P_{max}, sprinting power, and maximal stroke volume.

Statistical analyses

Although the study question was included in the original study plan, the original sample size was calculated for the primary outcome of the previous study (rise in energy expenditure during prolonged cycling test) [8]. No sample size calculation was performed on the outcome measures of this study. Data is presented as mean (standard deviation). Statistical tests were calculated by 28.0 (SPSS Inc, Chicago, IL, USA) or by Mathematica 13.0 (Wolfram Research, USA). The Shapiro-Wilk test was used to examine the normality together with visual inspection. Change in fat oxidation failed to be normally distributed. The variables in the low- and high intensity performance categories were selected before performing the analyses. Before the final analysis, it was determined, applying Kurskal-Wallis, if the magnitude of changes in the variables differed between sexes. No differences were detected in any variables and therefore, females and males were analyzed in a combined group.

Between-group differences were tested with repeated measure ANOVA. If sphericity assumption failed, Greenhouse-Geisser correction was used. In the paired comparison 95% CI were calculated and t-test was used, except for fat oxidation where Wilcoxon test was utilized. The effect size (ES) of differences for the main variables were calculated with a corrected effect size Hedge's g. Effect size for between-group differences was calculated by subtracting within-group effect sizes from each other [24]. Small, moderate, large, and very large effect size magnitudes for Hedge's g were categorized as 0.20, 0.50, 0.80, and 1.2.

The variables were pooled in low- and high intensity performance categories by averaging z-score values, from which pooled p-value was calculated. Effect sizes were pooled following the suggestion by [24]: Cohen d_i ES$\rightarrow$ Biseral r_i ES$\rightarrow$ Fisher $Z_{ri}$$\rightarrow$ Taking average $\bar{Z}_r = Mean(Z_{ri}) \rightarrow$ Averaged biseral $\bar{r}$ ES $\rightarrow$ Averaged $\bar{d}$ ES $\rightarrow$ Averaged Hedge's $\bar{g}$, where i is the different variables from which averages were taken.

Results

Low intensity performance improved on average in the LIT group (pooled p = 0.01, pooled ES = 0.49), while no change was observed in the HIT group (pooled p = 0.20, pooled ES = 0.20) (Table 2). However, no time x group difference was detected on average (pooled p = 0.62, pooled ES = 0.28) (Table 2). The post-exercise recovery-HRV after the prolonged test with sprint was similar in the pre and post -conditions in both groups (Fig 3), and there were no time x group differences between the groups (pooled p = 0.87, pooled ES = 0.06).

Table 2. Low intensity performances in the LIT and HIT groups. Description as mean (SD) and change from pre to post as Mean (95% CI).

	Low intensity training group (n = 16)				**High intensity training group (n = 19)**				**Between group time x group (pre to post)**
	pre	**mid**	**post**	**Change (pre to post)**	**pre**	**mid**	**post**	**Change (pre to post)**	
Power (W) at LT_1	98 (28) (n = 15)	109 (26) (n = 15)	115 (26) (n = 15)	16 (8–25) $p < 0.001$ ES = 0.60	96 (29)	105 (32)	111 (32)	15 (5–25) p = 0.005 ES = 0.49	p = 0.93 ES = 0.11
Oxygen consumption (% VO_{2max}) at LT_1	54.8 (5.8) (n = 14)	55.7 (5.5) (n = 14)	58.1 (5.5) (n = 14)	3.4 (0.2–6.5) p = 0.04 ES = 0.57	55.9 (4.2)	53.8 (5.0)	55.8 (4.9)	-0.1 (-2.8–2.6) p = 0.93 ES = -0.02	p = 0.09 ES = 0.60
Fat oxidation (mg/min) at low intensity exercise	155 (58)		187 (84)	31 (-5–67) p = 0.06 ES = 0.42	168 (109)		174 (79)	6 (-40–52) p = 0.36 ES = 0.06	p = 0.86 ES = 0.36

LT_1 First lactate threshold. *ES* Effect size. *p* p-value.

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High intensity performance did not improve on average in the LIT group (pooled p = 0.34, pooled ES = 0.05), while it enhanced on average in the HIT group (pooled p = 0.007, pooled ES = 0.48) (Table 3). There was a time x group difference between the groups on average (pooled p = 0.02, pooled ES = 0.46) (Table 3).

Body mass index increased in the HIT group (+0.5 kg/m^2, 95% CI: 0.2–0.7 kg/m^2, $p<0.001$, ES = 0.88), but not in the LIT group (+0.1 kg/m^2, 95% CI: -0.2–0.5 kg/m^2, p = 0.35, ES = 0.23) with no time x group difference (p = 0.09, ES = 0.65).

Discussion

The aim of the present study was to investigate whether a lack of intensity could be compensated for by increasing volume, i.e., the duration and frequency of the exercises in low and high intensity performances. The main finding was the specificity of training. When the total training hours were moderately high (averaging 10.3 ± 1.8 h in the last week), very low intensity cycling training (63% HR_{max}, or 87% HR_{LT1}, or 42% VO_2Reserve, or 47% VO_{2max}) enhanced pooled low, but not high, intensity performance of untrained participants. Conversely, HIT improved pooled high intensity performance without concurrent improvements in low intensity one. This highlights two points. First, training volume alone cannot fully compensate for very low intensity of exercise even for untrained people, as averaged high-intensity performance adaptations did not occur. Second, the intensity threshold for low intensity performance is lower than for high intensity performance, and therefore, the success of low intensity exercise intervention cannot be monitored by high intensity performance tests alone.

Low intensity performance

Surprisingly, HIT did not lead to distinct improvements in low intensity performance, although there was no difference between the HIT and LIT groups. This finding is unexpected, since HIT has been previously reported to be as effective as LIT in enhancing low intensity performance, including the first lactate threshold [16,25] and fat oxidation [14].

First lactate threshold and fat oxidation

Both LIT and HIT improved cycling power at the first lactate threshold, which is usual observations in literature [16,25]. However, only LIT improved LT_1 relative to VO_{2max}. Usually

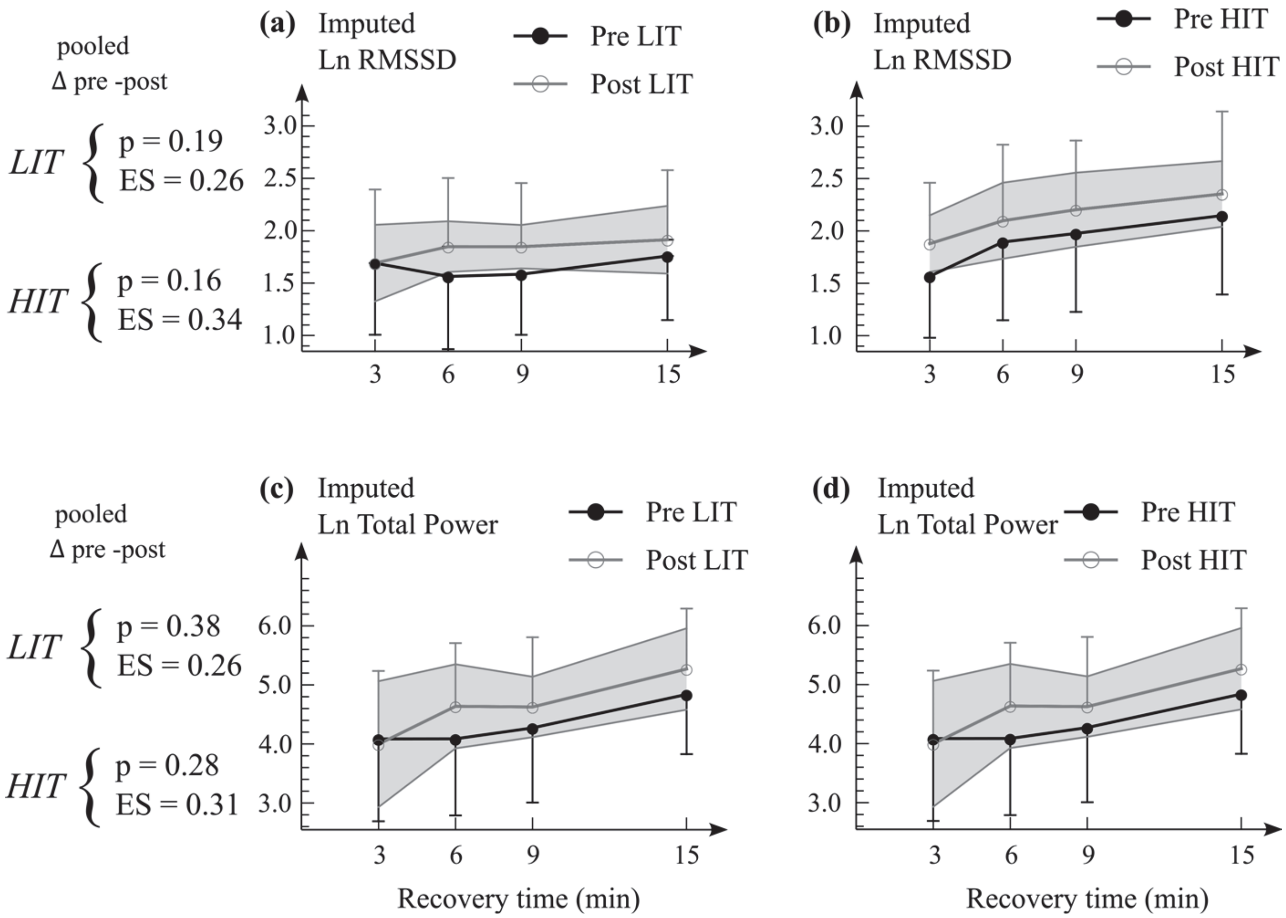

Fig 3. (A–B) Mean (SD) Ln of imputed RMSSD, (C–D) Ln of imputed total heart rate variability power during 15 min recovery after the prolonged test. Pooled p-values and ES were averaged from the measured time points to represent the average change. Sample sizes were n = 8 for the LIT and n = 14 for the HIT group. The gray area represents 95% confidence interval for the change in variable (i.e. if pre-value is outside gray area, the change in that time point is significant at p = 0.05 level). There were no time x group differences on average between the groups in LnRMSSD nor LnTotal power ($p > 0.20$). *LIT* Low intensity training group, *HIT* High intensity training group. *p* p-value. *ES* Effect size (Hedge's g). *Ln* Natural logarithm. *RMSSD* Root mean square of standard deviation. *Total power* Combined low (0.04–0.15 Hz) and high (0.15–1.1 Hz) frequency bands.

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lactate thresholds are linked to peripheral factors, such as general oxidative capacity of a muscle, fiber type, capillary density, and mitochondrial density [26–28]. These peripheral adaptations often coincide with a shift from glycogen to lipid utilization [26,27]. However, in the present study, this joint development was not found, as fat oxidation was not unambiguously altered. This discrepancy might be attributed to at least two factors. First, our sample size might have been insufficient to detect the increased lipid utilization. Secondly, the participants in our study were not in a fasted state, and the previous meal may influence fat oxidation values at exercise [29].

HRV recovery

Neither LIT nor HIT had an impact on HRV recovery in the present study. This is partially supported by the previous literature. Endurance training can accelerate post-exercise HRV recovery following endurance exercises by improving parasympathetic reactivation [10,30]. However, these improvements have typically been observed after submaximal exercises. On

Table 3. High intensity performances in the LIT and HIT groups. Description as mean (SD) and change from the pre to posttest as mean (95% CI).

	Low intensity training group (n = 14)				**High intensity training group (n = 19)**				**Between group time x group (pre to post)**
	Pre	**Mid**	**post**	**Change (pre to post)**	**pre**	**mid**	**post**	**Change (pre to post)**	
Power (W) at LT$_2$	162 (42) (n = 15)	164 (39) (n = 15)	168 (37) (n = 15)	6 (-1–13) p = 0.14 ES = 0.14	158 (42)	170 (40)	178 (38)	21 (15–27) p < 0.001 ES = 0.51	p = 0.007 ES = 0.37
Oxygen uptake (% VO$_{2max}$) at LT$_2$	77.6 (6.5)	76.0 (4.5)	77.8 (5.2)	0.1 (-3.4–3.6) p = 0.95 ES = 0.03	79.1 (5.8)	77.4 (3.4)	78.9 (4.4)	-0.2 (-2.9–2.6) p = 0.90 ES = -0.03	p = 0.97 ES = -0.06
VO$_{2max}$ (l/min)	2.90 (0.62)	2.96 (0.61)	2.93 (0.51)	0.02 (-0.11–0.16) p = 0.71 ES = 0.04	2.76 (0.55)	2.97 (0.61)	3.08 (0.59)	0.32 (0.22–0.42) p < 0.001 ES = 1.55	p < 0.001 ES = 1.51
P$_{max}$ (W)	217 (47)	223 (49)	228 (45)	11 (3–19) p = 0.008 ES = 0.23	212 (48)	231 (49)	239 (47)	27 (21–33) p < 0.001 ES = 0.55	p < 0.001 ES = 0.32
Max stroke volume (ml)	126 (21) (n = 8)		120 (27) (n = 8)	-6 (-25–13) p = 0.50 ES = -0.22	127 (41) (n = 13)		135 (42) (n = 13)	8 (-3–20) p = 0.13 ES = 0.20	p = 0.14 ES = 0.42
15 s sprint (W)	650 (152)		647 (147)	-3 (-13–7) p = 0.57 ES = -0.02	635 (161)		656 (166)	21 (10–32) p < 0.001 ES = 0.13	p = 0.003 ES = 0.14

LT$_2$ Second lactate threshold. *VO$_{2max}$* Maximal oxygen uptake. *P$_{max}$* Power associated to VO$_{2max}$. *ES* Effect size. *p* p-value.

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the other hand, post-exercise HRV recovery following maximal efforts, such as sprint in our study, is usually unaffected by exercise interventions [31].

This could be attributed to the fact that post-exercise HRV can serve as an indicator of exercise intensity, with the anaerobic contribution playing a significant role in determining the extent of parasympathetic reactivation. Thus, irrespective of training status, a maximal effort characterized by equal anaerobic contribution could result in a comparable post-exercise HRV state.

High intensity performance

VO$_{2max}$ and P$_{max}$. Although HIT can induce slightly greater enhancement in VO$_{2max}$ than LIT [13], also LIT elicits clear positive adaptations in P$_{max}$. Improved VO$_{2max}$ is mostly explained by central adaptation, particularly improved cardiac output [32]. This, in turn, is mostly explained by increased blood volume, as structural and functional changes within myocardium takes longer than a few weeks [32]. Therefore, it seems plausible to suggest that the very low intensity training employed in our study was inadequate to elicit a substantial increase in blood volume, although increase in blood volume does not necessary lead to improved maximal stroke volume and hence VO$_{2max}$ [16].

Although VO$_{2max}$ did not improve following LIT, the aerobic power P$_{max}$ improved slightly. This is in practice often more important than improved oxygen uptake. After all, although heavily linked, aerobic performance ultimately depends on external power produced rather than internal energy expenditure. Peripheral adaptations might be enough to improve cycling capacity without VO$_{2max}$ improvement [28]. Although economy of cycling movement is difficult to improve, it may be possible for untrained participants [33]. Enhanced anaerobic capacity could also result in improved P$_{max}$. Although it is possible to improve anaerobic performance through LIT [18], it did not materialize in the present study, as evaluated by unchanged 15-second sprinting ability. It is also possible, that unaccustomed participants learned during the intervention how to implement graded test.

It has been proposed that the relatively modest stimulus elicited by low intensity endurance exercise may be counterbalanced by extending the duration of the exercise [34]. However, this may not capture the full complexity of the matter. A meta-analysis suggests a possible existence of a critical threshold of intensity, below which training fails to improve aerobic capacity [2]. Specifically, for untrained individuals with an initial aerobic capacity exceeding 40 ml/kg/min, this critical intensity required to improve aerobic capacity would be around 50% of VO_{2max} [2]. In the present study, the baseline aerobic capacity of the LIT group was close to this threshold (40.9 ml/kg/min for males, 34.5 ml/kg/min for females), while their training intensity averaged 47% VO_{2max}. Consequently, our findings provide empirical support for the idea that intensity plays a pivotal role in driving enhancements in VO_{2max} and variables in high intensity performance category, in general.

Second lactate threshold and sprint

The second lactate threshold was increased exclusively in the HIT group, despite the fact that both thresholds are associated to the peripheral factors. A similar phenomenon, in which HIT exhibits a greater emphasis on the development of LT_2 compared to LIT, has been reported previously [25]. The observed different response between the present HIT and LIT groups may be attributed to their distinct mechanisms of muscle fiber activation. LT_2 represents the intensity level at which almost all fast twitch fibers are recruited [35]. While prolonged LIT sessions can recruit also fast twitch fibers [35], the LIT group likely focused mainly on training slow twitch fibers, whereas the HIT group recruited a broader range of muscle fibers in each session.

HIT, but not LIT, improved sprint. That could be explained by enhanced muscle strength, which has been observed to occur after high intensity endurance training in untrained participants [36].

Time courses of adaptations

The intervention of the present study included 8 weeks training and two recovery weeks. This timeframe has usually been sufficient for noticeable endurance adaptations. Peripheral adaptations in oxidative energy production and metabolism occur rapidly. Indeed, within less than two weeks, mitochondrial density can increase up to 30% [37] and fat oxidation 10% [38]. On the other hand, central adaptations are typically of lesser magnitude and slower, apart from plasma expansion, which may be up to +20% in three days [39]. While cardiac remodeling may not be visible after six weeks [32], it becomes apparent after three months, characterized by ~10–15% greater left ventricular mass and mean wall thickness [40]. In conclusion, if the training introduced in the present study were to induce endurance adaptations, they would likely have become apparent during the intervention period.

Training

The implementation of the training was successful. The LIT group did not exceed LT_1 power, and the work intervals in the HIT group were on average +17% above LT_2 power. Therefore, heart rate drift and kinetics presumably explain why HR distribution was not more LIT emphasized in the LIT group, or more polarized in the HIT group. For untrained participants, the volume of training in the LIT group was large, although not exceptionally large. The total volume averaged 6.7 h /week and the last three weeks 9.6 h/week. For example, in a meta-analysis [13] none of the 21 included studies that contained LIT/MIT exceeded 5 weekly hours. Moreover, studies comparing different volumes of LIT usually contain 1–5 weekly hours [41–44]. In line with the present study, these comparable studies also suggest that adding LIT volume above certain threshold does not offer advantages in VO_{2max} improvements. Further, excess amount of LIT, such as 6 h daily skiing [45,46], has not impacted VO_{2max}, while peripheral adaptations, although not excessive, occurred.

Applications to practical training

Athletes engage in periods of LIT- or HIT-focused training [12], although not necessarily as fully dedicated as in this study. Surprisingly, periodizing testing is not a heavily debated subject. Our results would suggest distinct test patterns for these types of LIT and HIT emphasized periods. It would not be even expected that high intensity variables would improve during the emphasized LIT period, and conversely with the HIT period.

Our results would also indicate that an athlete wanting to excel in very long steady state competitions have straight benefits from high volume LIT. These include e.g. ironman triathlon and ultradistance running, where competition intensity is near LT_1, and fat oxidation and relative LT_1 intensity have direct effect on competition. On the other hand, for short-distance endurance athletes with competition intensity above LT_2, such as middle distance runners, cycling time triallists or 400 m swimmers, our results would indicate a direct benefit from emphasized HIT.

However, real life situation is not so straightforward. First, high VO_{2max} would be warranted also in very long-distance athletes, as it enables also high LT_1, so they should also be engaged in HIT in some part of training year. On the other hand, although directly LIT does not seem to offer help for short-distance athletes, it may offer indirect benefits. For example, improved fat oxidation leads to spared glycogen stores during exercises and thus faster glycogen replenishment after exercise sessions.

Limitations

The sample size was not designed to meet the requirements of this study. Additionally, dietary monitoring was not incorporated, although diet could have impact on potential endurance adaptations, especially fat oxidation [47]. Further, insufficient caloric intake may lead to insufficient recovery and subsequently compromise endurance training adaptations [48]. However, participants were encouraged to eat sufficiently to meet the potentially increased energy demands caused by the training. This was successful, although not in terms of weight management, in that weight increased rather than decreased during the intervention. Additionally, conducting the prolonged test without fasting may have contributed to the fat oxidation results. However, the previous meal was standardized, and fat oxidation represents only one aspect in low intensity performance, and its influence alone cannot alter the observed results.

The baseline measurements may influence the adaptations due to regression to the mean -phenomenon. The most efficient ways to minimize the regression to the mean is to have a control group, to make duplicate measurements of the initial values, and to use surrogate measurements [49]. However, the most potential problem with regression to the mean is when the treatment is assessed in subgroups based on pre-treatment values (i.e. 'low' and 'high' level -groups) and when the intra-individual SD is large compared to inter-individual SD [49]. Although regression to the mean is always present, our study may not have a major problem with it, as the groups were not classified by pre-treatment values, and e.g. intra-individual SD of VO_{2max} (typically around 4% [49]) was not particularly high compared to inter-individual SD of ~20%. Finally, the present study used many surrogate measurements, which formed low- and high intensity performance variables.

The training dose between the groups were equalize with a rare metric based on a weekly RPE. However, this idea merely extends the well-accepted session RPE [50] to a weekly level. This allows scientifically controlled individual progression to the training. The incorporation of additional low and high intensity performance variables would have contributed to a more comprehensive understanding of the findings. We did not assess the economy of movement, as endurance training has typically only minimal effect on cycling economy [51]. Further, the present study protocol did not allow for the implementation of the fatmax concept since the graded test was not conducted at fasted state and step lengths were too short. Another aspect of interest would be durability, which refers to the ability to resist fatigue in a prolonged submaximal effort [8]. However, we have already reported, based on the same intervention, that both LIT and HIT improved durability [8]. Adding durability result from [8] to the pooled low intensity performance would slightly lower the p-value of the HIT group (from $p = 0.20$ to 0.13), but it would not change the conclusion of the present study. Two interesting high intensity performance variables could have been time trial performance and maximal enzyme activities, which would have provided more in-depth explanations for the observed results.

Conclusions

The present study showed training specificity on pooled low and high intensity performances. HIT improved high intensity performance but had no impact on low intensity performance. On the other hand, the effect of very high volume of very low intensity training (63% HR_{max}) was the opposite. These findings have two implications. Firstly, very low intensity cannot be fully compensated by high training volume even for untrained participants, as pooled high intensity performance determinants were unaltered. Secondly, minimal threshold for low intensity training zone depends on the specific performance aspect targeted for improvement. Based on the present findings, the minimal intensity required to enhance high intensity performance (including sprint, VO_{2max}, P_{max}, maximal stroke volume, and the second lactate threshold) is higher than the intensity required to improve low intensity performance (including fat oxidation, HRV recovery, and the first lactate threshold). Consequently, evaluating the effectiveness of LIT on endurance performance cannot be solely determined by high intensity performance tests.

Practical applications

There are two practical applications of this study. First, in order to see the benefits of LIT on endurance performance, one should consider low intensity performance tests, as high-intensity performance tests (e.g., time trial or VO_{2max} test) may not provide a comprehensive picture of the benefits of LIT. Second, very high volume alone cannot compensate for the lack of sufficient intensity for the overall development of endurance performance.

Author Contributions

Conceptualization: Pekka Matomäki, Olli J. Heinonen, Ari Nummela, Heikki Kyröläinen.

Data curation: Pekka Matomäki.

Formal analysis: Pekka Matomäki.

Funding acquisition: Heikki Kyröläinen.

Investigation: Pekka Matomäki.

Methodology: Pekka Matomäki, Olli J. Heinonen.

Supervision: Olli J. Heinonen, Ari Nummela, Heikki Kyröläinen.

Writing – original draft: Pekka Matomäki.

Writing – review & editing: Pekka Matomäki, Olli J. Heinonen, Ari Nummela, Heikki Kyröläinen.

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IV

HOW TO EQUALIZE HIGH- AND LOW-INTENSITY ENDURANCE EXERCISE DOSE?

by

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How to equalize high and low intensity endurance exercise dose?

Pekka Matomäki[1,2]; Olli-Pekka Nuuttila[1], Olli J. Heinonen[2]; Heikki Kyröläinen[1]; Ari Nummela[3];

[1]Faculty of Sport and Health Sciences, University of Jyväskylä, Finland
[2]Paavo Nurmi Centre & Unit for Health and Physical Activity, University of Turku, Finland
[3]Finnish Institute of High Performance Sport KIHU, Finland

Corresponding author:
Pekka Matomäki, Faculty of Sport and Health Sciences, University of Jyväskylä, P.O. Box 35 (VIV), FIN-40014 Jyväskylä, Finland; E-mail: pejamato@jyu.fi; Tel. +358405456534

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ABSTRACT

Purpose. Without appropriate standardization of exercise doses, comparing high (HI) and low intensity (LI) training outcomes might become a matter of speculation. In athletic preparation, proper quantification ensures an optimized stress-to-recovery ratio. This review aims to compare HI and LI doses by estimating theoretically the conversion ratio, 1:x, between HI and LI: How many minutes, x, of LI are equivalent to one minute of HI using various quantification methods? A scrutinized analysis how the dose increase in relation to duration and intensity was also made.

Analysis. An estimation was conducted across four categories encompassing 10 different approaches: (1) “arbitrary” methods; (2) physiological and perceptual measurements during exercise; (3) post-exercise measurements; comparison to (4a) acute and (4b) chronic intensity-related maximum dose.

The first two categories provide the most conservative estimation for the HI:LI ratio (1:1.5–1:10) and the third slightly higher (1:4–1:11). The category (4a) provides the highest estimation (1:52+), and (4b) suggests 1:10–1:20. The exercise dose in the majority of the approaches increases linearly in relation to duration and exponentially in relation to intensity.

Conclusion. As dose estimations provide divergent evaluations of the HI:LI ratio, the choice of metric will have a large impact on the research designs, results, and interpretations. Therefore, researchers should familiarize themselves with the foundations and weaknesses of their used metrics and justify their choice. Lastly, the linear relationship between duration and exercise dose is in many cases assumed rather than thoroughly tested, and its use should be subject to closer scrutiny.

Keywords: Low intensity training, High intensity training, Training load, Exercise dose, Session RPE, TRIMP

Introduction

In endurance exercise studies, the quantification of exercise dose has been acknowledged as a crucial factor for the interpretation of the results[1]. The meaningful and rational comparison of exercises performed at different intensities relies on the appropriately balanced exercise doses and stimuli. In the context of athletic training, quantification of a training dose is also needed to ensure an optimized stress-to-recovery ratio, thereby mitigating the risks of both over- and undertraining as well as musculoskeletal injuries. Quantification of training dose also serves to elucidate the relationship between training and performance[2,3].

In this review, *exercise* is defined as a single endurance bout, whereas *training* is a systematic repetition of such exercises over an extended period. Further, *exercise dose* is defined as a physiological strain resulting from the combination of the intensity and duration of an endurance exercise session[4,5]. Multiple exercise doses over an extended period constitute a *training dose*.

In practice, studies with different metrics have usually given surprisingly similar exercise dose values for both low- (LI) and high intensity (HI) exercises[6,7], making 45 - 60 min LI exercise theoretically equally straining than 4 x 4 min HI interval exercise. However, often metrics used in these comparisons, such as Edwards', Lucia's, Banister's, or individual training impulse (TRIMP), as well as total work done, are based on *assumed* relationship between intensity, duration, and the strain they cause. Many methods lack validation as measures of exercise dose, and there is no formal explanation of how these methods would connect physiological strain to the quantified value they propose [8]. As a result, they are deemed inadequate to quantify exercise doses[9]. Indeed, if strain is directly measured, either by the acute performance decrements[6,8], excess post-exercise oxygen consumption (EPOC)[10], or by recovery time[11], it soon becomes evident that a single HI exercise disrupts the body's homeostasis more strongly than an hour LI exercise.

The concept of "physiological strain", that different metrics aim to assess, is elusive and may vary depending on specific objectives of researchers and practitioners. Ways to calculate exercise dose are based on different presumptions and perspectives. The objective of this narrative -style review is to compare and connect various quantification methods from three angles:

(1) To explore how various quantification metrics balance exercise and training doses within LI and HI zones. This is done by relying mostly on pure theoretical calculations showing how many LI minutes are equivalent to one HI minute in different approaches in a hypothetical exercise session.
(2) To theoretically evaluate the growth rate of each approach with respect to duration and intensity.
(3) To elucidate excplicitly the premises upon which the metrics are based and critically discuss their weaknesses.

Methods

Of the numerous approaches aiming to quantify the elusive exercise and training doses, ten are presented in this review. The choice was to include all "basic" metrics that are in use in comparison studies and reviews[2,4,6–8]. Methods for directly measuring strain were explored and there existed enough studies on acute performance decrements, EPOC, and maximal dose to enable HI:LI ratio estimations. The methods (Table 1) are divided into four categories: (1) "Arbitrary" methods; (2) Physiological and perceptual measurements during exercise; (3) Post exercise measurements; (4a) Comparison to acute maximum dose; (4b) Comparison to chronic maximum sustainable dose.

Table 1. Used methods to theoretically estimate the exercise dose, and the foundation of the different methods.

Quantification method	Physiological base
(1) “Abitrary” methods	
Lucia’s TRIMP	Dose increases “arbitrarily” across lactate thresholds
Edwards’ TRIMP	Dose increases “arbitrarily” across “arbitrary” thresholds
(2) Physiological and perceptual measurements during exercise	
Total work done/Energy expenditure	The dose is solely determined by the expended energy
Session RPE	Perceived exertion has one-to-one similarity with the dose
Blood lactate	Blood lactate concentration has one-to-one similarity with the dose through HR
Banister’s TRIMP	Blood lactate curve determines the dose through HRR
(3) Post exercise measurements	
EPOC	Disturbance to homeostasis determines the dose
Loss of performance	Performance decrement determines the dose
(4) Comparison to maximum dose	
Comparison to acute maximum dose	Body is equally strained with a duration relative to an acute intensity-dependent maximum effort
Comparison to chronic sustainable dose	Body is equally strained with a duration relative to a chronic intensity-dependent maximum effort

HR Heart rate; *HRR* Heart rate reserve; *EPOC* Excess post-exercise oxygen consumption.

The focus is to analyze the impact of exercise duration, intensity, and density. Other factors such as exercise mode, cognitive load, psychological states, nutritional status, and ambient temperature, are intentionally excluded from the analysis, despite their potential influence on the exercise dose.

We will calculate theoretical HI:LI ratios mostly based on widely adopted two submaximal anchors. The first and the second lactate/ventilation thresholds divide intensities into three zones: Low, moderate (MI), and high intensity zones. Although prescribing exercise intensities based on these anchors may be far from optimal one, as there is no assurance that the chosen anchor truly represents a shift in the metabolic state of the working muscle[12], it is nevertheless one of the strongest there is currently available[12]. The etiology of fatigue also strongly aligns with the division established by the anchors[13,14].

Calculating HI:LI ratios

To compare methodologically different approaches, where applicable, the balanced HI:LI ratios were theoretically calculated based on ideal exercises with a hypothetical participant as summarized in Table 2. Especially, 90–95% VO_{2max} intensity was used as the high intensity, which is commonly used in interval training[15] and 50–60% VO_{2max} intensity as the low intensity[16]. These turn into 95–97.5% HR_{max} and 70 – 80% HR_{max} values[17], respectively. Furthermore, the "intensity goal" method was adopted, where the exercise dose is determined based on the target intensities of the session, without considering factors such as the kinetics of HR or VO_2. To enable a pure direct comparison between LI and HI, only a continuous exercise format both for the LI and HI exercises were considered. Selection of used metrics are presented in Supplement 1 for simulations and detailed calculations are provided in Supplement 2.

Table 2. The used presumptions to theoretically calculate HI:LI ratios during ideal LI and HI exercise sessions.

	Intensity						
	% VO_{2max}	% HR_{max}	Blood lactate (mmol/l)	RPE (0–10)	RER	Acute maximum time	Chronic maximum time / week
LI exercise	50–60	70–80	0.8–1.5	1–4	0.71–0.95	≥24 h	≥ 35 h
HI exercise	90–95	95–97.5	6–10	7–10	1.00	10–20 min	3.5 h

Premises of the metrics

(1) “Arbitrary” methods

In *Lucia's TRIMP* method, the three HR zones are designated with linear weights of 1, 2, and 3[18]. These weights are then multiplied by the time spent in the respective zone to estimate the exercise dose. Similar linear scale is used in *Edwards’ TRIMP*, where there are five “arbitrarily” chosen HR zones, 50–60%, 60–70%, 70–80%, 80–90%, and 90–100% HR_{max}, with weights ranging from 1 to 5[8,19].

(2) Physiological and perceptual measurements during exercise

Exercise doses have traditionally been balanced by equalizing the *total work done* or the *energy expended*. To reach the work from VO_2 -intensity, the American College of Sports Medicine conversion equation for the bicycle ergometer is: $\mathrm{VO_2(ml/kg/min)} = 11.016 \times P\mathrm{(W)/body\ mass(kg)} + 7$ [20]. To estimate the energy expenditure, corrected Weir equation with 0% nitrogen[21] was used: Energy expenditure (kJ/min) = $(16.62 + 4.51 \times \mathrm{RER}) \times \mathrm{VO_2(l/min)}$.

In *session rating of perceived exertion* (session RPE), the duration of the exercise session is multiplied by its RPE, rated on a scale 0–10[22].

In *individualized TRIMP*, each HR value is linked to an individual weight factor derived from a blood lactate concentration curve from an incremental VO_{2max} test multiplied by time spent at the particular HR [23]. Using a rough estimation, blood lactate concentrations are 0.8–1.5 mmol/l in the LI zone and 6–10 mmol/l in the HI zone[24].

Banister's TRIMP is based on average HR of an exercise session or of different segments of a session, and the TRIMP is determined by the formula: $\mathrm{duration} \times \Delta\mathrm{HR} \times e^{b\Delta\mathrm{HR}}$, where $\Delta\mathrm{HR} = \frac{\mathrm{HR_{avg}} - \mathrm{HR_{rest}}}{\mathrm{HR_{max}} - \mathrm{HR_{rest}}}$ and $b = 1.92$ for males and 1.67 for females[25]. The nonlinear term ($e^{b\Delta\mathrm{HR}}$) has been added to replicate a lactate curve. In our theoretical estimations, $\mathrm{HR_{max}}$ range between 170–195 bpm[1] and $\mathrm{HR_{rest}}$ between 50–80 bpm[2].

(3) Post exercise measurement

EPOC is a general indicator for disturbance to homeostasis[10]. Only one suitable direct HI vs. LI exercise comparison study was identified[26]. A magnitude of EPOC increases exponentially in response to exercise intensity and linearly to duration[27]. Based on this finding, we used data from the meta-analysis on the LI vs. MI studies[27] to make an estimation of HI:LI ratio by extra- and/or interpolating[3]. These estimations contain a total of eight original studies[28–35].

An acute strain of the exercise can be measured by its immediate impact on *loss of performance*[8]. In our estimation, we have used the facts that a maximal 20 min HI session led to an 18% reduction in 5-minute maximal performance, while a 40 min LI exercise resulted in a 4% reduction[36]. Furthermore, time to exhaustion at 80% $\mathrm{P_{max}}$ was reduced by 75% and 8% following a 30 min cycling in the HI- and LI zones, respectively [37]. Lastly, a reduction in maximal voluntary contraction has been comparable (~15%) after both a 20 km time trial [38] and a 3–4 h LI bout[39,40].

(4a) Comparison to an acute maximum dose

Here the idea is to quantify the exercise dose relative to the acute intensity-related maximum duration[9]. For example, the exercise dose of an exercise with a duration of 60% of an intensity-related maximum is double that of 30%. The intensity related maximum durations can be estimated by regression methods or by directly measuring. Dividing a maximum LI time with a maximum HI time gives theoretical HI:LI ratio.*Regression models* are utilizing times to exhaustion at various intensities in the HI zone. Then it is possible to construct a log-linear regression line that extends into the LI zone[41]. Power law is also commonly used regression estimation, especially with running, to model the connection between time and distance by $t = as^{-b}$, where t is time (min), s running distance (km), and a and b positive coefficients[42,43].

In *measured maximum acute dose* it is directly measured how long will it take until exhaustion. If energy intake is adequate, LI exercise can be sustained until sleep deprivation eventually compels an individual to stop[44], allowing for durations of at least 24 hours [45]. On the other hand, sustaining exercise at 90–95% of $\mathrm{VO_{2max}}$ intensity is only possible for 10–20 minutes[46,47].

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[1] Predicited $\mathrm{HR_{max}}$ with an equation 205.8 – 0.685×age for ages 18–50 [17].

[2] Normal limits of $\mathrm{HR_{rest}}$ [84].

[3] First, a linear transformation was made to convert the duration of LI exercise to match the duration of MI exercise. For example, in a case of 41 min LI exercise vs. 34 min MI exercise, it was determined what would be the corresponding EPOC following 34 min LI exercise. Second, using these two iso-timed EPOC points, an exponential model was constructed to extrapolate and/or interpolate EPOC values for the intensity ranges of 50–60% and 90–95% $\mathrm{VO_{2max}}$.

(4b) Comparison to a chronic sustainable dose

An acute maximum dose model is not sustainable for extended training periods. To illustrate this, consider three weekly HI sessions with 7 x 5 min at an intensity corresponding to 15 min maximum intensity. This amounts to 750% of the maximum acute dose for HI training in a week. In comparison, if the maximum acute dose for LI exercise is set at 24 h, achieving an equivalent amount of LI training time require 7.5 d in a week, which is clearly impossible to achieve. Therefore, a more refined model is needed to better incorporate the demands of chronic training.

The intensity-related maximum sustainable dose is defined as “a maximum amount of training at a given intensity that body can sustain chronically without non-functional overreaching”. In this method the idea is to quantify the exercise dose in relation to the chronic maximum sustainable dose instead of acute maximum duration. This concept is similar to the training threshold saturation[48]

To theoretically calculate HI:LI ratio, one would need to estimate the maximum sustainable amounts of both HI and LI averaged in a given time frame, e.g. week, and then divide these numbers. A potential HI candidate would be the strenuous endurance training intervention conducted by Hickson et al.[49]. The study involved six weekly HI sessions for a duration of 10 weeks. Sessions consisted of alternating 6 x 5 min maximal cycling intervals and 40 min of maximal continuous running. The intervention led to a linear increase in fitness, indicating that no overreaching occurred. However, the training program is teetering on the edge of overreaching, as the same program has led to overreaching within six weeks in trained runners[50]. Using the “intensity goal” approach, the total weekly HI time here amounts to 3 x 6 x 5 min + 3 x 40 min = 3.5 h. These findings suggest that the weekly HI time of 3.5 h might be close to the maximum sustainable dose.

Some insights into the maximum sustainable amount of LI training can be obtained from a study, where soldiers skied (~45 % VO_{2max}) an average of 33 h weekly for 8 weeks[51]. Further, during weeks long expeditions in Artic areas, daily skiing durations ranged between 5.7–10 h[52–55] corresponding to 40–70 weekly hours. As such, weekly 33–70 h is the best estimation for the maximum sustainable LI dose.

Results

HI:LI ratios

The theoretical HI:LI ratios of the different approaches very between 1:1.5–1:100+ (Figure 1).

Increase of the dose

Theoretical increase of the doses in relation to duration and intensity are analyzed below and illustrated in Figure 2.

In **“Arbitrary” methods**, both *Lucia’s* and *Edwards’ TRIMP* increase linearly in relation to duration and intensity.

Physiological and perceptual measurements during exercise. *Energy expenditure* and *total work done* both create a linear relationship with both duration and intensity. In *session RPE* duration increases RPE value linearly[56,57]. For instance, during the LI session, RPE may initially be 3 after 30 min, but after 3 h, RPE may linearly increase to 6 due to the fatiguing effect of the prolonged duration[56]. When this inflated RPE value is multiplied by duration, the duration is effectively added twice into the final value. Hence, session RPE is increasing quadratically with respect to duration, while it increases only linearly with respect to intensity[58]. *Individualized TRIMP* increases linearly in relation to duration. Lactate curve dictates the increase of TRIMP related to intensity, and both exponential[59] and 3rd order polynomial growth[60] have been used. *Banister's TRIMP* is linearly related to the duration and exponentially related to intensity.

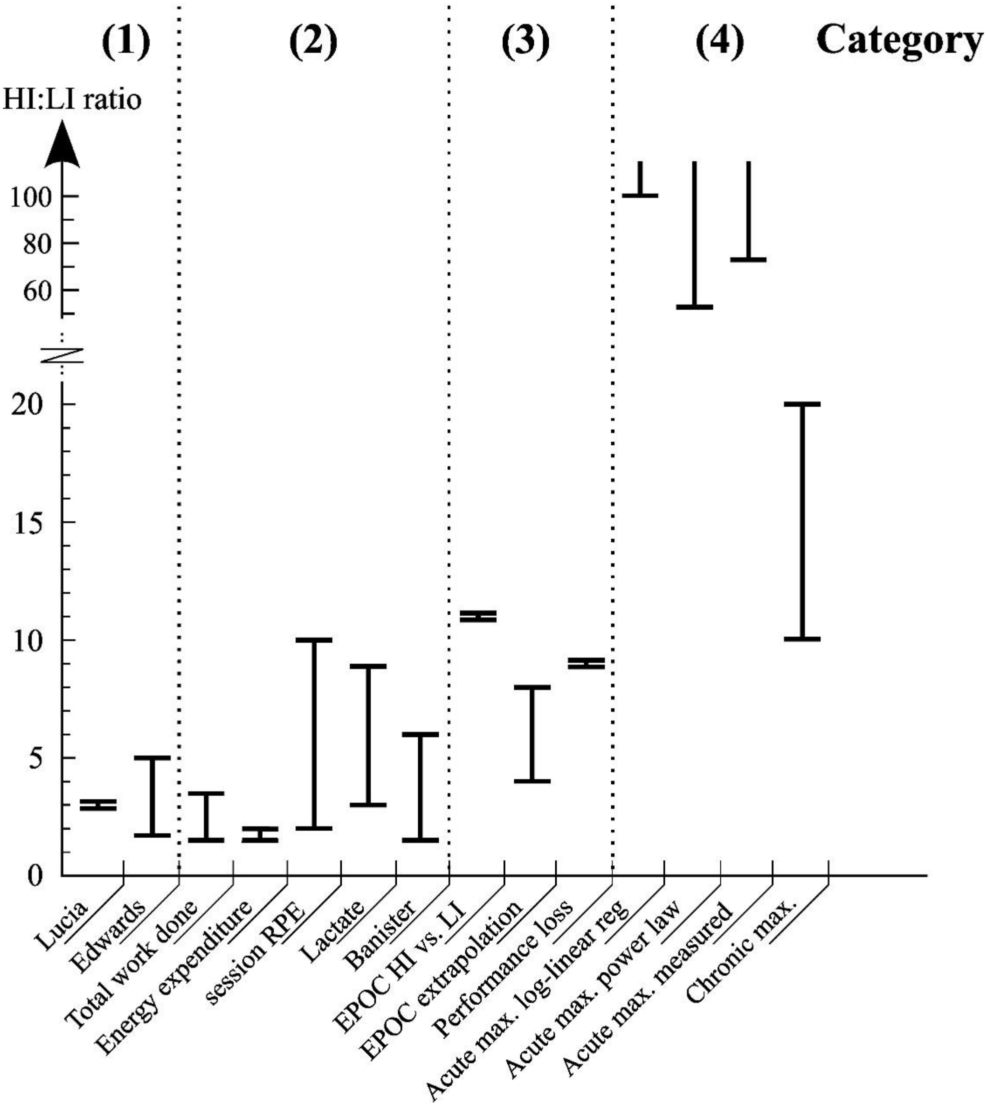
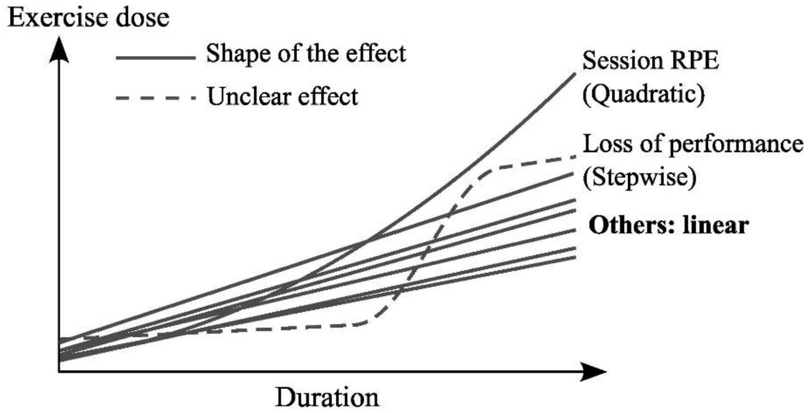


Figure 1 — Theoretical estimations of HI:LI ratios. How many LI minutes equal to 1 HI minute using different methods. EPOC indicates excess postexercise oxygen consumption; HI, high intensity; LI, low intensity; RPE, rating of perceived exertion.

Post exercise measurement. A magnitude of *EPOC* increases exponentially in response to exercise intensity and linearly to duration[27]. While conclusive results are lacking, the fatiguing effect of intensity to the *loss of performance* might follow an exponential relationship[8]. On the other hand, duration, at least for the LI and MI sessions, may have a step-like impact[39,40,61,62], referring to a case where at first, fatigue is not cumulated, but when it does, it increases large amount in a short time frame.

In **Comparison to maximum duration/dose** exercise dose increases linearly related to duration. In acute setting, the increase related to intensity depends on the estimation method. The *log-linear regression* indicates exponential relationship, while *power law* leads to a polynomial relation with an order 12–21 (Supplement 2). *Measured maximal dose*, both acute and chronic settings appear to be exponential with no absolute certainty.

(A) Impact of exercise duration to the exercise dose



(B) Impact of exercise intensity to the exercise dose

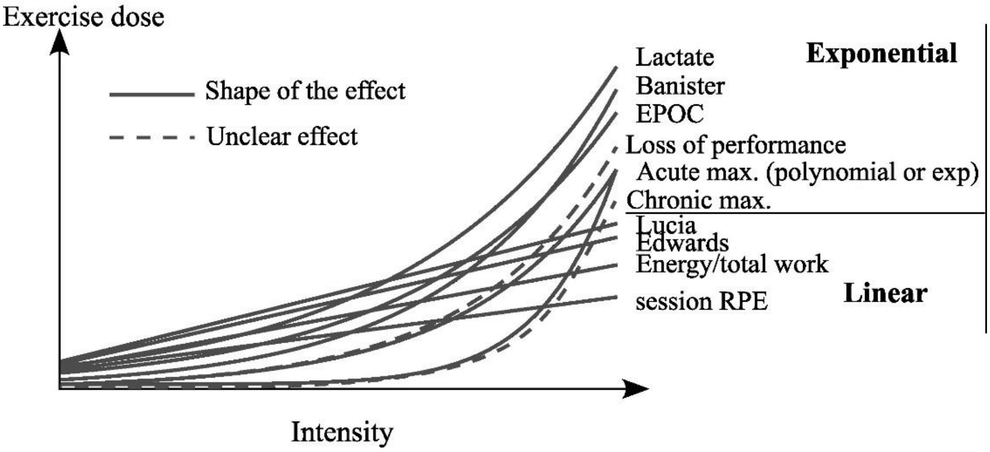


Figure 2 — Impact of an exercise (A) duration and (B) intensity to the exercise dose in different quantification methods. Notice that only the shape is illustrated, not the magnitude. (A) Duration has a nonlinear effect for 2 methods. Others follow linear relationship. (B) Intensity has mainly exponential or a linear effect. A polynomial effect may also be used in lactate and comparison to acute maximum methods. EPOC indicates excess postexercise oxygen consumption; RPE, rating of perceived exertion.

Discussion

Our main aim was to compare theoretically how different metrics quantify exercise doses. The calculated HI:LI ratios varied between 1:1.5 to 1:100+. Consequently, the choice of metric will have a large impact on the research designs, results, and interpretations. Therefore, researchers should familiarize themselves with their used metrics and explicitly justify the use of a particular metric. Majority of the approaches show an exponential increase with intensity and a linear one with duration. A more detailed analysis, see below, reveals that the relationship between linearity and duration is largely assumed rather than tested.

Discrepancy of HI:LI ratios

Typically used metrics for evaluating exercise dose, that is Lucia’s, Edwards’, Banister’s, and individual TRIMP, as well as session RPE and total work done/expended energy fall into the first two categories: arbitrary (1) and measured during the exercise (2). Their theoretical estimations for HI:LI ratios overlap for the most parts, giving ratios around 1:3–1:5. Interestingly, methods directly measuring the dose, in categories measured after the exercise (3) and comparison to maximums (4), provide visibly higher estimations, mostly 1:9 or higher. This discrepancy suggests that conventional training load metrics are not effectively capturing the intended physiological strain, at least not in a manner similar to EPOC, loss of performance, and relative to maximum dose. This division is evident in the literature as well. If only metrics from categories (1) and (2) are compared, a very harmonious HI:LI ratio is seen among the metrics [6]. However, if other approaches, such as loss of performance, are included, the resulting stance is more critical [6,8]. The discrepancy is fueled by the fact that there is no formal explanation of how many of the conventional methods from categories (1) and (2) would connect physiological strain to the quantified value they propose [8]. This has also led to a recent critical commentary suggesting that conventional training load metrics used to quantify exercise dose between high and low intensity exercises are inadequate[9].

In our theoretical calculations HI:LI ratio ranged from 1:1.5 to 1:100+ making it impossible to equalize simultaneously HI and LI exercises across all metrics[63]. This raises the question of whether certain metrics hold superiority over others. A definitive answer may not exist, as the concept of "physiological strain", that these metrics aim to assess, is elusive and may vary depending on specific objectives of researchers and practitioners. For example, the same HI exercise may give different strain on the neuromuscular system, the cardiovascular system, or the psychological sensation of stress. As a result, comparison to acute maximum dose[9], loss of performance[8], and expended energy[64] all have their advocates. There has also been a suggestion that balancing may not be necessary[63]: A final conclusions comparing proven and known effective HI and LI protocols could be drawn without balancing their doses. Nonetheless, since fatigue manifests in different physiological systems, at different time scales, and with varying magnitudes, no single metric can be entirely comprehensive[65].

Effects of increase in duration and intensity

Relationship between duration and estimated dose has received surpsingly little attention. The most shocking fact is that although most metrics show theoretically a linear increase with duration, only two of them effectively quantify the impact of duration: EPOC and loss of performance. Of these two, EPOC increases linearly, whereas loss of performance potentially increases in a stepwise manner. A duration threshold concept also advocates a stepwise relationship[61]. Therefore, the assumption of linearity, used in practically all conventional training load metrics, may not be based on a very solid foundation, and additional support would be greatly needed. In real life, the gradual rise in HR and VO_2, averaging 14% and 6%, respectively, during a 3 h LI exercise[56], would affect the linearity similarly to how the rise in RPE affected in session RPE. This would introduce a modest exponential growth in relation to duration in Banister’s and individual TRIMP.

An exponential increase with intensity is seen in most approaches, and this relationship is quite well addressed also in literature[8,9]. It is also supported by evidence, as a total of five metrics approximate the impact of an intensity. Among these, blood lactate, EPOC, loss of performance, and comparison to acute maximum have exponential behavior, while RPE, at a scale 1–10, have a linear relationship.

Weaknesses of the approaches

The metrics are based on different rationality and their weaknesses may be summarized as follows.

(1) "Arbitrary" methods

In Lucia's and Edwards' TRIMP, the weight factors lack physiological rationale[8], which may cause some uncertainty in their application.

(2) Physiological and perceptual measurements during exercise

The total work done/expended energy approach has lately been criticized[8,9,66], but it also has advocates[64,67]. The main arguments against its use are that iso-energetic doses of HI and LI exercises are not equally stressing, as they lead to vastly different exertion states[9] and performance losses[8], not to mention about EPOC[27] or recovery time[11]. Additionally, total work done is a purely external measure so its ability to estimate internal physiological strain could be limited. Lastly, incorporating the strong anaerobic component within the calculations of the total energy expenditure of HI exercise could be challenging[68].

In *session RPE* a limitation is the arbitrary upper limit of 10 on the scale, which does not allow HI:LI ratios greater than 1:10. This raises the question of why 10 is considered the optimal upper limit. For example, if one uses a scale ranging from 1 to 100, the mean RPE at the threshold between MI and HI is 35% of maximum[69] instead of 60–70% as in 1 to 10 scale[70]. This highlights the impact of scale selection.

In *individualized TRIMP*, weight factors are taken straight from the lactate curve. However, the concept of blood lactate being an accurate measure of an exercise dose is challenged[71]. Blood lactate indicates the intensity at which the muscles were recently working, without necessarily reflecting the extent of the exercise dose. It is not stable either; during a HI session at a constant intensity, the blood lactate concentration gradually increases[57,72]. Moreover, blood lactate concentration can be influenced by changing the level of free fatty acid in the blood[73] or by exercising at an altitude[71], and the association between blood lactate and HR is not fixed[74]. Finally, the change in blood lactate concentration does not fully correspond to the change in the concentration in the working muscle[75].

In Banister's TRIMP the first limitation is that it uses an average exercise HR, thereby constraining its applicability if HR fluctuations are considerable. Secondly, it contains a nonlinear term ($e^{b\Delta \mathrm{HR}}$) to replicate a lactate curve. This makes the critique about the use of lactate as an exercise dose indicator relevant here as well. The limitation of ΔHR is that its lower range is seldom used during exercise. It has been proposed that 45% ΔHR would be the lower limit of moderate physical activity[76] suggesting that 0–44% $\Delta \mathrm{HR}_{\mathrm{max}}$ are seldom used in exercise settings. By replacing $\mathrm{HR}_{\mathrm{rest}}$ in the ΔHR equation with a more refined lower threshold for the LI zone, Banister's TRIMP would separate the HI- and LI zones more effectively.

(3) Post exercise measurement

EPOC based exercise dose has one notable weakness: intensities below 50 % $\mathrm{VO}_{2\mathrm{max}}$ do not accumulate EPOC[27]. This would suggest that exercise performed at such low intensities do not generate exercise dose. However, an intensity as low as 35% $\mathrm{VO}_{2\mathrm{max}}$ can induce decreased isokinetic strength[77]. This indicates that LI sessions can elicit fatigue, which may not be captured by the EPOC metrics.

In *loss of performance*, to establish a reliable HI:LI ratio, further studies including the effect of duration would be necessary, especially a long fatiguing LI exercises. For some individuals, there may not exist performance decrement following 30-90 min[36,37,78] or 4 h[79]. For them, exercise dose after a prolonged exercise would be zero, which may be counterintuitive. Further, the comparison between HI and LI exercises is complicated by the fact that the reduction in performance is similar after maximal HI exercise, whether it is 6 min or 60 min time trial[38], whence reduction per minute is far more intense in short maximum exercises. Also, as the coefficient of variance of the impairments can be rather large, for example greater than 40%[38], suggesting that caution is needed when using the method.

Exercise dose may only be an indirect indicator to the potential positive endurance training adaptations. What if exercise dose quantification would rely on the acute responses observed in the cell signaling pathways that induce long-term adaptations? *Peroxisome proliferator-activated receptor gamma coactivator 1-alpha* (PGC-1α) is frequently identified as the "master regulator" in peripheral endurance training adaptations[80]. However, the upregulation of PGC-1α mRNA content is not associated with the duration of an exercise session, but only with its intensity[80,81]. Consequently, the HI:LI ratio is undefined, because even a long LI session could never equate to one minute of HI. This narrow analysis suggests that the exercise dose is distinct from the adaptive response of the dose[63]. This is understandable since the highest training dose does not necessarily result in the most beneficial training adaptations.

(4) Comparison to maximum dose

The clearest weakness in the maximum dose approaches is the practicality. Determining the precise intensity-related maximum can be challenging, especially with LI and in the chronic setting. In addition, in acute setting the within-subject variability in time to exhaustion in the HI zone can be quite considerable, with a coefficient of variation being 25%[82]. Compared to all the previous estimations, the maximum acute dose-based HI:LI ratio estimation seems to overestimate the needed amount of LI time. One explanation is that replenishment strategies are typically allowed in prolonged LI sessions. Without additional nutrition, exhaustion can already be reached within 3–6 h[13,83], which would give a 1:9–1:18 HI:LI ratio. Another explanation could be that reasons forcing to stop the LI session can be ignored acutely. For example, one can acutely tolerate sleep deprivation, inadequate energy intake, and dehydration even for a prolonged time, but not chronically over weeks of training.

Challenges of estimating HI:LI ratios

There are at least five challenges when comparing theoretically the HI and LI exercise doses. First of all, in our methodological estimations of HI:LI ratio we utilized the "intensity goal" method. In real-life situations, the lag in HR and VO_2 response most likely modify HI:LI ratios. This inflates the ratio and potentially equalizes differences to a certain degree.

The second challenge arises from the partially distinct sources of fatigue[13], which is the primary reason why comparing the HI and LI exercise doses is inherently problematic. The presence of different fatigue mechanisms would similarly complicate the comparison of doses between endurance exercise and, for example, strength exercise or cognitive tasks.

The third challenge arises from the limited precision of estimations based on three training zones, as intensities can still exhibit variation within these zones. For instance, the loss of performance is comparable following both a 4 km and a 20 km cycling time trial[38]. Hence, these HI sessions could elicit equivalent exercise dose, despite the latter time trial involving five times more HI time. Furthermore, even a minor change in HR, such as one beat per minute, can alter the interpretation of the training zone.

The fourth challenge is the impact of duration on an exercise dose, which has not been studied to the same extent as intensity. The influence of duration in most metrics presented here is presumed rather than directly measured, giving rise to speculation. Fifth, although the presented metrics quite comprehensively introduce the main ideas of how to quantify exercise doses, they nevertheless represent only a handful of the existing metrics.

Practical Applications

The results of our review showed how the choice of exercise dose method has a dramatic effect on how HI and LI exercises are balanced. The choice of metric will further have a large impact on the research designs, results, and interpretations, as well as athletic monitoring. Evidently, different metrics are not estimating similarly the physiological strain they are supposedly measuring. Therefore, researchers should explicitly justify why they have chosen a specific exercise dose method, rather than simply stating, for example, that it matches energy expenditure. They should also definitely familiarize themselves with the foundations and weaknesses of different approaches, as outlined, for example, in this review article. Especially, the majority of metrics plainly assume that exercise dose increases linearly with relation to duration. This assumption has not been rigorously tested, and its use should be subject to closer scrutiny.

Conclusion

The debate surrounding the appropriate quantification of exercise dose is ongoing. This review introduced 10 methods for achieving theoretically balanced doses of the HI and LI exercises, which were categorized into four categories based on their physiological rationale. These methods estimated a balanced HI:LI ratio ranging from 1:1.5 to 1:100, making it impossible to equalize simultaneously HI and LI across all metrics. Therefore, researchers and practitioners should familiarize themselves with the foundations and weaknesses of their used metrics and justify their choice. It was also discovered that the commonly used linear increase in the metrics with respect to duration is mainly assumed rather than thoroughly tested.

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“Whenever I walk in a London street,
I’m ever so careful to watch my feet;
And I keep in the squares,
And the masses of bears,
Who wait at the corners all ready to eat
The sillies who tread on the lines of the street,
Go back to their lairs,
And I say to them, “Bears,
Just look how I’m walking in all the squares!”

– A.A. Milne –