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TRAINING ZONES ESTIMATION

STANOVENÍ TRÉNINKOVÝCH ZÓN

MASTER'S THESIS

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1) Conduct a literature review of aerobic threshold estimation using detrended fluctuation analysis using its alpha 1 parameter. 2) Using a Polar H10 chest strap, record tachograms during various intensities of sports activities and create a test dataset including load rate annotations. 3) Propose a method for estimating stress zones based on detrended fluctuation analysis. 4) Implement an application for displaying load zones during training. 5) Statistically evaluate the accuracy of the load zone estimation. 6) Interpret the results and discuss the applicability and limits of the proposed application.

RECOMMENDED LITERATURE:

[1] ROGERS, Bruce, David GILES, Nick DRAPER, Olaf HOOS a Thomas GRONWALD. A New Detection Method Defining the Aerobic Threshold for Endurance Exercise and Training Prescription Based on Fractal Correlation Properties of Heart Rate Variability. *Frontiers in Physiology*. 2021, 11. ISSN 1664-042X, doi:10.3389/fphys.2020.596567

[2] ROGERS, Bruce, David GILES, Nick DRAPER, Laurent MOUROT a Thomas GRONWALD. Influence of Artefact Correction and Recording Device Type on the Practical Application of a Non-Linear Heart Rate Variability Biomarker for Aerobic Threshold Determination. *Sensors*. 2021, 21(3). ISSN 1424-8220, doi:10.3390/s21030821

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ABSTRACT

Training based on training zones is a vital part of modern-day sports. These training zones are typically determined through gas exchange parameters or lactate levels in the blood, measured during a laboratory graded exercise test. Based on these tests, athletes are provided with heart rate or workload thresholds within which they should maintain their desired exercise intensity. In recent years, a new method has emerged for measuring training zones in the laboratory, with the ability to display them to athletes in the same metric as they were measured—based on the DFA alpha1 coefficient of heart rate variability (HRV).

This thesis presents an application for real-time displaying of training zones based on the DFA alpha1 coefficient of HRV and calculation of their representation by heart rate from laboratory tests. However, real-time displaying of training zones seems to bear almost no resemblance to ground truth data (accuracy 22.39%, Cohen's $\kappa=0.05$), therefore, in this way, the application is unusable. On the other hand, it shows sufficient results during laboratory testing (mean absolute error $\approx 3 \pm 2$ bpm, $p>0.05$) to be deemed usable in this manner.

KEYWORDS

DFA alpha1, HRV, training zones

ABSTRAKT

Tréning založený na tréningových zónach je dôležitou súčasťou moderného športu. Tieto tréningové zóny sa zvyčajne určujú na základe parametrov výmeny plynov alebo hladín laktátu v krvi, ktoré sa merajú počas laboratórneho odstupňovaného záťažového testu. Na základe týchto testov sa športovcom určia prahové hodnoty srdcovej frekvencie alebo záťaže, v rámci ktorých by mali udržiavať požadovanú intenzitu cvičenia. V posledných rokoch sa objavila nová metóda merania tréningových zón v laboratóriu s možnosťou ich zobrazenia športovcom v rovnakej metrike, v akej boli namerané - na základe koeficientu DFA alfa1 variability srdcovej frekvencie (HRV).

Táto práca predstavuje aplikáciu na zobrazovanie tréningových zón v reálnom čase na základe koeficientu DFA alfa1 HRV a výpočet ich reprezentácie tepovou frekvenciou na základe laboratórneho testu. Zobrazovanie tréningových zón v reálnom čase na základe DFA alpha1 však nesie minimálnu podobnosť s referenčnými dátami (presnosť 22,39%, Kohenovo $\kappa=0,05$), preto je v tomto smere aplikácia nepoužiteľná. Na druhej strane však dosahuje dostatočné výsledky pri laboratórnom testovaní ($\approx 3 \pm 2$ bpm, $p>0.05$), aby bola v tomto smere označená za použiteľnú.

KLÚČOVÉ SLOVÁ

DFA alpha1, HRV, záťažové zóny

ROZŠÍŘENÝ ABSTRAKT

Úvod

Sledovanie a vyhodnocovanie intenzity cvičenia sú dôležitou súčasťou tréningu každého profesionálneho športovca. Znalosť intenzity cvičenia umožňuje športovcom posúdiť, či trénujú optimálne, a vyhnúť sa tak rizikám pretrénovania alebo podtrénovania. Na riadenie intenzity cvičenia sa používajú rôzne ukazovatele, ako napríklad záťaž, tempo alebo najčastejšie srdcová frekvencia. Intenzita cvičenia sa zvyčajne delí na zóny, z ktorých každá je charakterizovaná špecifickými metrikami. Napríklad zóna 3 môže byť definovaná ako srdcová frekvencia medzi 140 a 155 údermi za minútu. Tieto zóny tréningu alebo intenzity cvičenia vychádzajú z bodov zlomu v ľudskom metabolizme počas cvičenia, ktoré sú známe ako aeróbne a anaeróbne prahy. Tieto prahy sa zvyčajne určujú pomocou analýzy výmeny plynov alebo meraním hladiny laktátu v krvi počas stupňovaného testu cvičenia.

V posledných rokoch štúdie preukázali vysokú koreláciu medzi aeróbnymi a anaeróbnymi prahovými hodnotami a špecifickými prahovými hodnotami v koeficiente alfa1 analýze detrendovaných fluktuácií (DFA alpha1) variability srdcovej frekvencie počas cvičenia. Na základe toho je možné odvodiť, že DFA alfa1 môže slúžiť ako ďalšia metrika na opis intenzity cvičenia, ktorá dopĺňa tradičné metódy. Výpočet DFA alfa1 vyžaduje len časový rad RR intervalov, ktorý sa dá ľahko získať pomocou monitora srdcovej frekvencie. To dáva zónam intenzity cvičenia založeným na DFA alfa1 výhodu oproti tradičným modelom, kde je analýza výmeny plynov často nákladná, pričom najlacnejšie zariadenia majú cenu viac ako 1 000 eur. Naproti tomu monitor srdcovej frekvencie stojí len približne 75 eur, čo z neho robí dostupnejšiu možnosť. Okrem toho invazívny charakter merania hladiny laktátu v krvi ho robí nevhodným na monitorovanie v reálnom čase počas pohybu.

Táto práca sa zameriava na vytvorenie aplikácie na monitorovanie tréningovej zóny v reálnom čase na základe DFA alfa1. Aplikácia môže mať dva typy využitia: pomoc pri regulácii intenzity cvičenia počas každodenného tréningu alebo pomoc pri zisťovaní tréningových zón v laboratórnych podmienkach s minimálnym vybavením.

Riešenie

Prvé tri kapitoly práce sa venujú literárnej rešerši ohľadom zisťovania záťažových zón a výpočtu DFA alpha1. Následne v štvrtej kapitole sú stanovené ciele pre praktickú časť tejto práce. Hlavným cieľom tejto práce je vytvoriť aplikáciu na vyhodnocovanie záťažových zón v reálnom čase, vedľajším následná validácia tejto aplikácie. Kapitoly od piatej ďalej sa venujú praktickému riešenie zadania - vytvoreniu aplikácie a

jej testovaniu.

Aplikácia je napísaná v programovacom jazyku Python. Pri jej písaní boli využité knižnice Asyncio a Bleak. Knižnica Asyncio umožňuje zavedenie asynchrónnych procesov a beh viacerých procesov naraz. Nakoľko aplikácia sa zameriava na výpočet a zobrazenie udalostí v reálnom čase, nevyhnutne musí prebiehať viacero procesov súčasne - napríklad výpočet DFA alpha1, ktorý je z princípu časovo náročný, prijímanie nových dát z monitora srdcovej frekvencie a ovládanie užívateľom. Knižnica Bleak umožňuje pripojenie k zariadeniam komunikujúcim pomocou Bluetooth Low Energy. Práve takýmto zariadením je Polar H10, ktorý bol zvolený ako použitý monitor srdcovej frekvencie na základe jeho využitia v iných výskumoch venujúcich sa problematike intenzity záťaže a DFA alpha1, ako aj jeho vysokej presnosti pri monitorovaní HRV (variability srdcovej frekvencie).

Samotnú aplikáciu je možné rozdeliť na štyri časti. Prvou je pripojenie k Polar H10 a začiatok prijímania dát. Táto časť funguje lineárne a začína inicializáciou aplikácie a končí začiatkom prijímania dát z Polar H10. Následne všetky časti aplikácie fungujú súbežne. Jedna z častí sa stará o preloženie dát do formátu použiteľného v ďalších výpočtoch a ukladanie dát do tzv. "bufferu". Buffer kumuluje dáta, kým ich nie je dostatok na následné použitie. Je potrebný kvôli výpočtu DFA alpha1 - tento výpočet prebieha na časovej postupnosti RR intervalov (vzdialeností R vln EKG v čase), t.j. získame jednu hodnotu DFA alpha1 pre každých n vzoriek RR intervalov. Výpočet DFA alpha1 a následne záťažových zón je ďalšia samostatne prebiehajúca časť. Prebieha súbežne s ostatnými procesmi kvôli časovej náročnosti výpočtu DFA alpha1. Samotný výpočet DFA alpha1 je založený na klasickom postupe pre tento výpočet, nie na žiadnych z objavujúcich sa rýchlych verziách. Poslednou zo súbežne prebiehajúcich častí algoritmu je možnosť ovládania užívateľom. Táto časť je vytvorená ako aplikácia Kivy frameworku.

Testovací dataset pozostáva z dvoch častí - dát získaných počas každodenného použitia (behy rôznej intenzity a trvania) a dát získaných v laboratórnych podmienkach (počas stupňovaného záťažového testu). Tieto dáta majú simulovať dva možné spôsoby využitia aplikácie: kontrolu intenzity každodenného tréningu a zisťovanie tréningových zón v laboratóriu. Dáta získané počas každodenného tréningu sú z autorovho osobného archívu (22 behov rôznej dĺžky a intenzity, autor je športovec, muž, 23 rokov) a dáta z laboratórneho testovania sú z bakalárskej práce vytvorenej Bc. Tobiášom Goldschmidtom na CESA VUT v Brne (14 záznamov, aj muži aj ženy, rôzny vek a rôzna kondícia) a z meraní vykonaných v laboratóriách CESA VUT v Brne autorom pre potreby tejto práce (14 záznamov, aj muži aj ženy, rôzny vek a rôzna kondícia).

Výsledky

Pre laboratórne použitie boli prvotne dosiahnuté veľké rozdiely medzi prahmi v reprezentácii záťažových zón pomocou tepovej frekvencie (priemerná absolútna chyba $\approx 6 \pm 3$ bpm, $p < 0,05$). Avšak po aplikovaní korekcie -9 bpm pre AeT a $+7$ bpm pre AnT sa tieto rozdiely zmenšili a bola dosiahnutá štatisticky nevýznamná odchýlka (priemerná absolútna chyba $\approx 3 \pm 2$ bpm, $p > 0,05$). Korekcia bola vypočítaná z validačnej časti testovacieho datasetu (merania uskutočnené pre potreby tejto práce) a bola aplikovaná na testovaciu časť testovacieho datasetu (dáta z bakalárskej práce vytvorenej Bc. Tobiášom Goldschmidtom na CESA VUT v Brne).

Pre každodenné použitie bola zhoda referenčných hodnôt záťažových zón a hodnôt záťažových zón vypočítaných na základe DFA alpha1 minimálna (presnosť 22,39%, $\kappa = 0,05$). Po aplikácii hodnôt prahov medzi zónami na základe hodnôt DFA alpha1 dosiahnutých pri laboratórnom testovaní namiesto prahov určených v už publikovaných štúdiách sa výsledok testovania ešte zhoršil (presnosť 18,58%, $\kappa = 0,05$).

Záver

Cieľom tejto práce bolo vytvoriť aplikáciu pre analýzu záťažových zón v reálnom čase. Táto aplikácia mala mať dva spôsoby využitia - určenie záťažových zón pri laboratórnom testovaní a určenie záťažových zón v reálnom čase pri športovej aktivite. Táto aplikácia bola úspešne implementovaná v programovacom jazyku Python s užívateľským rozhraním implementovaným pomocou Kivy frameworku. Aplikácia je funkčná ako pre výpočet DFA alpha1 a následne aj záťažových zón v reálnom čase, tak aj pre výpočet reprezentácie záťažových zón pomocou tepovej frekvencie z laboratórneho merania. Je potrebné otestovať aplikáciu pri použití mobilným zariadením, nakoľko výpočetná náročnosť výpočtu DFA alpha1 môže byť príliš veľká pre možnosti mobilných zariadení.

V oblasti určovania záťažových zón ukazujú výsledky dobrú použiteľnosť aplikácie pre tento účel. Avšak na dosiahnutie tohto výsledku bolo potrebné na výsledky aplikovať korekciu vo forme konštanty. Na základe dosiahnutých výsledkov a výskumu vykonaného na túto tému nie je jasné, či potreba aplikovania korekcie vznikla kvôli chybe pri meraní, ktorú vnieslo vybavenie a postup merania v laboratóriu, kde merania prebiehali, alebo je problém v samotných prahoch v DFA alpha1. Pre presnejšie preskúmanie potreby aplikovania korekcie by bolo potrebné vykonať ďalší výskum v oblasti vzťahu prahu DFA alpha1 a ventilačných prahov, ako aj rozšíriť testovací dataset o dáta merané v iných laboratóriách inými špecialistami.

V oblasti určovania záťažových zón ukazujú výsledky nedostatočnú spoľahlivosť aplikácie pre tento účel. Zhoda medzi referenčnými hodnotami záťažových zón a

hodnotami záťažových zón na základe DFA alpha1 je minimálna a preto sa neodporúča používať vytvorenú aplikáciu na tento účel. Nakoľko dáta namerané pri každodennom použití neprejavujú znaky popísané v predchádzajúcich štúdiách venovaných sa problematike DFA alpha1 a záťaže, je potrebné vykonať ďalší a hlbší výskum v tejto oblasti.

Aplikácia v jej finálnej podobe predstavuje alternatívny prístup k analýze záťažových zón v laboratóriu a ponúka lacnejšiu a prenosnejšiu alternatívu k stanoveniu reprezentácie záťažových zón tepovou frekvenciou oproti momentálne používaným spôsobom. Prináša tak potenciál na testovanie záťažových zón, testu potrebného pre každého vytrvalostného športovca, len za pomoci smartfónu či dokonca iba športtestru.

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Author's Declaration

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Topic: Training zones estimation

I declare that I have written this paper independently, under the guidance of the advisor and using exclusively the technical references and other sources of information cited in the paper and listed in the comprehensive bibliography at the end of the paper.

As the author, I furthermore declare that, with respect to the creation of this paper, I have not infringed any copyright or violated anyone's personal and/or ownership rights. In this context, I am fully aware of the consequences of breaking Regulation § 11 of the Copyright Act No. 121/2000 Coll. of the Czech Republic, as amended, and of any breach of rights related to intellectual property or introduced within amendments to relevant Acts such as the Intellectual Property Act or the Criminal Code, Act No. 40/2009 Coll. of the Czech Republic, Section 2, Head VI, Part 4.

Brno

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author's signature*

*The author signs only in the printed version.

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Introduction

Exercise intensity tracking and evaluation are vital parts of every professional athlete's training. Knowing the exercise intensity allows athletes to gauge whether they are training optimally, avoiding the risks of overtraining or undertraining. Various metrics are used to manage exercise intensity, such as workload, pace, or, most commonly, heart rate. Exercise intensity is typically divided into zones, each characterized by specific metrics. For example, Zone 3 might be defined as a heart rate between 140 and 155 beats per minute. These training or exercise intensity zones are based on breakpoints in human metabolism during exercise known as aerobic and anaerobic thresholds. These thresholds are usually determined through gas exchange analysis or by measuring lactate levels in the blood during a graded exercise test.

In recent years, studies have shown a high correlation between aerobic and anaerobic thresholds and specific thresholds in the alpha1 coefficient of detrended fluctuation analysis (DFA alpha1) of heart rate variability during exercise. From this, it is proposed that DFA alpha1 can serve as another metric to describe exercise intensity, complementing traditional methods. DFA alpha1 computation requires only the time series of RR intervals, which can be easily obtained using a heart rate monitor. This gives exercise intensity zones based on DFA alpha1 an advantage over traditional models, where gas exchange analysis is often costly, with the cheapest devices priced over 1000 euros. In contrast, a heart rate monitor costs only about 75 euros, making it a more accessible option. Additionally, the invasive nature of blood lactate level measurement makes it unsuitable for real-time monitoring during movement.

This thesis focuses on creating an application for real-time training zone monitoring based on DFA alpha1. The application can have two types of use: assisting in regulating exercise intensity during everyday training or aiding in finding training zones in laboratory conditions with minimal equipment.

1 Physiological thresholds in exercise intensity assesment

There are two possible ways in which the human body can metabolize nutrients to produce energy: aerobic and anaerobic metabolism. Aerobic metabolism is generally preferred because it yields greater energy compared to anaerobic metabolism. However, aerobic metabolism requires adequate oxygen intake. When oxygen intake is insufficient, anaerobic metabolism begins, resulting in lower energy yield and the production of waste products such as lactate. The involvement of each type of metabolism leads to breakpoints in the function of exercise intensity. Under normal conditions, only aerobic metabolism is present due to adequate oxygen intake. As physical strain increases, the energy metabolism becomes a mixture of aerobic and anaerobic metabolism because oxygen intake becomes inadequate. This is when the first breakpoint occurs. With further increases in physical strain, the proportion of anaerobic metabolism in the overall energy metabolism also increases. When anaerobic metabolism predominates, the second breakpoint occurs. These two breakpoints are known as the aerobic and anaerobic thresholds, respectively. They serve as cornerstones for the estimation of exercise intensity zones and are assessed during laboratory testing. In laboratory tests, exercise intensity gradually increases in a controlled manner (e.g., through changes in speed and slope on a treadmill), and physiological parameters that can describe these thresholds are measured. [20, 34, 35]

1.1 Aerobic threshold

The Aerobic Threshold (AeT) is the first of the two thresholds mentioned in paragraph before. It marks a point till which the energy metabolism is purely aerobic and there is no build-up of lactate level in blood. Up to this point a person can exercise for a very long time, possibly all day for several days in a row. In laboratory testing it is determined by ventilation threshold 1 (VT1) or lactate threshold 1 (LT1). [17]

The main difference between these two VT1 and LT1 is, that VT1 can be assessed with non-invasive tests. Otherwise, these two thresholds are identical; VT1 is just LT1 described by parameters that can be measured non-invasively. To assess VT1, gas exchange need to measured during a graded exercise test. It is calculated as the breakpoint in the dependence of $V'\text{CO}_2$ (volume of carbon dioxide in breath) on $V'\text{O}_2$ (volume of oxygen in breath). Figure 1.1 shows a graphical representation of this calculation. This is the most commonly used calculation, but there are many

other possible methods based on RER (Respiratory Exchange Ratio), ventilation or $P_{ET}O_2$ (partial oxygen pressure). [1, 19]

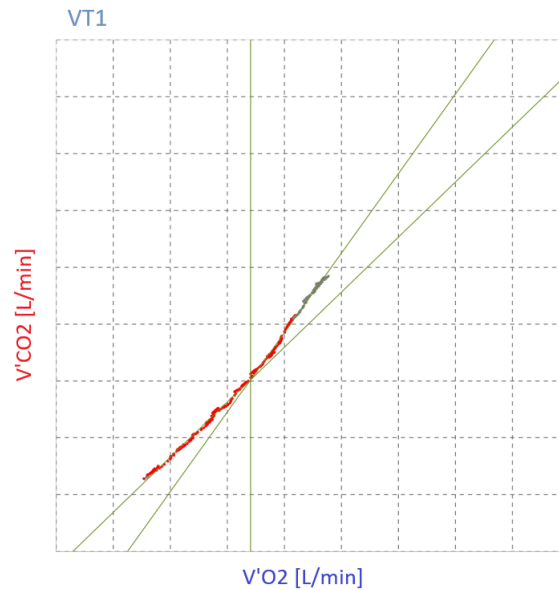


Fig. 1.1: Ventilation threshold 1 based on the $V'CO_2/V'O_2$ dependency

LT1 is based on the fact that with a linear increase in exercise intensity, blood lactate concentration does not increase linearly. It is found as the first abrupt change in the lactate workload (WL) dependence (see Figure 1.2). This abrupt change happens because anaerobic metabolism starts and lactate level start slowly build-up in blood. The main advantage of LT1 over VT1 is that the standards for its assessment are generally agreed and do not vary as much as those for VT1. On the other hand, blood lactate is measured invasively by testing the patient's blood, which is a less attractive option than non-invasive measurement of respiratory parameters. [1]

1.2 Anaerobic threshold

The anaerobic threshold (AnT) is the second physiological threshold. It marks the point from when the body cannot metabolise the lactate produced during exercise. Above this point, an average person can exercise for a short period of time, while trained endurance athletes can exercise for up to an hour. This threshold can traditionally be determined by ventilation threshold 2 (VT2) or lactate threshold 2 (LT2) and alternatively by critical power (CP), respiratory compensation point (RCP) or maximal lactate steady state (MLSS). [17, 16]

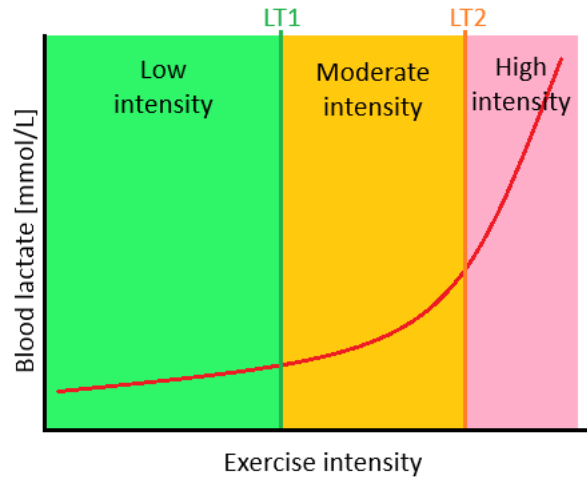


Fig. 1.2: Lactate thresholds [42]

The determination of AnT from a graded exercise test is in principle the same as the determination of AeT. In fact, they are usually obtained from the same test. For AnT, there are more approaches to determining it from the test than for AeT. The most common approach is from VT2, as it is a non-invasive and proven method. It involves measuring gas exchange during a graded exercise test. The calculation is then based on the breakpoint in the dependence of $\dot{V}'E$ (ventilation) on $\dot{V}'CO_2$ (volume of carbon dioxide in breath). An example of this can be seen in Figure 1.3. There are also some alternative approaches to calculating VT2, such as calculation from RER (respiratory exchange ratio), heart rate (HR) or $P_{ET}CO_2$ (partial pressure of carbon dioxide). [1, 19]

LT2 is then based, similarly to LT1, on the blood lactate level obtained by invasive measurement during a graded exercise test. As the definition of AnT (see chapter 1.2) suggests, LT2 is found as the second breakpoint in the lactate-WL dependence (see Figure 1.2). This breakpoint occurs because body is not able to metabolise all produced lactate and therefore build up of lactate in blood is faster than before. There are the same advantages for LT2 over VT2 as for LT1 over VT1 - standards for its assessment are generally agreed and do not vary as much as those for VT2 assessment. On the other hand, obtaining a blood sample from a person at near-maximal exercise is much more difficult than measuring gas exchange. It is also important to remember that blood lactate levels can vary depending on where the blood sample is taken. [1]

For AnT, there are also a number of alternative methods of assessment. The main difference between the alternative means of assessing AnT and LT2 or VT2 is the protocol used. While VT2 and LT2 use a graded exercise test, CP uses repeated

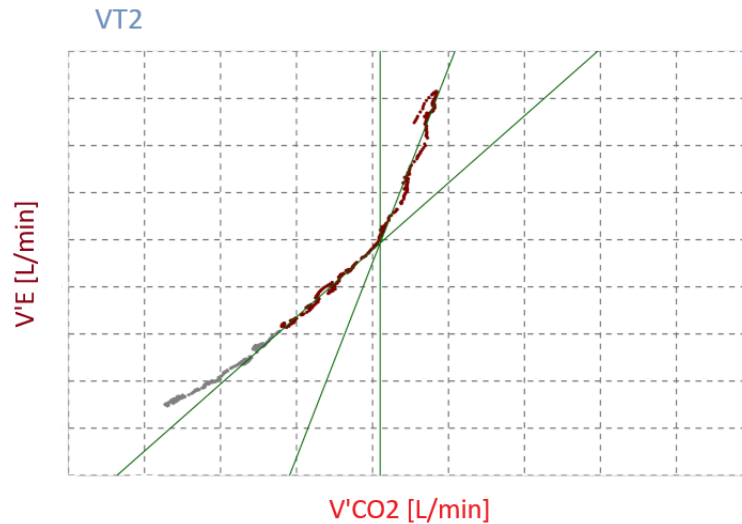


Fig. 1.3: Ventilation threshold 2 based on $V'E / V'CO_2$ dependency

exhaustive tests (where the workload is constant and the participant must continue to exhaustion, which occurs between 1-20 minutes, and the workload is based on a graded exercise test) and MLSS uses repeated constant power tests (where the power is constant and based on the lactate change in the previous test). RCP uses a graded exercise test. CP measures time to exhaustion, MLSS measures lactate and RCP measures gas exchange. These means of assessing AnT give similar results to those obtained by VT2 or LT2, and are therefore alternatives to the classic functional indices of AnT assessment. Because of the effort required to perform them (a graded exercise test takes about 20 minutes, repeated tests take an hour or more) or the similarity in methodology (RCP uses the same type of test and is based on the same physiological parameters as VT2), they are not very convincing alternatives to the classic functional indices of AnT assessment. [16]

1.3 Exercise intensity zones calculation based on ventilation thresholds

When a laboratory test is conducted and AeT and AnT are determined, the patient (or athlete) receives results in the form of heart rate (HR), blood lactate (BL), $V'O_2$ or WL (work load) range for each zone. These parameters are relatively easy to measure outside the laboratory and are therefore commonly used during training. Among these parameters, HR representation of exercise intensity zones is the most widely used due to its accessibility.

The simplest way to divide exercise intensity into zones is by creating three zones with AeT and AnT as thresholds between zones (see Figure 1.4). This model is the most basic one with clearly defined thresholds. In Table 1.1, the zones are represented in terms of the percentage of HR_{max} (maximum heart rate), $V'O_{2max}$ (maximum oxygen intake), or blood lactate. It is evident that there is a significant difference in the width of each zone (20% vs. 10% of HR_{max}), so this model has limited practical use and is not commonly used in training. [1, 31]

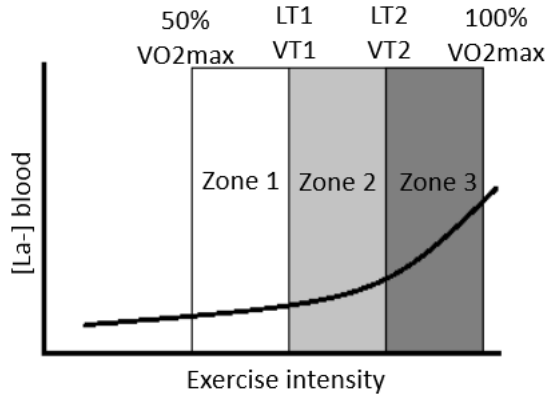


Fig. 1.4: Three zone model of exercise intensity shown on the dependency of level of lactate in blood on the exercise intensity [41]

Table 1.1: Overview of approximate parameters in the different zones of classic three-zone model [1]

Zone	% HR_{max}	% $V'O_{2max}$	BL [mmol/l]
1	<70	<55	<2.0
2	70-90	55-80	2.0-4.0
3	>90	>80	>4.0

In practice, the most commonly used model is the 5-zone model. This type of model allows for better differentiation between zones and creates zones with much more similar widths than the 3-zone model (see Table 1.2). However, this type of exercise intensity model allows for much more variance in zone threshold definitions. The thresholds between zones need to be derived from AeT and AnT, and therefore there is some degree of variance.

As can be seen in Figure 1.5, LT1 and LT2 (representations of AeT and AnT) lie in the middle of Zone 2 and Zone 4, respectively. In Figure 1.6, VT1 and VT2 (representations of AeT and AnT) lie at the end of Zone 2 and Zone 4, respectively.

These are the two main approaches in the practical use of the 5-zone model of exercise intensity zones, but many other approaches are used and can differ from specialist to specialist. This variance can cause disagreement between specialists and severely disrupt the training process if an athlete does not adhere to one type of 5-zone model in training. [13, 28]

Table 1.2: Overview of approximate parameters in different zones of 5 zone model [28]

Intensity zone	%HR _{max}	BL [mmol/l]
1	<72	0.8-1.5
2	72-82	1.5-2.5
3	82-87	2.5-4.0
4	88-93	4.0-6.0
5	94-100	6.0-10.0

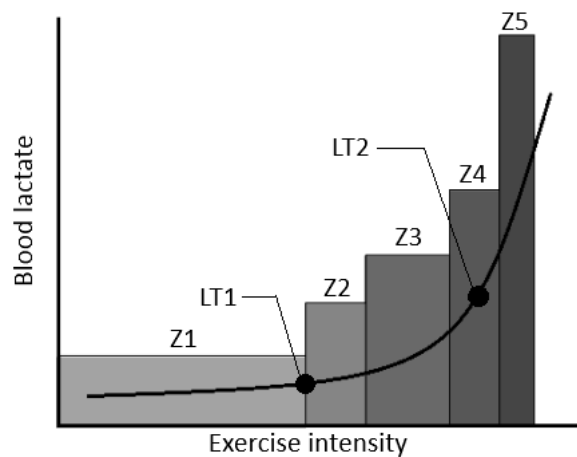


Fig. 1.5: Five zone model of exercise intensity shown on dependency of level of lactate in blood on exercise intensity [13]

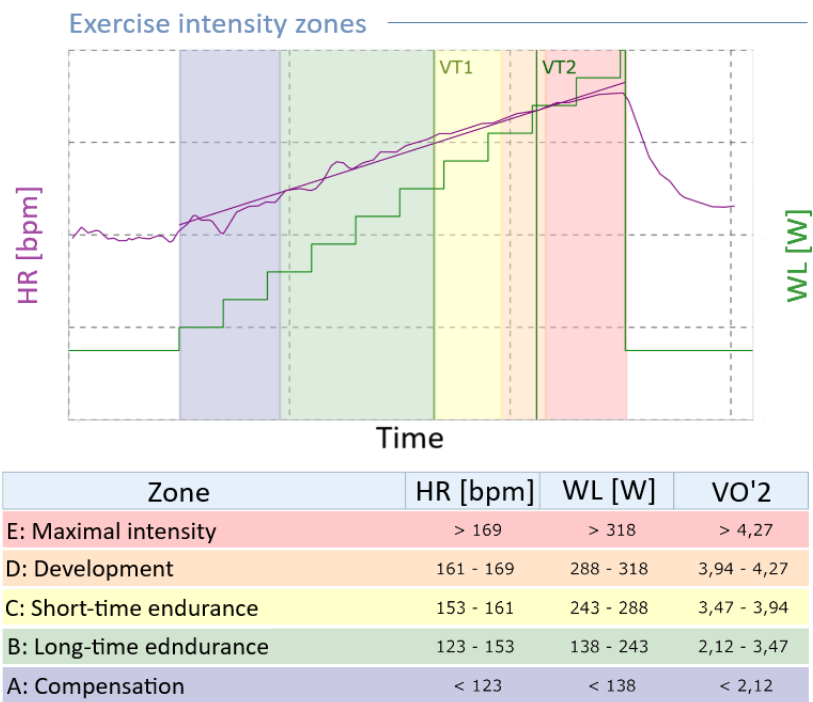


Fig. 1.6: Example of 5 zone model from results of laboratory test.

2 Heart rate variability

Heart rate variability (HRV) is the variation of time intervals between heartbeats. It is affected by the function of the sympathetic and parasympathetic nervous systems, together called the autonomic nervous system (ANS). The sympathetic system increases heart rate and decreases HRV, while the parasympathetic system does the opposite. Increased activity of one or another system, and therefore ANS imbalance, can be seen as an indicator of a medical condition. Nowadays, HRV is used as an early warning system before sudden cardiac death or diabetic neuropathy. It can also be used in the prognosis of neurological diseases and has a close connection to several cardiovascular diseases. There have also been studies about HRV and its relationship with renal failure, stress, sleep, or anthropometric parameters. Importantly for this thesis, HRV has been studied in relation to physical activity and sport [5, 18].

The most common technique to measure HRV is to measure intervals between R waves in successive heartbeats. From this, a series of RR intervals is obtained, which can be analyzed by various methods. These methods can be categorized into three groups based on what parameters of the RR series they concern.

The first type of methods is time-domain methods. These methods analyze how RR intervals change over time, and the most used measures from this group are the mean value of RR intervals (\overline{RR}) or the standard deviation of normal-to-normal RR intervals (SDNN).

The second type is frequency-domain methods, which focus on the spectrum estimate from RR intervals series. Methods in this category include dividing the spectrum into bands based on frequency, such as very low (VLF), low (LF), and high (HF) frequency, and power estimation or peak counts for these bands. These measurements are useful because each band corresponds to another part of the autonomic nervous system (high frequency to parasympathetic activity and low frequency to sympathetic activity).

The last group of methods is nonlinear methods, such as Poincaré plot, entropy methods, or detrended fluctuation analysis (DFA). Methods from this group are closely described in Chapter 2.1. A brief description and abbreviations of methods from all three groups can be seen in Table 2.1. [33, 37]

2.1 Nonlinear methods of HRV analysis

The heart is a complex system, and not all occurrences in it can be accurately described by linear models, whether in frequency or time domain. Therefore, nonlinear models have been applied. These models aim to capture characteristics of RR series

as a whole, not only in a certain domain. The first of these nonlinear methods is the Poincaré plot. The Poincaré plot is a graphical representation of the correlation between two successive RR intervals. From this plot, the distribution on a plane is analyzed. Next are entropy methods, which focus on entropy (degree of disorder or uncertainty) and therefore describe the irregularity or complexity of RR series. The last method mentioned in this thesis is detrended fluctuation analysis (DFA). As the name suggests, this method focuses on measuring fluctuations in correlations at different time scales of RR intervals. This method is further described in Chapter 3 as it is the main focus of this thesis. [33]

Table 2.1: Methods of heart rate variability (HRV) assessment [33]

Parameter	Units	Description
<i>Time-domain methods</i>		
RR	[ms]	The mean of RR intervals
STD RR (SDNN)	[ms]	Standard deviation of RR intervals
HR	[1/min]	The mean heart rate
STD HR	[1/min]	Standard deviation of instantaneous heart rate values
RMSSD	[ms]	Square root of the mean squared differences between successive RR intervals
NN50	[count]	Number of successive RR interval pairs that differ more than 50 ms
PNN50	[%]	NN50 divided by the total number of RR intervals
HRV triangular index	[-]	The integral of the RR interval histogram divided by the height of the histogram
TINN	[ms]	Baseline width of the RR interval histogram
<i>Frequency-domain methods</i>		
VLF, LF, HF peaks	[Hz]	Peak frequencies for VLF, LF and HF bands
VLF, LF, HF powers	[ms]	Absolute powers of VLF, LF and HF bands
VLF, LF, HF powers	[%]	Relative powers of VLF, LF and HF bands
LF and HF powers	[n.u.]	Powers of LF and HF bands in normalized units
LF/HF	[-]	Ratio between LF and HF band powers
Total power	[msa]	Total spectral power
Continued on next page		

Table 2.1 – continued from previous page

Parameter	Units	Description
EDR	[Hz]	ECG derived respiratory frequency
<i>Nonlinear methods</i>		
SD1, SD2	[ms]	Standard deviations of the Poincaré plot
ApEn	[-]	Approximate entropy
SampEn	[-]	Sample entropy
D2	[-]	Correlation dimension
Alpha1, Alpha2	[-]	Short-term and long-term fluctuations of detrended fluctuation analysis (DFA)
Lmean	[beats]	Mean line length of diagonal lines in recurrence plot (RP)
Lmax	[beats]	Maximum line length of diagonal lines in RP
REC	[%]	Recurrence rate (percentage of recurrence points in RP)
DET	[%]	Determinism (percentage of recurrence points which form diagonal lines in RP)
ShanEn	[-]	Shannon entropy of diagonal line lengths' probability distribution

3 Detrended fluctuation analysis

DFA is a nonlinear method for analyzing HRV. Since the early 1980s, there have been reports showing self-similar tendencies in components of RR series. DFA was first used for HRV analysis in 1995 by Peng et. al. [21] From there, the popularity of this method has only risen, and it is now deeply established in the practice of HRV analysis. DFA is used for evaluating conditions such as congestive heart failure or spinal lesions, analyzing sleep and heart rate dynamics during sleep, providing information on the autonomic development of the fetus, or serving as a prognostic factor for renal disease patients. [3, 4]

The basic idea behind Detrended Fluctuation Analysis (DFA) is that not all processes in heart rate dynamics are stationary, meaning their statistical properties do not change during the measurement period. These processes are viewed as complex but not random. Therefore, there are fluctuations in HRV caused by these complex inner processes, as well as fluctuations caused by outer uncorrelated stimuli. If these two types of fluctuations were distinguishable, they would have different correlation properties. Fluctuations based on uncorrelated stimuli would have a characteristic time scale related to the stimuli, and fluctuations arising from complex heart dynamics would exhibit long-range correlations. Fluctuations caused by uncorrelated stimuli therefore can be seen as a trend in the data and would show over different time scales. Ultimately, DFA quantifies the presence or absence of these fractal correlations in a time frame. Because of this, DFA is far superior to other methods in analyzing long-range correlations in time series, although it is computationally demanding. [4, 12, 21]

When using the DFA method in HRV analysis, two parameters are assessed - α_1 and α_2 . They differ in the length of fluctuations they denote - α_1 denotes short-term fluctuations, and α_2 denotes long-term fluctuations. Because of this, they describe mechanisms operating on different time scales - α_1 on a short time scale and α_2 on a long time scale. Distinguishing between these two parameters is a fundamental part of HRV analysis. [2, 4]

3.1 Computation

There are many ways to compute DFA, with the original computational pipeline described by Peng et al. in 1995. [21] From there, other approaches to compute DFA have emerged. This chapter will focus only on the original approach, while other approaches are discussed in Chapter 3.2. According to original approach, computation of DFA is split in to 5 steps. In those 5 steps is calculation of α_1 as well as α_2 . [21]

1. **Integration of time series:** Firstly, time series of length N of deviations of RR intervals from average RR interval of this series. This can be seen in equation 3.1, where $RR(i)$ is the current RR interval, and RR_{avg} is the average RR interval.

$$y(k) = \sum_{i=1}^k (RR(i) - RR_{avg}) \quad (3.1)$$

2. **Division in boxes:** Next step is division of signal to non-overlapping boxes of equal length n . This can be seen at Figure 3.1.

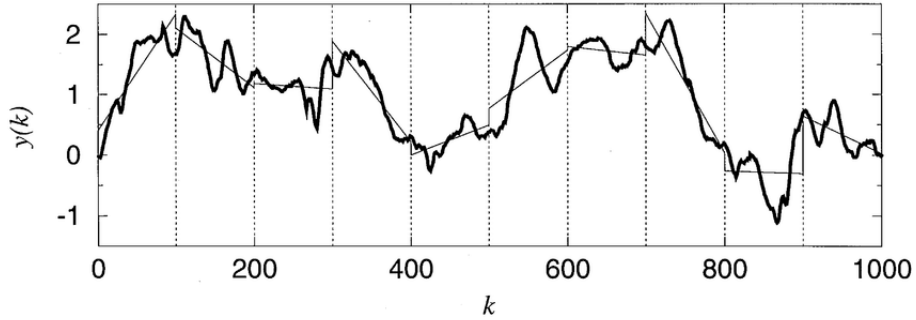


Fig. 3.1: Example of division of RR intervals into boxes of equal length and local trends in these boxes.

3. **Calculating local trend for each box:** In each of the boxes from step 2, a local trend is calculated. This is done by fitting a least squares line to each box. An example of this can be seen in Figure 3.1. The local trend is denoted as $y_n(k)$.
4. **$F(n)$ calculation:** The next step is subtracting the local trend from samples assigned to each box and then calculating the root-mean-square through all samples. The result is denoted as $F(n)$. The calculation can be seen in Equation 3.2.

$$F(n) = \sqrt{\frac{1}{N} \sum_{k=1}^N [y(k) - y_n(k)]^2} \quad (3.2)$$

5. **Finding parameter alpha:** Steps 2-4 are repeated over different box sizes. This provides $F(n)$ as a function of the size of the window n . From there, a log-log graph is made with $\log F(n)$ and $\log n$ on the axes. This relation is typically linear, which indicates the presence of scaling. Scaling is represented by slope of this relation. An example of this log-log plot can be seen in Figure 3.2. Typically, for $4 < n < 16$, we call the scaling factor alpha1, and for $16 < n < 64$, we call the scaling factor alpha2. [21, 33]

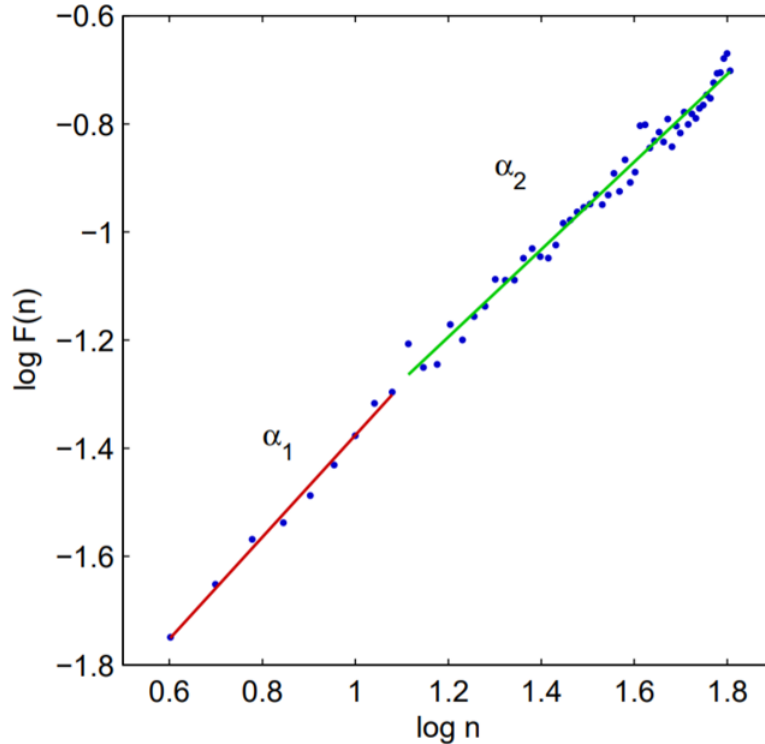


Fig. 3.2: Display of log-log plot with alpha1 and alpha2 highlighted [33]

3.2 Other methods of DFA computation

In addition to the classic DFA computation, there are also a few other approaches. One of these approaches is to use a simplified Kalman filter on $F(n)$ to obtain the alpha coefficient. This approach was deemed arbitrary because of its empirical definition. [4]

Another approach focuses on transforming the alpha coefficient from a two-slope representation to a function $\alpha(n)$ that describes how alpha changes over different scales, not just the values of alpha for short and long time scale correlations. This approach is mainly used to study multifractality. [4]

The third approach is to determine the alpha value from the first derivative of the $\log F(n)$ function. The upside of using this method lies in its higher resolution of the alpha coefficient, but due to its high sensitivity to noise, the $F(n)$ estimator needed to be optimized. This was achieved by splitting the series into as many overlapping boxes as possible instead of non-overlapping ones. The downside of this approach is that overlapping boxes increase computational load, making it unsuitable for fast DFA calculation or the calculation of DFA in long signals. [4]

3.3 DFA alpha1 and ventilation thresholds

In 2019, T. Gronwald and B. Rodgers began publishing about the correlation of ventilation thresholds and exercise intensity in general with the DFA alpha1 coefficient. Consequently, in the last four years, numerous studies have been conducted about DFA alpha1 coefficient and ventilation thresholds, mainly led by one or both of them. In 2019-2020, several studies confirmed that DFA alpha1 changes with changing exercise intensity during endurance performance and is suitable for exercise intensity assessment [8, 9, 10, 11]. Based on these findings, studies continued with the goal to confirm the possibility of identifying differences between low and high exercise intensity. It was confirmed that finding a difference between low and high intensity based on DFA alpha1 is possible. Moreover, there is a high correlation between the value of DFA alpha1=0.75 and LT1 and VT1, therefore it is possible to detect AeT (for the relationship between LT1, VT1, and AeT, see Chapter 1.1) based on DFA alpha1. [7, 22, 23, 25] There were also findings of high correlation of DFA alpha1=0.5 and VT2 and LT2, meaning that it is also possible to detect AnT (for the relationship between LT2, VT2, and AnT, see Chapter 1.2) based on DFA alpha1. [15, 26, 27, 30]

4 Aims of thesis

1. The main aim of this thesis is to create an application that calculates exercise intensity zones in real-time based on the DFA alpha1 coefficient and calculates HR representation of exercise intensity zones from graded intensity test based on DFA alpha1 values. To accomplish this aim, there is a need to complete several partial aims:
 - Connecting the Polar H10 to the PC and reading incoming data
 - Creating an algorithm for real-time DFA alpha1 calculation
 - Calculating exercise intensity zones from DFA alpha1
 - Creating a graphic user interface for controlling the process and displaying results
2. The secondary aim is to validate the created application. This aim can be split into two parts:
 - Validating the usage of the application during everyday training, meaning finding an answer to the question: *Is this application usable for displaying exercise intensity zones in everyday training??*
 - Validating the usage of the application during graded exercise tests, meaning finding an answer to the question: *Can this application be used to find AeT, AnT, and exercise intensity zones instead of traditional methods?*

5 Design and implementation

Design for the algorithm for exercise intensity zones calculation based on the DFA alpha1 coefficient consists of four parts. The first part is initialization, connecting to the heart rate monitor and streaming data from the heart rate monitor, and then there are three asynchronous (or cooccurring, running simultaneously) processes. Asynchronous processes are used because these processes work in different time-frames. The flowchart of this design can be seen in Figure 5.1. The algorithm is implemented in the Python language.

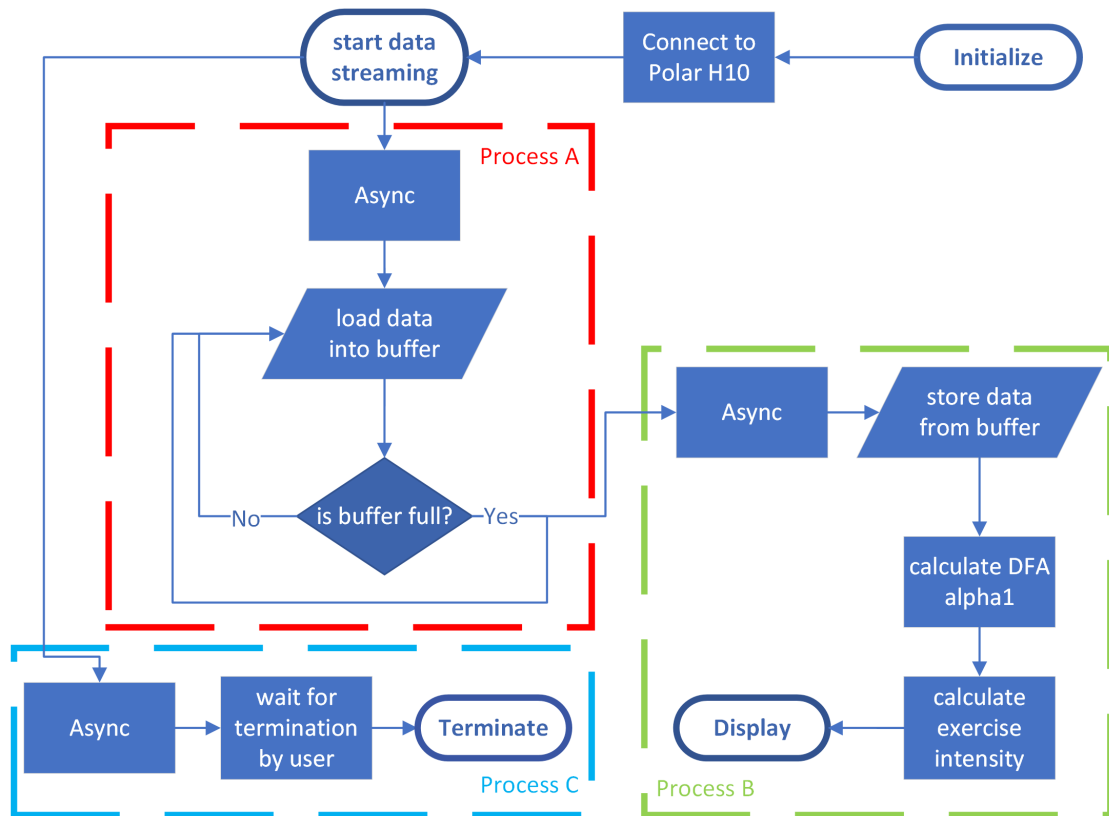


Fig. 5.1: Flowchart of implemented algorithm with marked three different asynchronous processes

The first asynchronous process (Process A in Figure 5.1) is responsible for buffering data before further processing. As mentioned in Chapter 3, the DFA alpha1 coefficient is calculated from the whole signal (or in this case, a part of the signal), so data cannot enter the DFA alpha1 computation sample-by-sample but need to be buffered beforehand. The size of the buffer determines the delay from real time - a bigger buffer size results in a bigger delay from real time but better precision in DFA alpha1 computation, while a smaller buffer size has the opposite effect. The buffer

also serves as a way to slow down the output frequency of DFA alpha1 computation. A healthy human can reach a heart rate around 200 bpm during maximal exercise intensity, which means a new RR interval sample is obtained every 0.3 seconds. DFA alpha1 computation is a computationally difficult task, and with a larger buffer size, 0.3 seconds might not be enough time to calculate it. More about the buffer, its function, design, and purpose are discussed in Chapter 5.2.

The second asynchronous process (Process B in Figure 5.1) involves DFA alpha1 computation and the computation and display of exercise intensity zones based on DFA alpha1. This process starts, when buffer is filled-up. From there, DFA alpha1 is computed, exercise intensity zones are calculated, and the result is displayed. The asynchronicity of this process is based on the potential inability to match the output frequency to the higher input frequency - if not asynchronous, this process would slow down the whole algorithm because it would still be running while new samples can be incoming. More information about this process can be found in Chapter 5.3 and 5.4.

The last process (Process C in Figure 5.1) is responsible for terminating the entire algorithm by the user, thus giving the user control over the algorithm. It is implemented using an asynchronous wait function. More details about are in Chapter 5.5.

5.1 Connecting to Polar H10

5.1.1 Polar H10

The first task at hand is to connect the heart rate monitor to the computer. Polar H10 heart rate monitor (can be seen at Figure 5.2) by Polar Electro Oy (Kempele, Finland) was chosen as the designated heart rate monitor for this purpose. I selected this heart rate monitor primarily because B. Rogers and T. Gronwald used either it or its older versions in their studies about DFA alpha1 as a marker for AeT and AnT when they were using a heart rate monitor [10, 22, 27, 30]. It is also commonly used during spiroergometry in medical examinations and during graded exercise testing in sports medicine. A validation study shows that the Polar H10 exhibits strong agreement with ECG measurements of RR intervals, and therefore HRV [29]. Other heart rate monitors I considered for use during this thesis were the Polar H7 and Polar H9 by Polar Electro Oy (Kempele, Finland) - these are older models of the Polar H10, the Suunto Smart Belt by Suunto OY (Vantaa, Finland), the Garmin HRM-Pro by Garmin Ltd. (Olathe, Kansas, USA), or the Wahoo Tickr X by Wahoo Fitness LLC (Atlanta, USA). I decided to use the Polar H10 instead of any other

heart rate monitor for the reasons mentioned above and/or the unavailability of the aforementioned heart rate monitors.

The Polar H10 communicates with other devices via Bluetooth Low Energy (BLE), which is Bluetooth version compatible with Bluetooth devices with Bluetooth version 4.0 or newer, or ANT+ 2.0 version. It is powered by a non-rechargeable 3V lithium battery type CR2025 and can last up to 400 hours collecting data. It has the possibility to store data. It has no control features, so control is possible only by other devices. It also incorporates an accelerometer, but use of it is irrelevant for this thesis [40].



Fig. 5.2: Polar H10 heart rate monitor. [40]

5.1.2 Establishing connection

The part of the program concerning the connection of the Polar H10 to the computer is loosely based on two programs - one code published by Wilbert van Ham [36] and one project by Mark M. Span [32]. The code from this thesis, in its final form, may not bear any resemblance to theirs, but initially, it was based on these two programs. The flowchart of the connection of the Polar H10 to the computer may be seen in Figure 5.3.

The code itself incorporates two libraries - Asyncio and Bleak. Asyncio is a library used for asynchronous programming and is utilized in nearly every aspect of this project because of the project's nature. It allows the user to create and

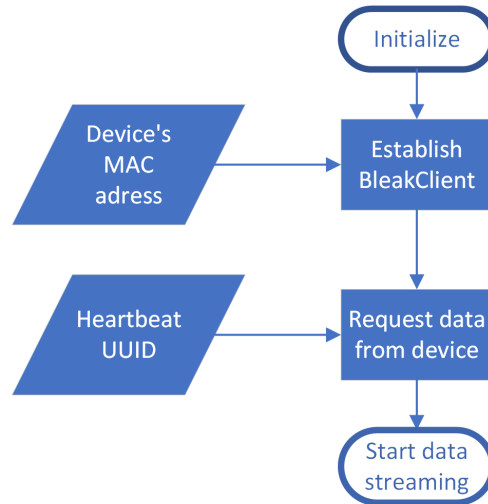


Fig. 5.3: Flowchart of algorithm for connection of Polar H10 to computer

run asynchronous functions and manage cooccurring events. The Bleak library is responsible for managing BLE (Bluetooth Low Energy) devices. It provides the possibility to connect to BLE devices and read data from them.

As can be seen from Figure 5.3, two inputs are needed until the data stream from the Polar H10 will start. The first one is the MAC address (media access control address) of the device from which data should be obtained. It serves as input for the BleakClient class. The BleakClient class acts as a GATT (generic attribute) client interface for connection to a specific BLE GATT server. In this case, it means that the GATT client (device accessing information on the remote server) is the computer running the created program, and the GATT server (device storing data and providing access to them) is the Polar H10. The MAC address provided to BleakClient specifies to which BLE GATT server (which Polar H10) the GATT client should connect. [38]

The second input needed for the successful start of the data stream from the Polar H10 is the UUID (Universal Unique Identifier). UUID is used for the unique identification of objects on the internet. In this case, it serves as a way to clarify what type of data the GATT client wants from the GATT server. The BleakClient operation is used to request data from the Polar H10, and the provided UUID specifies that data concerning heartbeats is wanted. The used UUID was obtained from the code by Wilbert van Ham. [36]

Since BleakClient has the possibility to be used as an asynchronous context manager to automatically connect and disconnect from the device, this whole block is run as an asynchronous function. [38]

5.2 Collecting the data with Polar H10

When the connection between the Polar H10 and the computer is established, and data streaming starts, there is a need to process incoming data. The flowchart of the algorithm for processing incoming data can be seen in Figure 5.4. It consists of two main parts - interpretation of data and data buffer. Interpretation of data is responsible for subtracting the desired information from the data and translating it into a data type usable in further parts of the algorithm. The data buffer is responsible for accumulating data and providing data to the intensity zones computation function. It also controls the frequency of intensity zones computation and the delay between data acquisition and the display of intensity zones.

The entire block responsible for data collection is implemented as an asynchronous function, which is called every time a new sample of data from Polar H10 is obtained. This means that multiple instances of this function can be running at the same time.

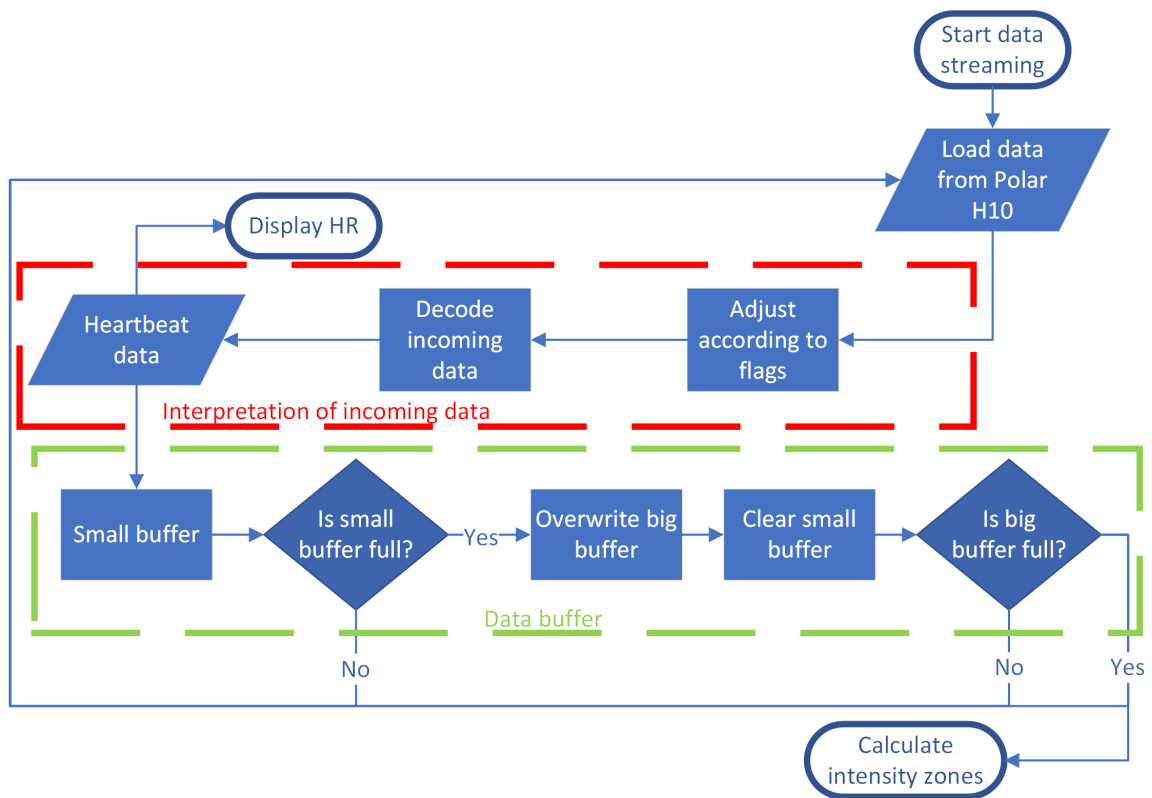


Fig. 5.4: Flowchart of algorithm for data acquisition

5.2.1 Interpretation of incoming data

Incoming data are of type bytearray. Because the Polar H10 uses BLE GATT characteristics, the encoding of these data can be found in the BLE GATT specification provided by Bluetooth SIG. [39] The specification for heart rate measurement data can be seen in Table 5.1.

Table 5.1: Description of each byte in bytearray of heartreat data incoming from Polar H10. [39]

Field	Data Type	Size [octets]	Description
Flags	boolean[8]	1	Information about data
HR Measurement (8 bit resolution)	uint8	0 or 1	Heart rate in beats per minute Present if bit 0 of Flags is set to 0
HR Measurement (16 bit resolution)	uint16	0 or 2	Heart rate in beats per minute Present if bit 0 of Flags is set to 1
EE Measurement	uint16	0 or 2	Energy Expenditure in juoles Present if bit 3 of Flags is set to 1
RR-interval	uint16[n]	0 or 2*n	RR intervals Present if bit 4 of Flags is set to 1

The Flags field is used to transfer information about incoming data from the Polar H10 to the computer. It contains information about the presence of different measured values and their position in the bytearray. The Flags field consists of 8 bits, and the description of each bit can be seen in Table 5.2. After the Flags field is read from incoming data, adjustments are made to correctly reference the position of the desired measured value in the bytearray. Adjustments are made in the case where Heart Rate is in uint16 format (usually it is not because uint8 covers values up to 255 and the heart rate of a healthy human should not exceed 220 beats per minute) and in the case where Energy Expenditure is present (in the current version of the Polar H10, it is not supported).

From the incoming data, only HR (heart rate) and RR intervals are wanted. HR is converted from hexadecimal to decimal numeral system and is displayed to the user. RR intervals are also converted from hexadecimal to decimal numeral system and then continue to buffer for further processing and subsequent processing in exercise intensity zones computation.

5.2.2 Data buffer

As can be seen in Figure 5.4, the data buffer actually consists of two buffers - a smaller one of size m and a larger one of size n samples, where $n = k \cdot m$ with k

Table 5.2: Description of bits in Flags field [39]

Bit	Definition
0	Heart Rate Value Format: 0 = Heart Rate Value Format is set to uint8 1 = Heart Rate Value Format is set to uint16
1	Sensor Contact detected
2	Sensor Contact Supported
3	Energy Expended present
4	RR-Interval present
5-7	Reserved for Future Use

being a whole number. The first one is filled with the smaller buffer, and upon its fulfillment, the larger one is filled. The larger one is a so-called "circular buffer," meaning that after its fulfillment, the oldest samples (samples first written into the buffer) are overwritten by new samples, while the smaller one is cleared upon its fulfillment. This architecture means that every m received samples, a new value of DFA alpha1 coefficient, and therefore exercise intensity zone, is calculated. It would be ideal to calculate DFA alpha1 with each incoming sample, but DFA alpha1 computation is a computationally demanding task, and it is possible that in higher intensity, multiple tasks of DFA alpha1 computation would occur concurrently, and the computation demand would be too great. Therefore, the smaller buffer has been introduced to slow down the process, and the algorithm does not rely only on the fact that DFA alpha1 is computed asynchronously. The size of the smaller buffer is set to 10 samples. With this setting, a new DFA alpha1 and intensity zone would be computed every 5 seconds in low intensity (around a heart rate of 120 beats per minute), 4 seconds in medium intensity (around a heart rate of 150 beats per minute), and 3 seconds in maximal intensity (heart rate over 180 beats per minute).

The larger buffer introduces a delay from real-time dependent on the size of the larger buffer. This is because DFA alpha1 is calculated from the signal over a certain timeframe and not a single sample. Therefore, there needs to be a minimal number of samples reached to compute DFA alpha1, and this is done by buffering them. It is advised that DFA alpha1 is computed over at least 5 times more samples than the length of the maximal window used to split the signal (for more about DFA alpha1 and its computation, see Chapter 3).[21] From this, and considering that the maximal window size for splitting the signal for DFA alpha1 computation is 16, the minimal window size of 80 samples is obtained. In practice, the length of the signal of 200 samples or 2 minutes is mostly used. Since the aim of this thesis is to create an application working in real-time, the minimal window size (80 samples) has been

chosen. If the result of the computation refers to the time in the middle of the time series over which it was made, this buffer introduces a delay from real-time of 20 seconds in low intensity (around a heart rate of 120 beats per minute), 16 seconds in medium intensity (around a heart rate of 150 beats per minute), and 13 seconds in maximal intensity (heart rate over 180 beats per minute).

The size of buffers has been chosen in samples rather than time because the number of samples over time changes with changing heart rate. It was deemed better to have a changing output refresh frequency and delay from real-time rather than changing the number of samples over which DFA alpha1 is computed.

5.3 DFA alpha1 computation

DFA alpha1 computation is based on the original computation method described in Chapter 3.1. The flowchart of the realization of this computation can be seen in Figure 5.5. The function is implemented as a linear function and is called within an asynchronous function responsible for exercise intensity zones computation. It is not necessary for this function to be asynchronous because further parts of the intensity zones computation function are entirely based on the result of the DFA alpha1 computation function.

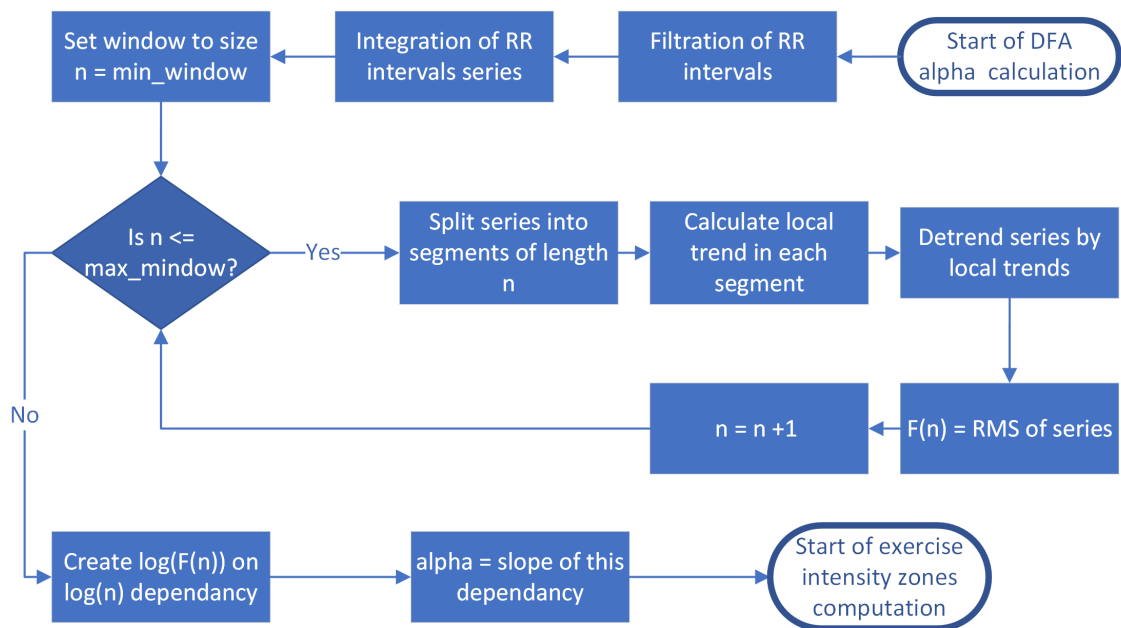


Fig. 5.5: Flowchart of algorithm for DFA alpha1 computation

For DFA alpha1 computation, only the NumPy library is used. Before the computation of DFA alpha1 itself, RR interval series must be filtered. It was shown that

uncorrected artifacts can affect the computation of thresholds based on DFA alpha1 [14, 24]. As artefacts are marked RR intervals which have a duration over 750 ms (corresponding to a heart rate under 80 bpm) or under 250 ms (corresponding to a heart rate over 240 bpm) or differ from at least one of their neighbors by 7% at least. Marked intervals are then corrected by replacing their value with the value of the mean of their neighbors (if both neighbors are not marked as artefacts) or by the mean of the whole RR interval series.

As for DFA alpha1 computation itself, firstly, the integration of RR interval time series is done. This is achieved by subtracting the mean of RR intervals from each sample in the series and then performing a cumulative summation over the entire series. Then, a loop is established to go through all window sizes from the minimal to the maximal window size. The minimal window size is set to 4, and the maximal window size is set to 16, according to the alpha1 description [21]. The series is then split into segments of equal length, with this length being the same as the current size of the window. In each segment of the series, a local trend is calculated as a least squares line (executed as a polynomial of the first order) fitted to the segment. The RR interval series is detrended by these local trends, and the root mean square of this detrended series is calculated. This is denoted as a sample in the series $F(n)$, where n is the size of the window. After going through all window sizes, the $\log(F(n))$ dependency on $\log(n)$ is calculated. The slope of this dependency is then denoted as the alpha1 coefficient. It is calculated as the highest power coefficient of the polynomial of the first order fitted to this dependency. A more detailed description of DFA alpha1 computation can be found in Chapter 3.1.

5.4 Intensity zones computation

As mentioned in the aims of this thesis, the created application should offer two possible ways of usage. The first is to calculate exercise intensity zones in real-time to help users better control their training on a daily basis. The second is to calculate HR representations of exercise intensity zones from graded exercise tests to minimize financial strain on conducting these types of tests. Therefore, two methods of intensity zone computation are needed: one during measurement and one after.

For intensity zone computation, a 5-zone model of exercise intensity zones was selected (see Table 5.3 for zone names and descriptions). The names and descriptions of the zones are based on those in MetaSoft Studio by Cortex Biophysik GmbH (Leipzig, Germany), which is software used for calculation of training zones based on gas exchange parameters for device MetaLyzer 3-B. The 5-zone model was chosen because it is the most commonly used model nowadays, for example, by sport watch and smartwatch manufacturers such as Garmin Ltd. (Olathe, Kansas, USA),

Table 5.3: Description of used zones in 5 zonal model. Zones names and descriptions are based on zones names and descriptions in MetaSoft Studio

Zone name	DFA alpha1	HR [bpm]	Zone description
Recovery	>1.0	<80% AeT or HR at beginning of test	Lowest intensity, used for warming up and cooling down
Long endurance	1.0-0.75	80-100% AeT	Low intensity, used for basic endurance training
Short endurance	0.75-0.62	100% AeT- 50% (AnT -AeT)	Medium intensity, used for increasing aerobic capacity
Development	0.62-0.5	50% (AnT -AeT) - 100% AnT	Medium to high intensity, used for performance improvement
Maximal	<0.5	>100% AnT	Highest intensity, used for racing and speed training

Polar Electro Oy (Kempele, Finland), or Suunto OY (Vantaa, Finland). The use of the 5-zone model means that there are four thresholds which separate these zones. These thresholds will be referred to in later parts of this thesis as T1, T2, T3, and T4, with T1 being the threshold between the lowest intensity zones (Recovery and Long Endurance) and T4 being the threshold between the highest intensity zones (Development and Maximal). In connection to physiological thresholds in human metabolism, T2 represents AeT (aerobic threshold) and T4 represents AnT (anaerobic threshold). For more information about exercise intensity thresholds, see Chapter 1.

5.4.1 Intensity zones computation during measurement

The computation of intensity zones during measurement is quite simple - it is done by thresholding. These thresholds can be seen in Table 5.3. They were based on findings by B. Rogers and T. Gronwald regarding the correlation between thresholds in DFA alpha1 and AeT and AnT. T2, representing AeT, is set at a value of DFA alpha1 = 0.75 based on multiple findings confirming its value [7, 22, 23, 25]. T4, representing AnT, is set at a value of DFA alpha1 = 0.5 based on multiple findings confirming its value [15, 26, 27, 30]. T3 value is set at value of DFA alpha1 = 0.62

which is mean value of DFA alpha1 between T2 and T4. T1 value is set at value of DFA alpha1 = 1.0 which represents value above which correlations cease to exist in power-law form - heart is under little to no stress, therefore Recovery zone. [21]

Intensity zones computation during measurement occurs immediately after DFA alpha1 value is computed so it is part of the asynchronous function controlling DFA alpha1 computation. It is realized as a multiple if-then statement block.

5.4.2 Intensity zones computation after measurement

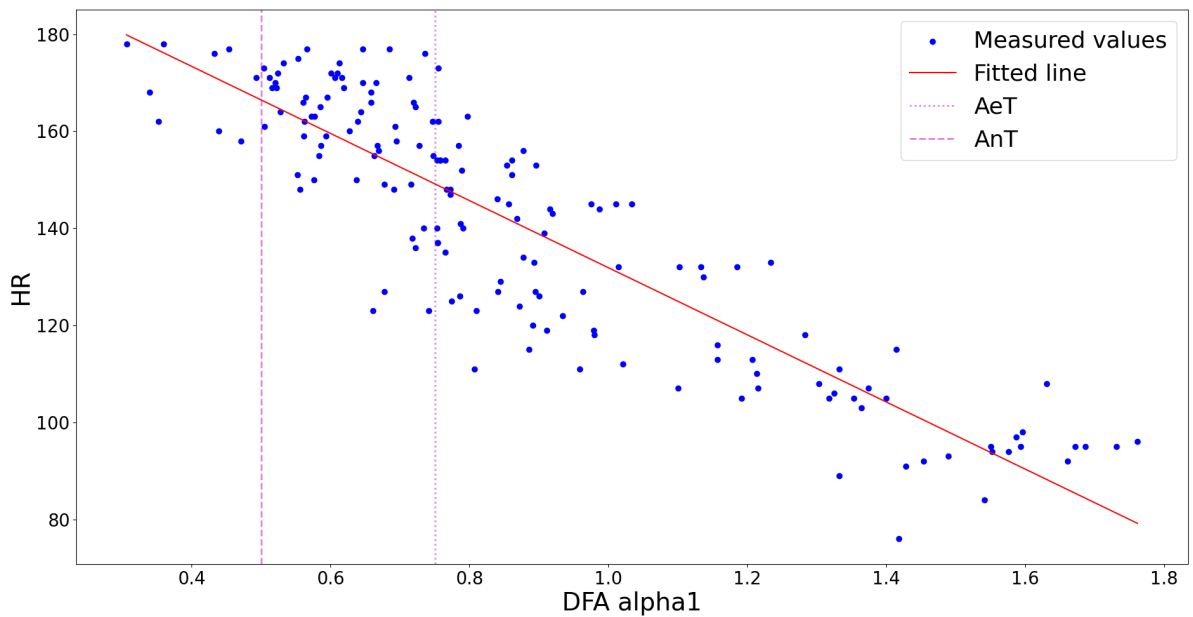


Fig. 5.6: Example of HR/DFA alpha1 dependency for subject nr. 8. HR on AeT and AnT lies at their respective intersections with fitted line.

Computation of exercise intensity zones after measurement is a bit different than computation during measurement because HR representation of thresholds needs to be found. It is found from HR dependency on DFA alpha1 (see Figure 5.6). Firstly, AeT and AnT are found. To find them, a polynomial of the first order is fitted to HR/DFA alpha1 dependency. After that, from the slope and intercept of this fitted line, AeT and AnT are calculated, based on values of DFA alpha1 on these thresholds. DFA alpha1 = 0.75 is the value of DFA alpha1 on AeT and DFA alpha1 = 0.5 is the value on AnT. As HR value on AeT is overestimated and on AnT underestimated by this approach, a correction of -9 bpm for AeT respectively +7 bpm for AnT is added (for more see Chapter 7.1). After HR on AeT and AnT

is estimated, training zones are calculated according to values of HR described in Table 5.3.

As was mentioned in Chapter 5.3, artifacts heavily affect DFA alpha1 value. Even though filtration was implemented (see Chapter 5.3), computed DFA alpha1 values can be disrupted by these artifacts and therefore line fitting can be problematic. To get rid of this problem, removal of outliers was implemented before line fitting to HR/DFA alpha1 dependency. For outlier removal, interquartile range was used - samples with DFA alpha1 greater than the 75th percentile plus the difference between the 75th and 25th percentile or smaller than the 25th percentile minus the difference between the 75th and 25th percentile were removed.

Intensity zones computation after measurement is realized as a linear function which is called only at the end of the measurement and only if the user permits it. Its calling and result display is part of the user interface so more about it can be found in Chapter 5.5.

5.5 User interface

The user interface is realized as a Kivy application. Kivy is a Python framework for multiplatform application creation. This user interface is developed using Kivy version 2.3.0. An example of the user interface itself can be seen in Figure 5.7.

At the topmost part of the application window is the so-called "Settings box". It contains two buttons which give the user the possibility to set conditions of measurement. The first button is to select the Polar H10 device to which the user wants to be connected. It is realized as a drop-down menu with all available Polar H10 devices listed. After the device is selected, its number is displayed on the button and the drop-down menu is automatically closed (as can be seen in Figure 5.7), and the MAC address of this device is used as input of the connection function (for more about connection to Polar H10 see Chapter 5.1.2). The number is displayed because Polar H10 devices have their numbers engraved on them, therefore the user can easily check if they are connected to the right device. Discovery of all available devices is done by the Bleak library. The second button is a toggle button which triggers the calculation of HR representation of training zones at the end of measurement. With this button, the user can basically switch between the two intended types of using the app - while the "Calculate training zones" toggle button is triggered, the application acts as a supplement for laboratory intensity zones estimation and besides displaying the current intensity zone it also calculates training zones at the end of measurement; otherwise, it only displays exercise intensity zone in real-time.

In the middle part of the application window is the so-called "Display box". It displays data of HR, DFA alpha1, elapsed time of measurement, and exercise

intensity zone. Exercise intensity zones are based on the 5-zonal model described in Table 5.3. Exercise intensity zone is color-coded for better visualization. Color-coding is gray, blue, green, yellow, and red for zones from the lowest to highest intensity.

At the bottommost part of the application window is the so-called "Control box" which consists of two buttons. These buttons are used to start and stop the measurement. The Start button triggers the start of data collection and zone calculation (more about the used algorithm in Chapter 5) and starts counting the elapsed time. After start, values of HR, DFA alpha1, and exercise intensity zones are returned. These values and elapsed time are then displayed in the "Display box". Values of HR, DFA alpha1, and elapsed time are also stored for the duration of measurement. The Stop button stops data collection and counting of elapsed time. It also creates a .csv file containing data stored in the dataframe in the logs directory. This file name is the date and time at which measurement started (e.g., 2024-04-16_18-55-53.csv). If "Calculate training zones" is triggered, also a .csv file containing HR representation of training zones based on the current measurement is created. This file name is the date and time at which measurement started with _ZONES at the end (e.g., 2024-04-16_18-55-53_ZONES.csv). An example of created files can be seen in Appendix C.

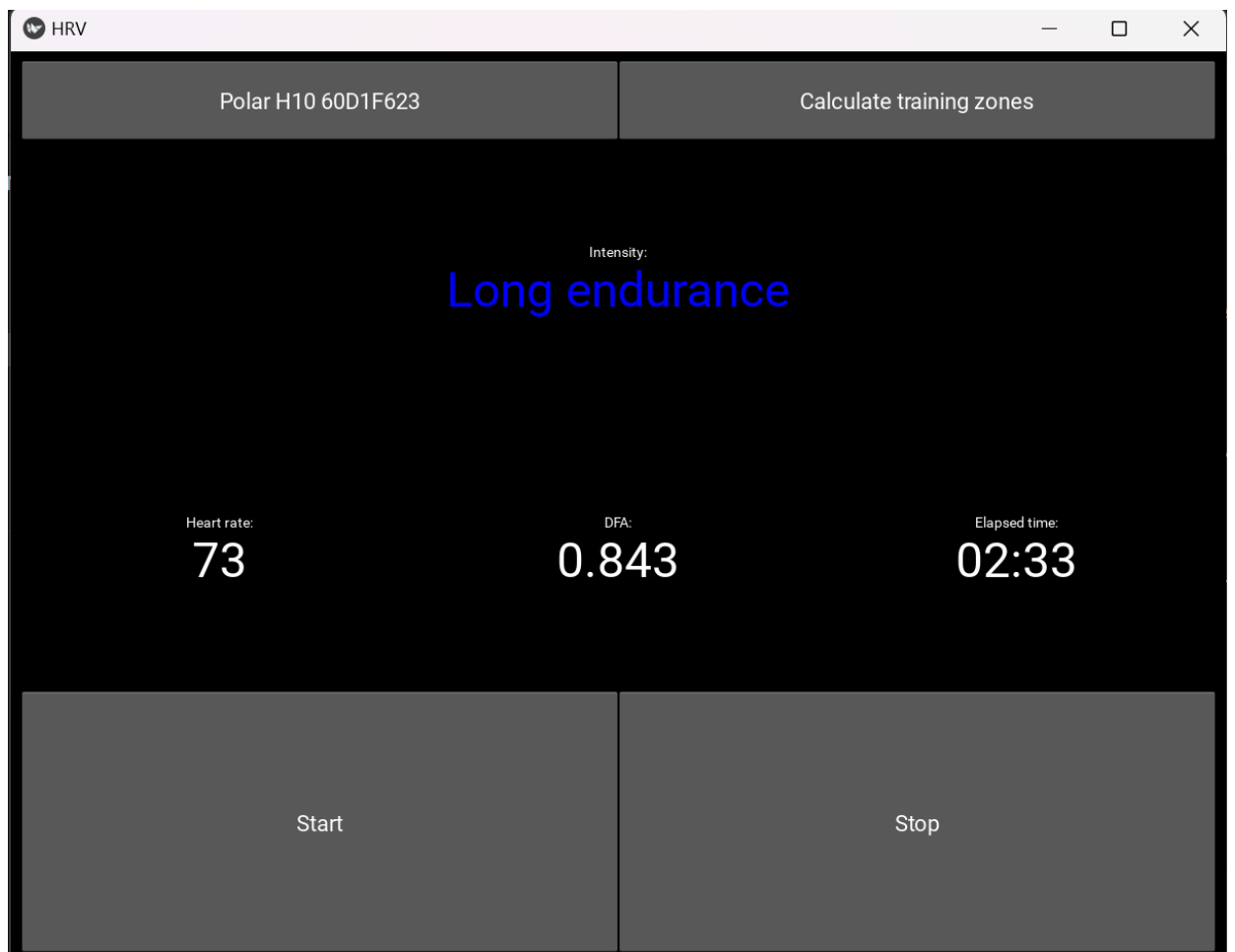


Fig. 5.7: Example of the user interface of the created application.

6 Testing dataset

The dataset on which the final algorithm will be tested is composed of two types of data differing in their place of origin. The first type is data measured outside of laboratory conditions during everyday training or sports activity, while the second type is measured inside in laboratory conditions during a graded exercise test. Splitting the testing dataset into data obtained during everyday usage and data obtained in laboratory conditions is done because of two possible ways to use the created application.

Data measured during everyday sports activity are part of the author's personal archive. Author is 24 years old male sportsman with multiple years of running experience. This dataset contains 22 runs conducted by the author between 3.10.2023 and 28.11.2023, with both heart rate (HR) and RR intervals time series measured during the run by the Polar H10 heart rate monitor. As a reference for exercise intensity zones and AeT and AnT during these runs, a graded exercise test was done on 31.10.2023 for the author's personal needs (results of this test have been used as an example of the five-zone model in Figure 1.6). Runs vary in intensity, ranging from those well under AeT in the so-called "Compensation" zone to running races well above AnT in the so-called "Maximal intensity zone." The length of each run ranges from 30 to 100 minutes. This wide variety of lengths and intensities of runs included in the dataset should simulate conditions during everyday usage. Only runs within 4 weeks around the graded exercise test were chosen to maintain the best possible accuracy of reference values of exercise intensity zones because the parameters of these zones may physiologically change over time.

For testing of usage in laboratory conditions, two separate sub-datasets were used. The first is a sub-dataset measured by the author in the laboratories of the Center of Sport Activities, Brno University of Technology. Twenty adults, both male and female, of age 18-30 and varying fitness levels participated in this testing. A graded exercise test on a treadmill (starting speed 10 km/h, then increasing by 1 km/h every 2 minutes with a constant incline of 1%) was conducted during which gas exchange parameters, HR, and RR intervals were measured. Ground truth data of thresholds between exercise intensity zones were obtained from gas exchange parameters measured with Metamax 3B by Cortex Biophysik GmbH (Leipzig, Germany) and their later analysis in MetaSoftStudio by Cortex Biophysik GmbH (Leipzig, Germany). HR and RR intervals were measured with Polar H10. Participants completed the graded exercise test at least until intensity was above AnT. As a result of the test, RR intervals and HR time series were obtained as well as data of exercise intensity zones thresholds. In the end, 6 participants were excluded from the dataset due to malfunction of the heart rate monitor used for HR and RR intervals

measurement; therefore, the dataset contains samples from 14 measurements. More about the testing itself can be found in the example of informed consent in Appendix A. Testing was carried out with the agreement of the Ethical Committee of the Department of Biomedical Engineering, Faculty of Electrical Engineering, Brno University of Technology under reference number 01b/2024.

The second sub-dataset for laboratory measurement is from the bachelor thesis written by Bc. Tobiáš Goldschmidt. [6] This dataset consists of measurements of HR and RR intervals during a graded exercise test, as well as gas exchange parameters. HR and RR intervals were measured with Polar H10, and gas exchange parameters with Metamax 3B. Ground true data of HR representation of training zones were obtained by using MetaSoftStudio for analysis of data from MetaMax 3B. The graded exercise test used during obtaining data in this dataset was done on a bicycle ergometer, with a ramp protocol (protocol where workload is increasing linearly) starting at 1 W/kg of body weight and then increasing by 30 W per minute. The dataset contains data of 20 participants, both male and female, of varying age and fitness levels. However data from 6 participants were excluded from dataset because of malfunction of HR measurement. Therefore, dataset contains only 14 measurements.

7 Results

As mentioned before, the created application can have two purposes of use - to monitor exercise intensity zones in real-time during everyday training or to estimate HR representation of exercise intensity zones during laboratory testing. The results chapter is accordingly split into two parts, one concerning laboratory usage and the other concerning real-time everyday usage. During testing of the application, DFA alpha1 values were calculated by the same algorithm described in Chapter 5.

7.1 Laboratory testing

For testing of the application's usage for laboratory testing, HR representation of thresholds between intensity zones was calculated in the same way as described in Chapter 5.4.2. Ground truth data were taken as values of thresholds based on gas exchange parameters. The testing dataset is described in Chapter 6. Mean absolute error, mean error, and Wilcoxon signed-rank test were used to describe differences between ground truth and HR intensity zones representation based on DFA alpha1.

Firstly, HR intensity zones representation based on DFA alpha1 was calculated without any compensation. Results of this approach can be seen in Table 7.1 and Figure 7.1. These results show that there is no statistically significant agreement between ground truth and calculated values of thresholds between zones, and the mean absolute error for each threshold is also quite big for practical use. It is also obvious that values of T2 and T4 are overestimated and underestimated, respectively. Because of this fact, the testing dataset was split into two - to a testing and validation dataset.

Table 7.1: Results of laboratory testing for the whole dataset without correction for HR representation of each threshold between zones.

Threshold	Mean absolute error \pm standard deviation [bpm]	Mean error [bpm]	p-value of Wilcoxon test
T1	4.36 \pm 3.37	3.00	0.025
T2	8.61 \pm 3.92	8.39	0.001
T3	3.39 \pm 3.06	0.46	0.463
T4	7.57 \pm 4.11	-7.36	0.001

As a validation dataset, the dataset measured by the author during the creation of this thesis (for more see Chapter 6) was denoted. Results for this dataset can be seen in Table 7.2 and Figure 7.2. From results, it can be seen that the trend of underestimation of T2 and overestimation of T4 is present. Based on results for

these thresholds, a correction factor of -9 for T2 (resp. for AeT because T2=100% of HR on AeT, see Table 5.3) and +7 for T4 (resp. for AnT because T4=100% HR on AnT, see Table 5.3) were introduced. These correction factors come from rounded values of mean error on these thresholds.

Table 7.2: Results of laboratory testing for validation dataset without correction for HR representation of each threshold between zones.

Threshold	Mean absolute error \pm standard deviation [bpm]	Mean error [bpm]	p-value of Wilcoxon test
T1	3.36 \pm 3.39	2.79	0.003
T2	8.93 \pm 4.11	8.50	0.000
T3	3.93 \pm 2.28	0.93	0.546
T4	7.21 \pm 4.90	-6.79	0.000

As a testing dataset was denoted the dataset from the bachelor thesis by Bc. Tobiáš Goldschmidt. [6] Results for this dataset without the use of a correction factor are not very positive (see Table 7.3 and Figure 7.3) - for most thresholds there is no statistically significant agreement and mean absolute errors are still quite big. In comparison to results without a correction factor, results with a correction factor applied (see Table 7.4 and Figure 7.4) look more positive - for all thresholds, there is statistically significant agreement and values of mean absolute errors are acceptable from a practical point of view. Based on this information, correction factors were used in final version of application.

Table 7.3: Results of laboratory testing for testing dataset without correction for HR representation of each threshold between zones.

Threshold	Mean absolute error \pm standard deviation [bpm]	Mean error [bpm]	p-value of Wilcoxon test
T1	5.36 \pm 3.04	3.21	0.049
T2	8.29 \pm 3.69	8.29	0.000
T3	2.86 \pm 1.64	0.00	0.972
T4	7.93 \pm 3.08	-7.93	0.000

Table 7.4: Results of laboratory testing for testing dataset with correction for HR representiton of each threshold between zones.

Threshold	Mean absolute error \pm standard deviation [bpm]	Mean error [bpm]	p-value of Wilcoxon test
T1	3.50 ± 1.72	-0.79	0.379
T2	3.00 ± 2.26	-0.71	0.305
T3	3.07 ± 1.58	-0.79	0.351
T4	2.79 ± 1.61	-0.93	0.297

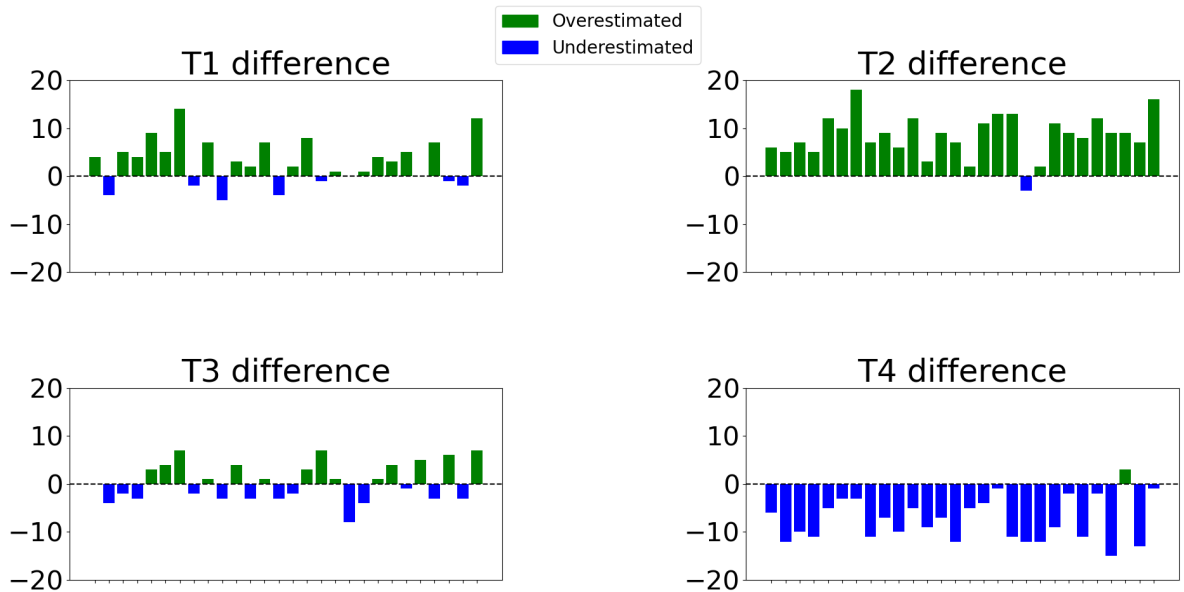


Fig. 7.1: Results of laboratory testing for the whole dataset without adding correction for HR representation of each threshold between exercise intensity zones. Underestimated means that the value was smaller than it should be, overestimated that it was bigger than it should be.

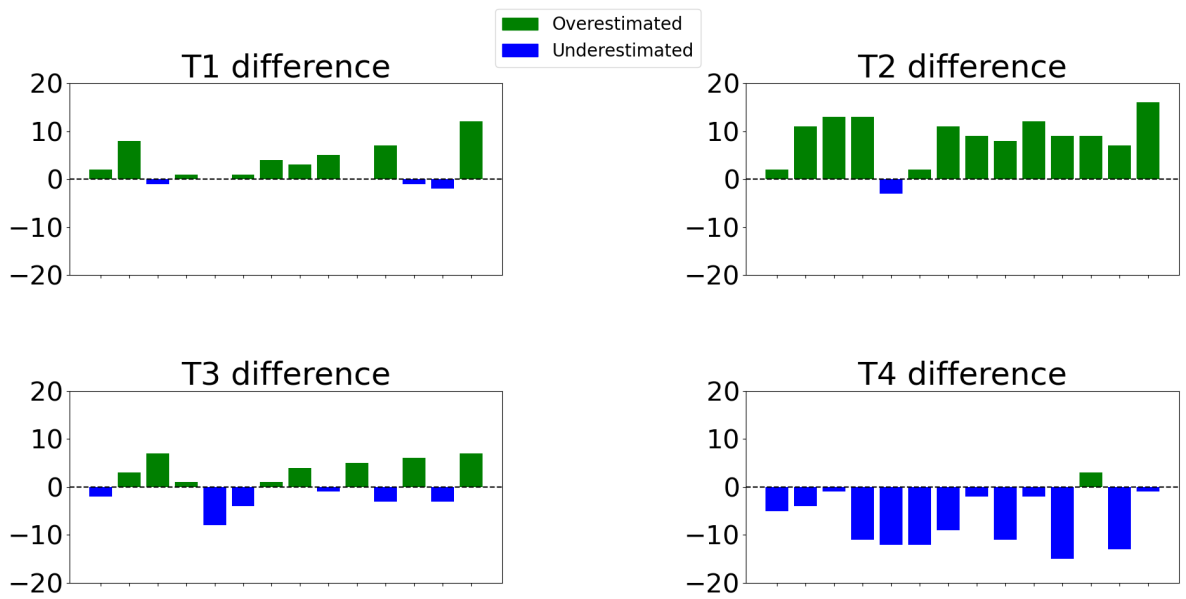


Fig. 7.2: Results of laboratory testing for validation dataset without adding correction for HR representation of each threshold between exercise intensity zones. Underestimated means that the value was smaller than it should be, overestimated that it was bigger than it should be.

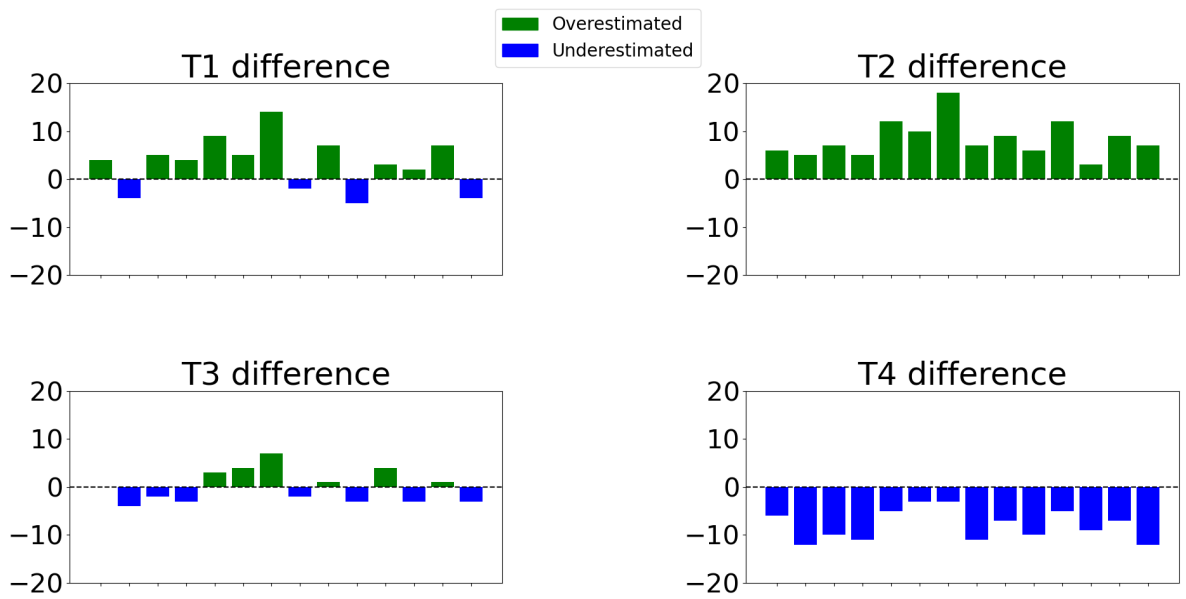


Fig. 7.3: Results of laboratory testing for testing dataset without adding correction for HR representation of each threshold between exercise intensity zones. Underestimated means that the value was smaller than it should be, overestimated that it was bigger than it should be.

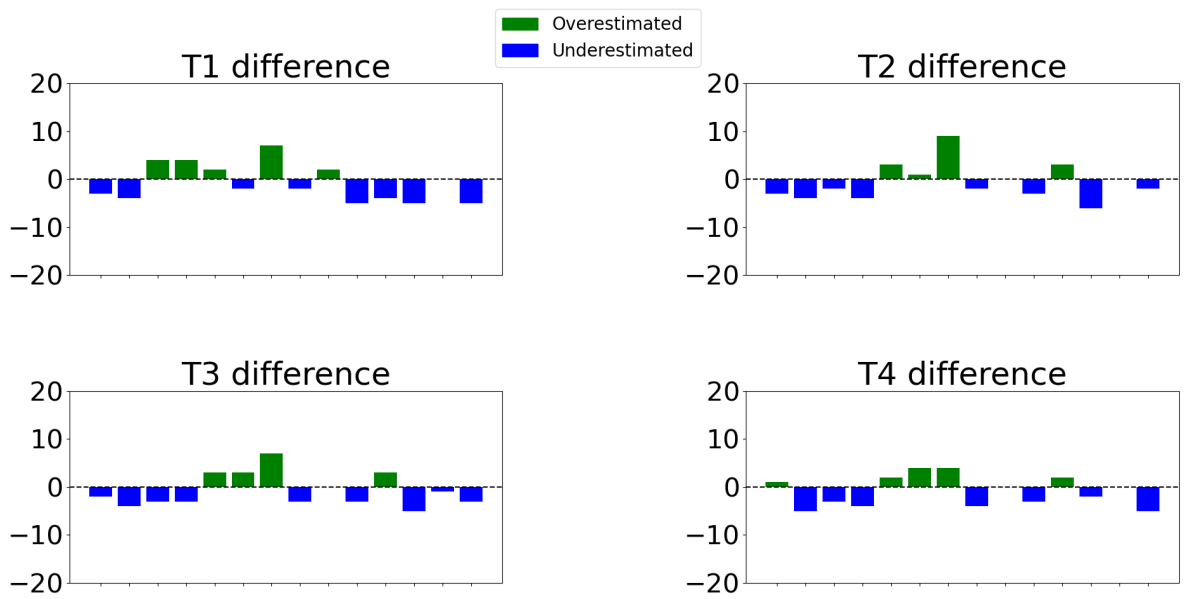


Fig. 7.4: Results of laboratory testing for testing dataset with adding correction for HR representation of each threshold between exercise intensity zones. Underestimated means that the value was smaller than it should be, overestimated that it was bigger than it should be.

7.2 Real time intensity zones calculation

For testing the application’s usage for everyday use (real-time intensity zones calculation), intensity zones were calculated as described in Chapter 5.4.1. The dataset used for testing is described in Chapter 6. Accuracy and Cohen’s kappa were used to describe the agreement between ground truth data and data based on DFA alpha1.

In Table 7.5, the mean accuracy for each zone can be seen, which is quite low, with the highest being at 12.22% for the Long Endurance zone and for other zones below 5%. In Figure 7.5, a stacked bar plot of accuracy with color-coded zones (gray, blue, green, yellow, and red for zones from the lowest to highest intensity) can be seen. Only one value exceeds 50%, with the majority being under 25%, and the average being 22.39%. These accuracy values are not very promising from a practical point of view. Cohen’s Kappa only confirms this from a statistical point of view because its value was $\kappa = 0.05$, which means no agreement. The reason why the Long Endurance zone has multiple times higher accuracy than others is that the majority of runs were done mainly in the Long Endurance zone. Also, the peak in accuracy at run 5 is explained by the majority of run 5 being in this zone.

Table 7.5: Results of real-time intensity zones calculation describing accuracy in each zone using default thresholds.

Intensity zone	Accuracy [%]
Compensation	4.30
Long Endurance	12.22
Short Endurance	1.55
Development	1.29
Maximal	3.02
Whole activity	22.39

Because these results were not satisfying, the value of DFA alpha1 on ground truth data of thresholds between zones from the dataset for laboratory testing were calculated. For this, the whole dataset for laboratory testing, validation as well as the testing part were used. Results can be seen in Table 7.6. These values were then used in real-time intensity zones calculation instead of values described in Chapter 5.4.1. Results can be seen in Table 7.7 and Figure 7.7. As can be seen, the results get slightly worse. The mean value of accuracy for 3 zones got a bit higher, however, the mean value for the whole activity got around 4% lower. Still, only one value of cumulated accuracy across all zones (Figure 7.7) is over 50%, and now the majority is under 15%, not 25% as it was with the default approach. Cohen’s Kappa stayed the same at $\kappa = 0.05$, meaning there is still no agreement between ground true and

DFA alpha1-based data. Therefore, these new thresholds were not incorporated into the final application.

Table 7.6: Values of thresholds between exercise intensity zones based on DFA alpha1 values on these thresholds in testing dataset for laboratory use.

Threshold	DFA alpha1
T1	1.18
T2	0.88
T3	0.70
T4	0.53

Table 7.7: Results of real time intensity zones calculation describing accuracy in each zone using calculated thresholds.

Intensity zone	Accuracy [%]
Compensation	3.39
Long endurance	8.43
Short endurance	1.44
Development	2.01
Maximal	3.30
Whole activity	18.58

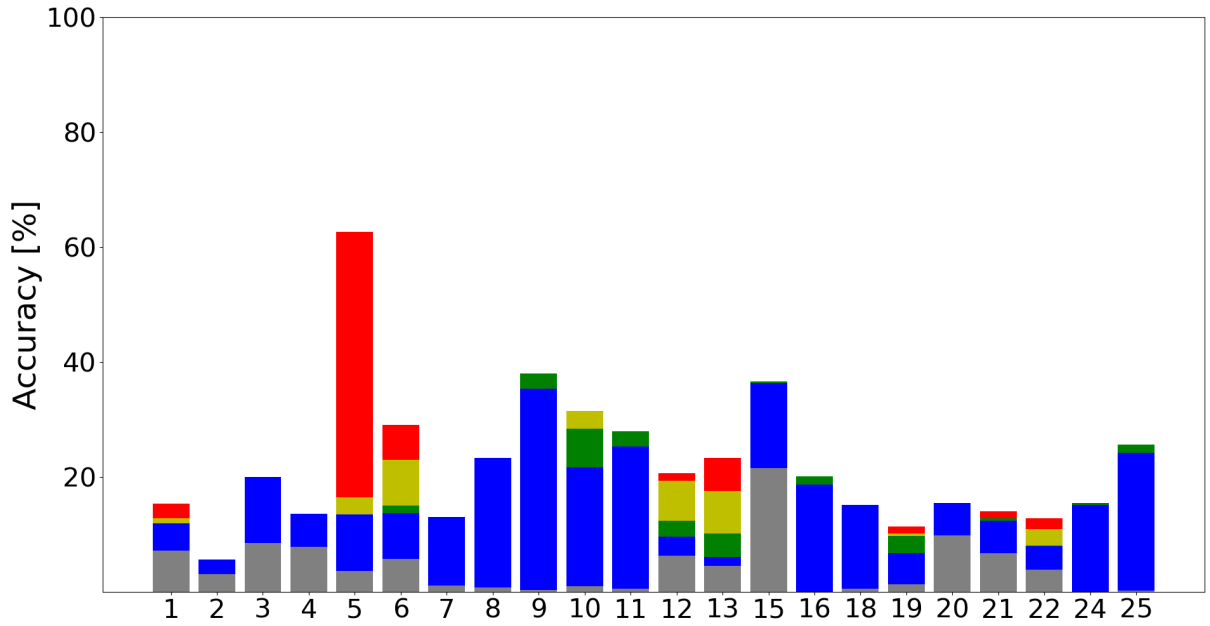


Fig. 7.5: Results of real time intensity zone calculation describing accuracy in each zone for each run using default thresholds. Colors of zones are gray, blue, green, yellow, and red for zones from the lowest to highest intensity.

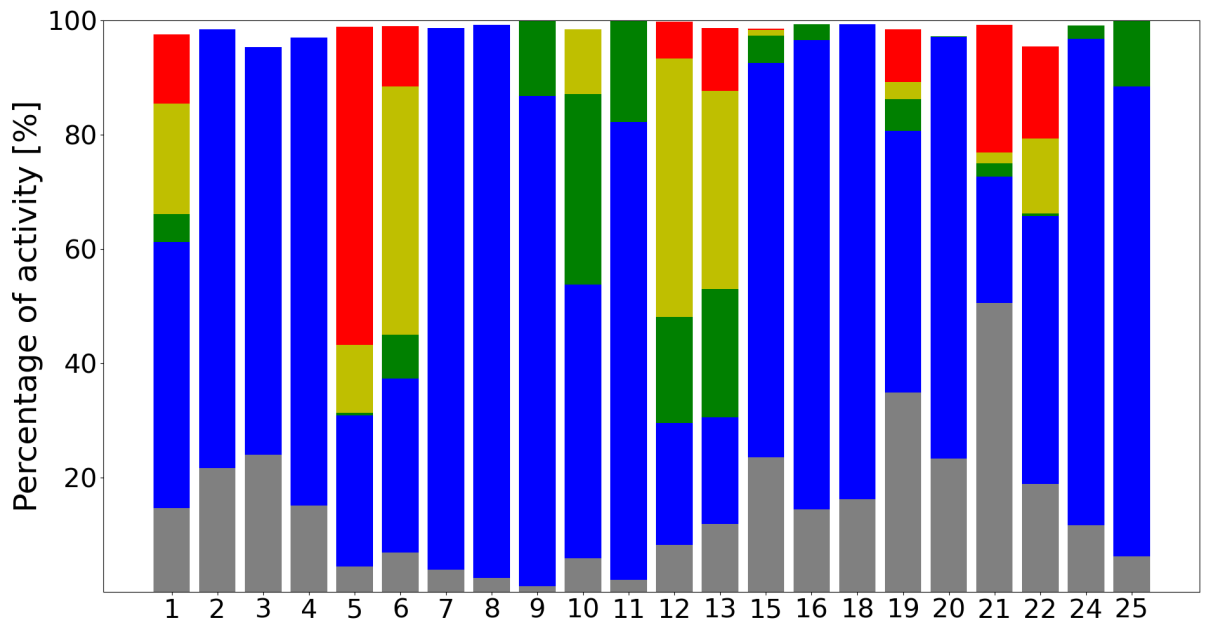


Fig. 7.6: Percentage of time spend in each activity zone during activity. Colors of zones are gray, blue, green, yellow, and red for zones from the lowest to highest intensity. Sum not reaching 100% is because of rounding errors.

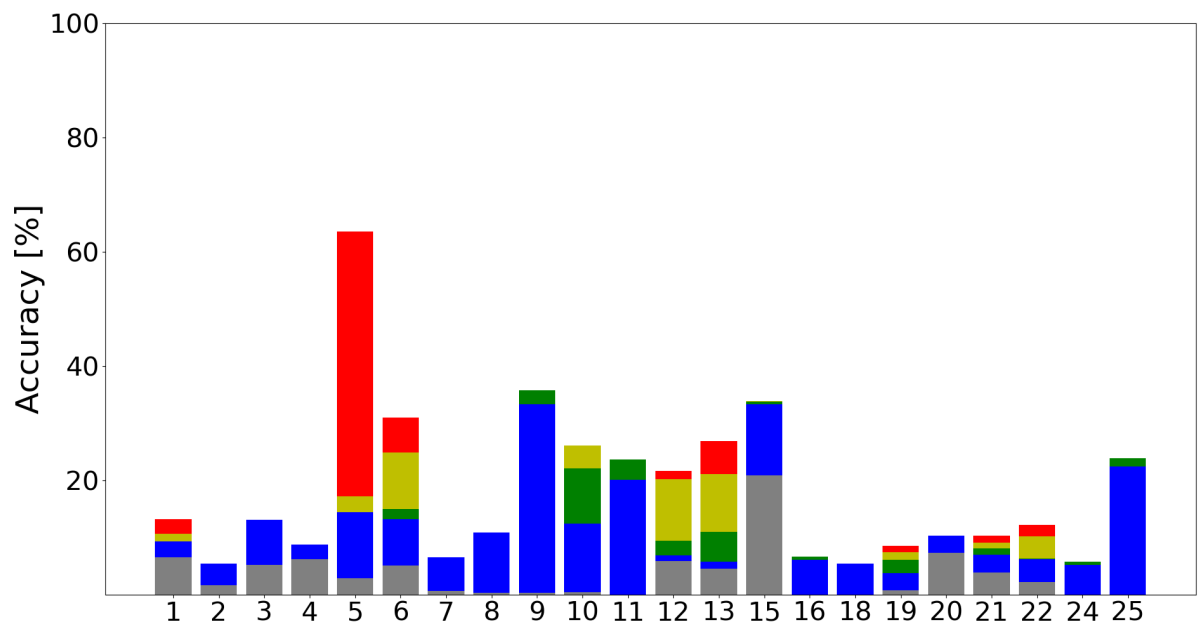


Fig. 7.7: Results of real time intensity zone calculation describing accuracy in each zone for each run using calculated thresholds. Colors of zones are gray, blue, green, yellow, and red for zones from the lowest to highest intensity.

8 Discussion

For the real-time estimation of exercise intensity zones using the created application, the results are terrible. Both accuracy (18.85%) and Cohen's Kappa ($\kappa = 0.05$) suggest that there is no agreement between exercise intensity zones calculation based on DFA alpha1 and ground truth data. A closer look at real-time exercise intensity zones estimation data also shows that DFA alpha1 does not consistently follow trends described by B. Rodgers and T. Gronwald. These trends indicate that with increasing exercise intensity, DFA alpha1 value decreases. [7, 22, 26, 27] In Figure 8.1, during interval running training, in the first three intervals where exercise intensity was only between Short Endurance and Development, DFA alpha1 did not decrease. It only decreased during the last three intervals when intensity reached Maximal. Therefore, the application is not suitable for real-time exercise intensity zones calculation.

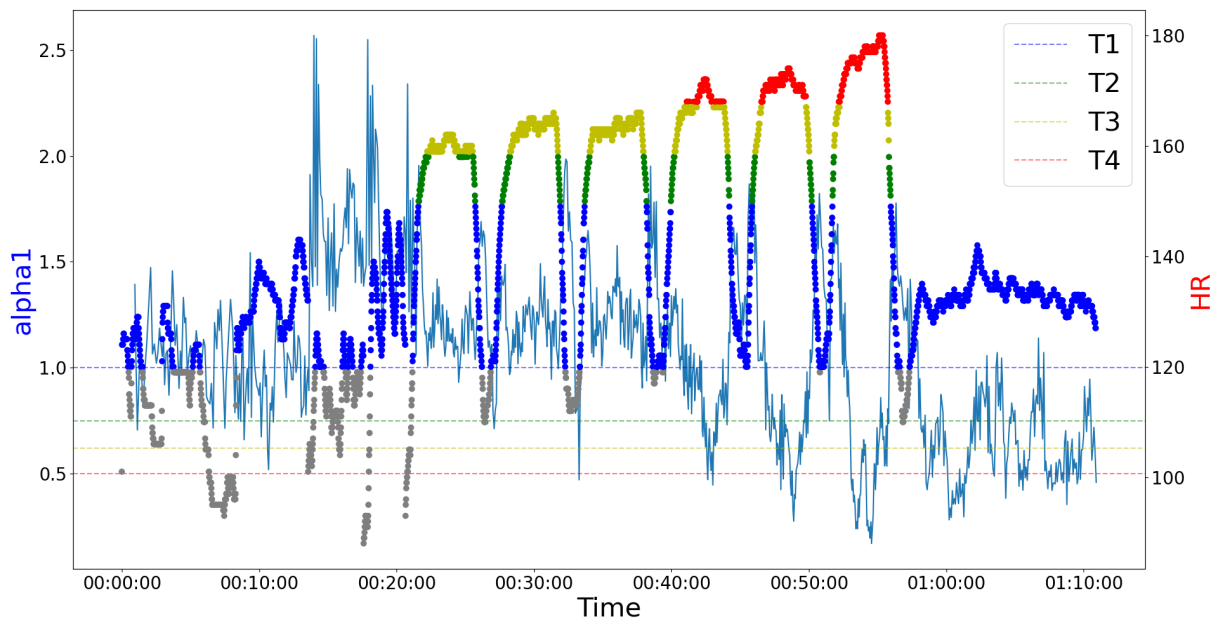


Fig. 8.1: Example of real time exercise intensity zone calculation during interval training. Colors of zones are gray, blue, green, yellow, and red for zones from the lowest to highest intensity. HR data are color coded, for DFA alpha1 data are line for thresholds between zones drawn and these lines are also color coded.

On the other hand, the application is suitable for supplementing traditional methods in exercise intensity zones estimation in the laboratory. It showed great results for all thresholds between zones (mean absolute error $\approx 3 \pm 2$ bpm, $p > 0.05$) and confirmed trends in DFA alpha1 dependency on exercise intensity described by

B. Rodgers and T. Gronwald (with increasing exercise intensity and HR, DFA alpha1 decreases, see Figure 5.6). [7, 22, 26, 27] Although these findings were confirmed, thresholds described by them overestimated AeT and underestimated AnT. Results previously described for exercise intensity zones estimation in the laboratory were only achieved after correction of these thresholds was applied, with a magnitude of -9 bpm for AeT and +7 for AnT.

The overestimation and underestimation of AnT and AeT, respectively, may arise from various factors. One possible explanation is that the thresholds described by B. Rogers and T. Gronwald are inaccurate. In Table 7.6, it is shown that at T2 (equivalent to AeT), the mean DFA alpha1 is 0.88, and at T4 (equivalent to AnT), the DFA alpha1 is 0.53. B. Rogers and T. Gronwald found that these thresholds are DFA alpha1 = 0.75 for AeT and DFA alpha1 = 0.5 for AnT. From this, it appears that there is a slight underestimation of AnT (higher DFA alpha1 value should mean lower exercise intensity, therefore lower HR), but without further research, it is challenging to determine if a 0.03 difference in DFA alpha1 can result in a difference of 7 bpm in HR representation of AnT. The case of AeT is quite different. The difference between the threshold values of DFA alpha1 found by B. Rogers and T. Gronwald and the value found in this thesis is 0.13, which is quite noticeable in the magnitude of DFA alpha1 values. Based on the correction, the HR representation of AeT is overestimated, but based on DFA alpha1 value, it is underestimated. This contradiction suggests that for AeT measurement, there is a problem not only in the DFA alpha1 threshold but also possibly in some error in ground truth data measurement. However, to confirm this, further research on DFA alpha1 threshold and its relationship with AeT needs to be conducted. Overall, further research on the correlation between thresholds in DFA alpha1 and ventilation thresholds needs to be done to clarify discrepancies in results. It is also possible that measured results differ from proposed ones because of errors in laboratory measurement or differences in laboratory assessment of ventilation thresholds between this thesis and the findings of B. Rogers and T. Gronwald. This can be assessed only by broadening the dataset and introducing measurements in different laboratories by different professionals. [7, 15, 22, 23, 25, 26, 27, 30]

Regarding the design of the application, it incorporates essential needs for exercise intensity zones assessment in the laboratory and in real time. To improve user experience from laboratory exercise intensity zones assessment, the possibility to split the measured activity into warm-up, measurement, and cool-down phases could be incorporated. In the application's final version presented in this thesis, the user needs to start the measurement after the warm-up ends and stop the measurement before the cool-down starts. Splitting the measurement into phases can be achieved either by incorporating input to set the length of warm-up and cool-down

(e.g., warm-up was 5:00 minutes and cool-down was 4:30 minutes) or by creating a button that, upon triggering, creates the start of another phase flag (e.g., flag will be 0:00 = warm-up start, 5:00 = measurement start, 16:35 = cool-down start). The application also needs to be tested for use on mobile devices. Since DFA alpha1 computation is computationally demanding, it is unclear if mobile devices like mobile phones or tablets can run this application smoothly. Also, as mentioned at the beginning of this chapter, the application is not usable for exercise intensity assessment in real time. To improve its usefulness in this way of use, further research on DFA alpha1 and ventilation needs to be done.

Conclusion

This thesis aimed to create an application for assessing exercise intensity based on DFA alpha1 values. The first part involved theoretical research on the topic of ventilation thresholds and DFA alpha1. Building upon this research, the second part involved the creation of an application for assessing exercise intensity zones. The application was developed using the Python programming language with the Kivy framework. It offers two possible means of use in exercise intensity assessment: one for everyday sports, where exercise intensity is assessed in real time, and the other for laboratory measurements, where HR representation of exercise intensity zones is calculated from graded exercise tests in the laboratory.

For everyday use, the application successfully calculates DFA alpha1 values in a timeframe as close as possible to real-time, and exercise intensity is assessed by thresholding from DFA alpha1 values. However, DFA alpha1 values do not follow previously described trends during exercise, and exercise intensity zones are significantly different from ground truth data (Cohen's $\kappa = 0.05$, accuracy = 22.39%), so more research in the field of DFA alpha1 thresholds correlation with ventilation thresholds is needed for the application to be fully functional.

As for use in the laboratory, after applying corrections to the estimated HR representation of exercise intensity zones, no significant difference in results has been achieved ($p > 0.05$), while differences were minimal (mean absolute error $\approx 3 \pm 2$ bpm). In the end, DFA alpha1 thresholds correlation with ventilation thresholds is a relatively unexplored topic, so more research on this topic is needed to achieve better results or to better understand why results differ in the way they do.

Indeed, despite setbacks in real-time exercise intensity assessment, the application presents a revolutionary approach to HR representation of exercise intensity zones estimation in the laboratory. It significantly reduces the cost of equipment needed for tests and enables tests to be conducted anywhere during almost any type of activity, provided that exercise intensity can gradually increase during the duration of the test. This innovation could prove to be invaluable, potentially bringing laboratory assessment of exercise intensity zones to everyone's pocket in the form of a mobile application or even to the wrist in the form of a sport tester application.

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Symbols and abbreviations

AeT	Aerobic threshold
AnT	Anaerobic threshold
ANS	Automic nervous system
bpm	Beats per minute
BL	Blood lactate level
BLE	Bluetooth low-energy
CP	Critical power - exercise testing
DFA	Detreded flucation anlaysis
GATT	Generic attribute - programming
HF	High frequencies
HR	Heart rate
HR_{max}	Maximal heart rate
HRV	Heart rate variability
LF	Low frequencies
LT1	First lactate threshold
LT2	Second lactate threshold
MAC adress	Media access control adress
MLSS	Maximal lactate steady state
mmol/l	milimoles per liter
P_{ET}O₂	Partial end-tidal oxygen pressure
P_{ET}CO₂	Partial end-tidal carbon dioxide pressure
RCP	Respiratory compensation point
RER	Respiratory exchange ratio
\overline{RR}	Mean value of RR interval in series

RR intervals	Intervals between two R waves in ECG
SDNN	Standard deviation of normal-to-normal RR intervals
UUID	Universal unique identifier
$V'\text{CO}_2$	Volume of carbon dioxide output in breath
$V'\text{O}_2$	Volume of oxygen intake in breath
$V'\text{O}_{2max}$	Maximal volume of oxygen intake in breath
VLF	Very low frequencies
VT1	First ventilation threshold
VT2	Second ventilation threshold
WL	Work load
W	Watt

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A Example of informed consent

This appendix contains example of informed consent used during testing in CESA BUT laboratories. Consent is in Czech language.



Informovaný souhlas

k projektu výzkumné činnosti zahrnujícímu měření na lidských účastnících

Jméno a příjmení účastníka projektu (dále jen účastník):

Název a forma projektu: Diplomová práce na téma Stanovení tréninkových zón

Autoři (hlavní řešitel, spoluřešitelé): Bc. Tobiáš Goldschmidt

Vedoucí práce (v případě studentské práce): Ing. Oto Janoušek Ph.D.

Popis projektu:

1. Popis projektu: Trénink založený na tréninkových zónách je důležitou součástí moderního sportu. Tyto tréninkové zóny se obvykle určují na základě parametrů výměny plynů nebo hladin laktátu v krvi, které se měří během laboratorního stupňovaného zátěžového testu. Na základě těchto testů se sportovcům určí prahové hodnoty srdeční frekvence nebo zátěže, v rámci, kterých by měli udržovat požadovanou intenzitu cvičení. V posledních letech se objevila nová metoda měření tréninkových zón v laboratorii s možností jejich zobrazení sportovcům ve stejné metrice, v jaké byly naměřeny – na základě koeficientu DFA alfa1 variability srdeční frekvence (HRV). Tato práce představuje aplikaci pro zobrazení tréninkových zón v reálném čase na základě koeficientu DFA alfa1 HRV. Měření na lidských účastnících je potřebné kvůli validaci výsledné aplikace.
2. Cíl: Cílem měření je získat data RR intervalů během zátěžového testu. Během zátěžového testu budou současně měřeny parametry výměny dýchacích plynů určující aerobní a anaerobní práh. Aerobní a anaerobní práh zjištěné z dýchacích plynů slouží jako referenční hodnota pro stanovení aerobního a anaerobního prahu z RR intervalů.
3. Postup projektu (uvedení metodiky a způsobu hodnocení): Účastník podstoupí zátěžový test na běžeckém pásu. Cílem zátěžového testu je dosáhnout všechny intenzity zátěže od nejnižší po nejvyšší a zkoumat parametry vyskytující se při různých hodnotách zátěže. Zátěžový test začne fází zahřátí (minimálně 5 minut), následně bude následovat stupňované kontrolované zvyšování zátěže. Zvyšování zátěže bude kontrolováno zrychlováním běžeckého pásu, počáteční zátěž bude nastavená v rozmezí 6-10 km/h (podle účastníkovi subjektivní hodnocení jeho/její výkonnosti) a následně se bude zvyšovat o 1 km/h každé dvě minuty. Účastník absolvuje maximálně 12 zátěžových stupňů. Sklon běhacího pásu bude nastaven na 1% pro simulaci běžných podmínek běhu venku. Zvyšování zátěže probíhá do okamžiku, kdy účastník dosáhne maximální tepové frekvence vypočtené jako $HR_{max} = 220 - \text{věk}$ [bpm], nebo se subjektivně rozhodne, že vyšší zátěž už nezvládne, nebo absolvuje všech 12 stupňů zátěže a nebo celý jeden stupeň stráví v anaerobní zóně zátěže. Test končí fází zklidnění (minimálně 5 minut).

Účastníci budou před testem informováni, že by neměli minimálně 24 hodin před testem užívat návykové látky a minimálně 48 hodin před testem vykonávat fyzicky náročnou aktivitu. Měření RR intervalů bude probíhat pomocí hrudního pásu Polar H10 připojeného k hodinkám Polar Vantage V. Měření dýchacích parametrů probíhat pomocí zařízení Metalyzer 3-B a vyhodnocení prahů a zátěžových zón v programu MetasoftStudio. Projektu se účastní pouze osoby starší 18 let. Výsledky budou anonymizovány. Měření bude probíhat v laboratoři Fyziologie tělesné zátěže patřící pod CESA VUT v souladu s laboratorním řádem platným v této laboratoři. V laboratoři Fyziologie tělesné zátěže CESA VUT bylo v posledních letech úspěšně provedeno více než 100 zátěžových testů.

4. Rizika: Zátěžový test nepředstavuje zdravotní riziko pro zdravého dospělého jedince. Nicméně může představovat nebezpečí pro jedince trpící kardiovaskulárními onemocněními. Při běhu na páse existuje riziko pádu.
5. Zajištění bezpečnosti: Do projektu budou prioritně zapojeni účastníci, kteří mají zkušenosti se zátěžovým testem. S ohledem na riziko pro jedince trpící kardiovaskulárními onemocněními, takovýmito jedincům nebude dovoleno zapojit se do projektu. Stejně tak budou upřednostněni pravidelně sportující jedinci před běžnou populací. Pokud jde o riziko pádu na páse, účastník bude upevněn od závěsu, který ho chrání před zraněním i v případě pádu. V případě nevolnosti či jiných nepříjemných projevů bude test na žádost účastníka okamžitě ukončen.
6. Doba trvání celého projektu (od – do): 1.4.2024-1.5.2024
7. Doba trvání zapojení jednotlivce: Jednotlivec se zapojuje pouze do jednoho měření trvajících přibližně 30-45 minut v závislosti na fyzické připravenosti jedince.
8. Počet zapojených účastníků: 10-15
9. Popis nakládání s daty: Data budou anonymizovány (každý účastník bude mít přiřazeno číselné ID) a zůstanou v archívu CESA VUT po dobu minimálně 3 let. Budou uloženy na harddisku PC kterým jsou použita zařízení ovládaná opatřeným heslem.
10. Zajištění přístupu k datům pro mentory, členy EK a Ústavu (kde je měření prováděno): Data budou dostupná členům EK (etické komise) a mentorům na vyžádání. CESA VUT (ústav, kde měření probíhá), bude mít data uložené ve vlastním archívu.
11. Zajištění správného nakládání s osobními údaji: Získaná data z měření neobsahují žádné osobní údaje účastníků. Pro rozlišování mezi jednotlivými účastníky bude použito číselné ID, které bude přiřazeno každému účastníkovi.

Účastník svým podpisem stvrzuje, že byl seznámen s údaji podle Vyhlášky č. 226/2008Sb (s průběhem projektu a se všemi možnými riziky a následky) a souhlasí se zapojením do výše uvedeného projektu. Bere na vědomí, že účast je dobrovolná a může odmítnout účast v projektu kdykoliv. Účastník svým podpisem stvrzuje, že je starší 18 let, nemá žádnou historii kardiovaskulárních nemocí, diabetes mellitus, anémie či poruchy vylučování hormonů štítné žlázy. Podpisem účastník souhlasí se zpracováním osobních údajů.

V Brně dne _____

Podpis účastníka _____

Údaje uváděné v poučení subjektu hodnocení a písemném informovaném souhlasu

V poučení subjektu hodnocení a v písemném informovaném souhlasu se uvádějí následující údaje:

- a) upozornění, že klinické hodnocení je výzkumnou činností,
- b) cíle klinického hodnocení,
- c) léčebné postupy a upozornění na pravděpodobnost náhodného zařazení do jednotlivých skupin lišících se léčbou tam, kde jde o randomizované klinické hodnocení,
- d) postupy a výkony v průběhu klinického hodnocení včetně všech invazivních výkonů,
- e) odpovědnosti subjektu hodnocení,
- f) zdůraznění těch prvků klinického hodnocení, které mají povahu výzkumu,
- g) předvídatelná rizika či nepříjemnosti pro subjekt hodnocení, včetně případného rizika pro plod nebo kojene dítě,
- h) očekávané přínosy; subjekt hodnocení se uvědomí i v případech, že žádný klinický přínos pro něho není očekáván,
- i) alternativní léčebné postupy, které mohou být pro léčbu subjektu hodnocení použity, jejich výhody a rizika,
- j) léčba a podmínky odškodnění, které budou subjektu hodnocení poskytnuty v případě újmy na zdraví vzniklé v souvislosti s jeho účastí v klinickém hodnocení,
- k) předpokládaná výše odměny subjektu za jeho účast v klinickém hodnocení,
- l) předpokládané výdaje subjektu v souvislosti s jeho účastí v klinickém hodnocení,
- m) informaci o tom, že účast subjektu v klinickém hodnocení je dobrovolná a že subjekt může odmítnout účast nebo může odstoupit od účasti v klinickém hodnocení kdykoliv, bez postihu či ztráty výhod, na něž má jinak nárok,
- n) souhlas s tím, že monitoři, auditoři, příslušná etická komise a Ústav budou mít umožněn přímý přístup k původní klinické dokumentaci za účelem ověření průběhu klinického hodnocení anebo údajů, aniž dojde k porušení důvěrnosti informací o subjektech, v míře povolené právními předpisy, a že podepsáním písemného informovaného souhlasu subjekt či jeho pověřený zákonný zástupce souhlasí s touto skutečností,
- o) souhlas s tím, že záznamy, podle nichž lze identifikovat subjekt hodnocení, budou uchovávány jako důvěrné a nebudou, v míře zaručené právními předpisy, veřejně zpřístupněny; budou-li výsledky klinického hodnocení publikovány, totožnost subjektu nebude zveřejněna,
- p) souhlas s tím, že subjekt hodnocení anebo jeho zákonný zástupce budou včas informováni, pokud by se vyskytla informace, která by mohla mít význam pro rozhodnutí subjektu pokračovat v účasti v klinickém hodnocení,
- q) informace o osobách, od kterých bude možné získat další informace týkající se klinického hodnocení a práv subjektů hodnocení a informace o tom, koho kontaktovat v případě poškození zdraví v souvislosti s klinickým hodnocením,
- r) předvídatelné okolnosti a důvody, pro které může být účast subjektu v klinickém hodnocení ukončena,
- s) předpokládaná doba trvání účasti subjektu v klinickém hodnocení,
- t) přibližný počet subjektů hodnocení, které se účastní klinického hodnocení.

B Used code

This appendix contains the code used for the final application, as well as the code used for DFA calculation. There are 2 files and one directory in this appendix. File named "DFA_zones_app.py" contains the code for the application, including code for connecting to the Polar H10 device and reading data from it. File named "DFA_alpha1.py" contains functions to calculate the DFA alpha1 value, as well as a function to filter artifacts in the incoming RR intervals series. Directory "logs" is used to store data measured by the application. To successfully run the application, the content of this appendix should be stored in the same directory, and "DFA_zones_app.py" needs to be executed with Python 3.11.7. Additionally, the following libraries are required: Asyncio (version 3.4.3), Bleak (version 0.21.1), Kivy (version 2.3.0), NumPy (version 1.26.4), and Pandas (version 2.2.2).

```
/ ..... Root directory
├── logs ..... Directory for storing data measured by application
├── DFA_zones_app.py ..... Code for application
└── DFA_alpha1.py ..... Code for DFA alpha1 calculation
```

C Example of output of application

In this appendix can be found two files containinig data from measurement of exercise intenisty by proposed application in form, as they are created by application. File named "2024-04-16_19-15-15.csv" contains data from measurement, and file named "2024-04-16_19-15-15_ZONES.csv" contatins information about HR representation of training zones based on measurement.