Assessing the physical capabilities of sportsman using wearables and machine learning

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Master's dissertation submitted in order to obtain the academic degree of
Master of Science in de informatica

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Academic year 2019-2020

I, Jeroen De Clerck confirm that the work presented in this thesis is my own. Where information has been derived from other sources, I confirm that this has been indicated in the thesis.

Abstract

Acknowledgements

Table of Contents

Chapter 1

Introduction, with a citation

1.1 Summary of chapters

This is a brief outline of what went into each chapter. **Chapter 1** gives a background on duis tempus justo quis arcu consectetur sollicitudin. **Chapter 2** discusses morbi sollicitudin gravida tellus in maximus. **Chapter 3** discusses vestibulum eleifend turpis id turpis sollicitudin aliquet. **Chapter 4** shows how phasellus gravida non ex id aliquet. Proin faucibus nibh sit amet augue blandit varius.

Chapter 2

Medical Background

2.1 Anatomy of the heart

The heart is the organ responsible for pumping blood into the arteries and veins of the human body. It is located within the thorax (chest) in between the lungs, oriented slightly towards the lefthand side in its so called mediastinum. The shape is slightly triangular, pointing towards the feet. The superior portion is called the base, and the inferior portion is called the apex.

The pumping action is provided by the 4 chambers; left and right side each have an *atrium* and a *ventricle*. The atria act as a receiving chamber which contracts to push blood to the ventricles, which will in act as the primary pumping mechanism and propel it to either the lungs or the rest of the body. The atria receive blood on a nearly continuous basis, preventing flow from stopping while the ventricles are contracting.

Both sides of the heart have their distinct function. The righthand side delivers deoxygenated blood into the pulmonary trunk, which leads toward the capillaries in the lungs, where gas exchange occurs: Carbon dioxide exits the blood and oxygen enters. Highly oxygenated blood returning from these capillaries passes through a series of vessels that join together to conduct blood into the left atrium, which pumps the blood into the left ventricle, which in turn pumps oxygenated blood into the aorta and on to the many branches of the systemic circuit. Eventually, these vessels will lead to the various capillaries, where exchange with the cells of the muscles occurs. Oxygen and nutrients exit the capillaries to be used by the cells in their metabolic processes, and carbon dioxide and waste products (such as potassium, lactic acid and ADP) will enter the blood.

Not every muscle in the heart is equal. The atria only need to pump blood into the ventricles, so they are smaller. The muscle of the left ventricle is much thicker and better developed than that of the right ventricle, in order to overcome the high resistance required to pump blood into the long systemic circuit. The right ventricle does not need to generate as much pressure, since the path to the lungs is shorter and provides less resistance. With an average chamber volume of 70mL and an average heart rate of 75bpm, each chamber is capable of pumping 5250 mL blood per minute.

(Betts et al. 2013)

2.2 Innervation of the heart

Normal cardiac rhythm is established by the sinoatrial (SA) node, also known as the pacemaker of the heart. It initiates the *sinus rhythm*, or normal electrical pattern followed by contraction of the heart. The impulse is conducted from the SA node through a specialized internodal pathways, to the atrioventricular (AV) node. In addition, the interatrial band conducts the impulse directly from the right atrium to the left atrium. The wave of the electrical impulse spreads across the attria from the top to the bottom portions, pumping blood down into the ventricle. It takes approximately 50 ms (milliseconds) to travel from SA to AV node (figure 2.2, step 2 and 3).

The next step in the chain is the atrioventricular bundle. There is a critical pause before the AV node transmits the impulse to the AV bundle, partially attributable to the small diameter of the cells of the node, which slow the impulse. This results in an approximately 100ms delay for the impulse to pass through the node. This pause is critical to heart function, as it allows the atrial muscles to complete their contraction that pumps blood into the ventricles before the impulse is transmitted to the cells of the ventricle itself (figure 2.2, step 4).

The AV bundle devides into two atrioventricular bundle branches, Both bundle branches descend and reach the apex of the heart where they connect with the Purkinje fibers. This passage takes approximately 25 ms. The Purkinje fibers are additional conductive fibers that spread the impulse to the muscles in the ventricles. They extend from the apex of the heart toward the wall between the atrium and the ventricle, continues to the base of the heart. The Purkinje fibers have a fast inherent conduction rate, and the electrical impulse reaches all of the ventricular muscle cells in about 75 ms. Since the electrical stimulus begins at the apex, the contraction also begins at the apex and travels toward the base of the heart, similar to squeezing a tube of toothpaste from the bottom. This allows the blood to be pumped out of the ventricles. The total time elapsed from the initiation of the impulse in the SA node until relaxation of the ventricles is approximately 225ms (figure 2.2, step 5).

The SA node, without external control, would initiate a heart impulse approximately 80–100 times per minute. While a few exceptionally trained aerobic athletes demonstrate resting heart rates in the range of 30–40 beats per minute, rates lower than 50 beats per minute would indicate a condition called bradycardia. With extreme stimulation by the SA node, the AV node can transmit impulses maximally at 220 per minute. This establishes the typical maximum heart rate in a healthy young individual. Higher rates are possibly by damaged hearts or those stimulated by drugs, but the heart can no longer effectively pump blood at these rates

(Betts et al. 2013)

2.3 Fysiologische werking van het hart

- Modelling heart rate kinetics
- Analvsis of Heart Rate Dynamics During Exkrcise
- Exercise and the autonomic nervous system.

Er wordt een overzicht gegeven over de functionaliteit van het hart, en een introductie in de termen die verder in de thesis gebruikt worden. Er wordt extra focus gelegd op het effect van fysieke inspanning op hartslag, en andere relevante info om het concept "fitheid" te verduidelijken.

2.3.1 Parasympathische werking

2.3.2 Orthosympatische werking

2.4 Measuring heart rate

2.4.1 acoustic measurement

In a normal, healthy heart, there are only two audible heart sounds. The first sound is created by the closing of the valves between the atrium and the ventricle during ventricular contraction. The second heart sound, is the sound of the closing of the valves between the ventricle and the aortae during ventricular relaxation (Betts et al. 2013). This method of measurement has some novel applications and is showing potential to be as accurate as optical measurement, but has not yet been brought to market (Sharma et al. 2019) (Abbasi-Kesbi et al. 2018).

2.4.2 Electrocardiogram (ECG) measurement at the chest

By careful placement of surface electrodes on the body, it is possible to record the complex, compound electrical signal of the heart. This tracing of the electrical signal is the electrocardiogram (ECG). There are five prominent points on the ECG (see figure 2.3): the P wave, the QRS complex, and the T wave. The small P wave represents the impulse in the atria. The atria begin contracting approximately 25 ms after the start of the P wave. The large QRS complex represents the impulse in the ventricles, which will begin to contract as R wave reaches its peak. Lastly, the T wave represents the end of the impulse in the ventricles (the end of the impulse in the atria is obfuscated by the QRS complex). Segments are defined as the regions between two waves. Intervals include one segment plus one or more waves. In this thesis the most notable interval is the RR interval, or the interval between the peaks of the QRS complex. (Betts et al. 2013)

The standard electrocardiograph uses multiple electrodes to obtain 3, 5, or 12 leads. The greater the number of leads an electrocardiograph uses, the more information the ECG provides. The term “lead” typically describes the voltage difference between two of the electrodes. Electrocardiographs are also available in small, portable, battery-operated devices known as a Holter monitor, or simply a Holter, that continuously monitors heart electrical activity. Chest strap heart rate monitors, such as the polar H-series are a rudimentary electrocardiograph.

2.4.3 Photoplethysmogram measurement at the wrist

(Tamura et al. 2014)

(Horton et al. 2017)

2.5 Fitheid

2.5.1 Hoe manifesteert fitheid zichzelf

- Heart rate variability and aerobic fitness
- Post-exercise heart-rate recovery correlates to resting heart-rate variability in healthy men
- Heart rate recovery fast-to-slow phase transition: Influence of physical fitness and exercise intensity
- Recovery and performance in sport: Consensus statement

- The development of functional overreaching is associated with a faster heart rate recovery in endurance athletes
- Resting heart rate variability and heart rate recovery after submaximal exercise

We onderzoeken het verschil tussen een fitte persoon en een onfitte persoon op fysiologisch vlak, en trekken conclusies over wat wel en niet relevant is voor ons programma

2.5.2 Hoe wordt fitheid getrained

- Recovery and performance in sport: Consensus statement
- Overtraining syndrome
- Overtraining in Resistance Exercise: An Exploratory Systematic Review and Methodological Appraisal of the Literature
- Functional overreaching: The key to peak performance during the taper?
- Diagnosis and prevention of overtraining syndrome: an opinion on education strategies
- Effect of overreaching on cognitive performance and related cardiac autonomic control
- Does overtraining exist? An analysis of overreaching and overtraining research
- Training adaptation and heart rate variability in elite endurance athletes: Opening the door to effective monitoring
- The Multimodal Nature of High-Intensity Functional Training: Potential Applications to Improve Sport Performance
- Heart rate recovery in elite athletes: the impact of age and exercise capacity
- Assessing overreaching with heart-rate recovery: What is the minimal exercise intensity required?
- Is heart rate a convenient tool to monitor overreaching? A systematic review of the literature
- Overtraining syndrome

Functional overreaching Overtraining trainingsritme

2.5.3 muscle fatigue

2.5.3.1 neural fatigue

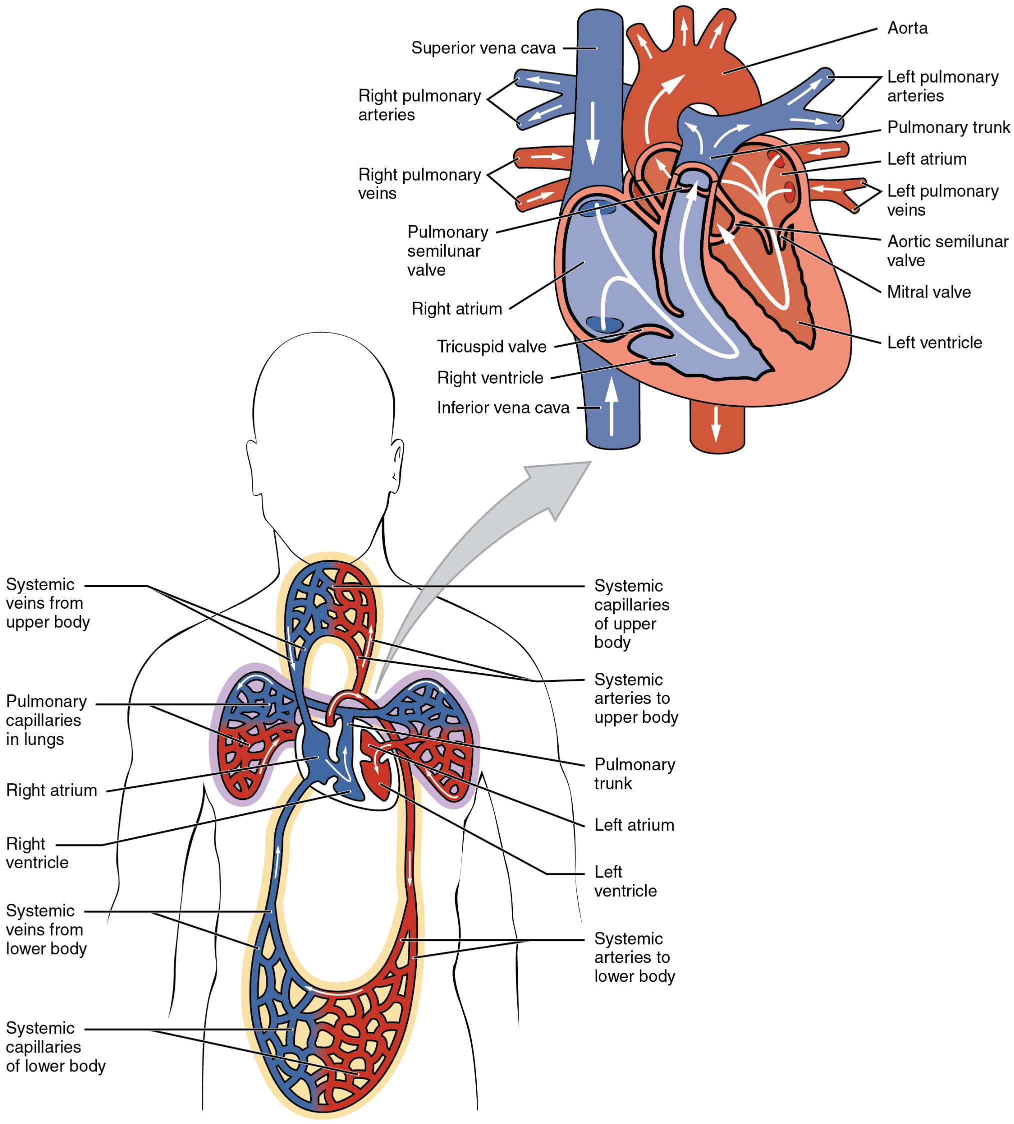

Figure 2.1: An anatomical overview of the heart

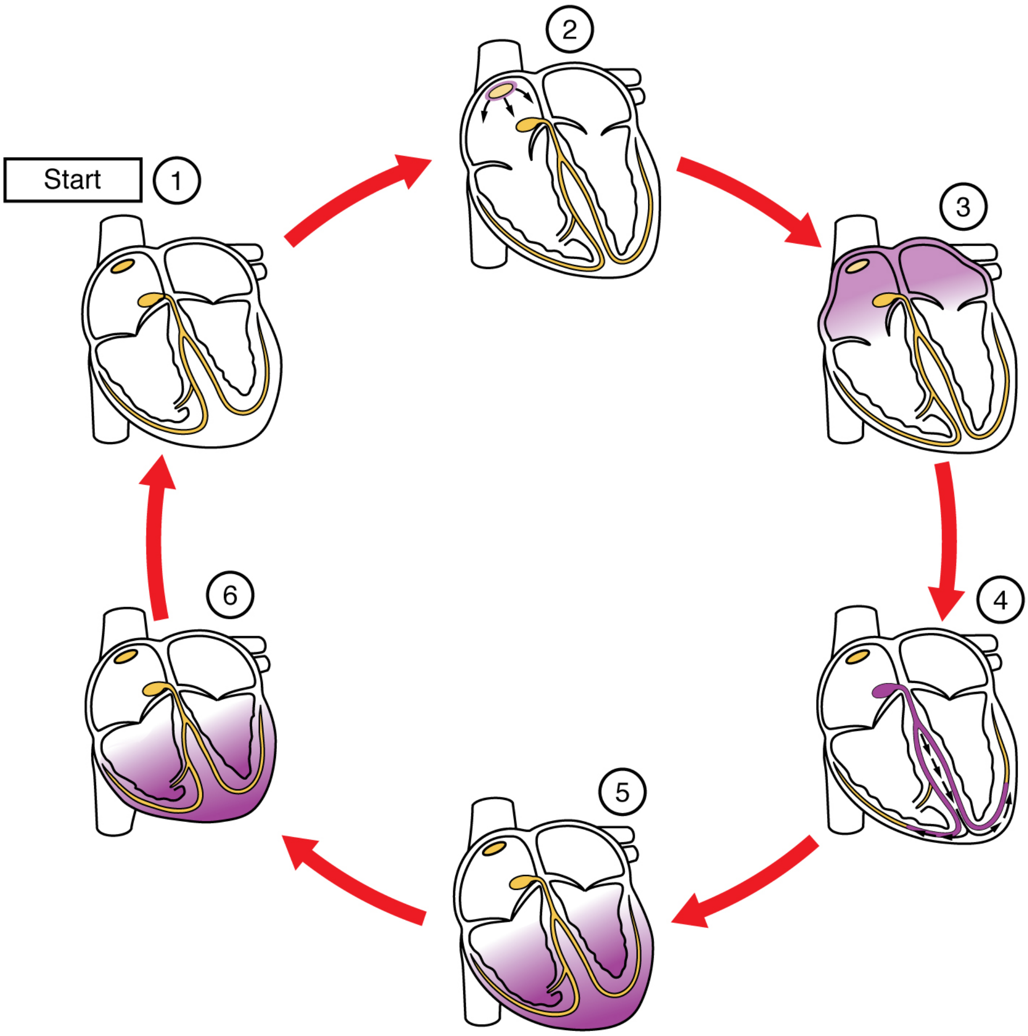

Figure 2.2: the innervation and pumping mechanism of the heart

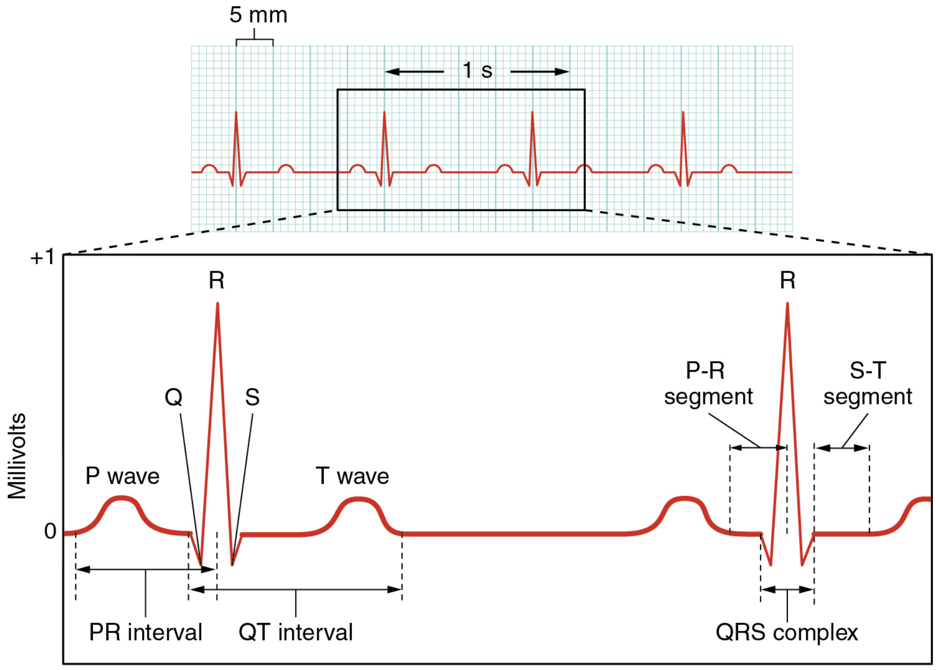

Figure 2.3: an example ECG tracing

Chapter 3

First research study, with code

3.1 metrieken

3.1.1 Accelerometer

Dit is een moeilijke metriek om te betrekken, aangezien dit heel afhankelijk is van het type van de trainingsessie. In deze sectie onderzoeken we in welke mate de accelerometer gebruikt kan worden in andere gevallen, en of dit een substantieel voordeel is om te betrekken in de fitnesscoach.

3.1.2 Verschillende soorten heartrate

Hartslag kunnen we zelf meten. Momenteel zijn smartwatches zelden accuraat genoeg om HRV te bepalen, maar in het onderzoek gaan we er van uit dat het wel mogelijk is. Zie sectie `Gevolgen van inaccurate metingen`. High-end borstkas hartmetingen zijn wel in staat om HRV te meden.

Dit zijn allemaal vaak gebruikte metrieken in medische literatuur, en komen vaak terug in het bepalen van inspanning en fysieke fitheid. Deze sectie overloopt ze allemaal, hun significantie in de context van dit onderzoek, en waar ze gebruikt worden.

3.1.2.1 Heart Rate

- RR Interval

3.1.2.2 Resting Heart Rate

- Determining target heart rate for exercising in a cardiac rehabilitation program: a retrospective study.
- Relationship between resting heart rate, blood pressure and pulse pressure in adolescents

Heart rate reserve Target heart rate opstellen met Karvonen method

3.1.2.3 Heart Rate Variability (HRV)

- Heart rate variability and aerobic fitness
- Deep neural heart rate variability analysis
- The relationship between resting heart rate variability and heart rate recovery

RMSSD: Root mean square of the successive differences RMSSD is strongly backed by research and is considered the most relevant and accurate measure of Autonomic Nervous System activity over the short-term. Here are a few studies referencing its use: ln(RMSSD): log van RMSSD NN50: The number of pairs of successive NN (R-R) intervals that differ by more than 50 ms PNN50: The proportion of NN50 divided by the total number of NN (R-R) intervals SDNN: Standard deviation of the NN (R-R) intervals

3.1.2.4 Heart Rate Recovery

- Heart rate recovery fast-to-slow phase transition: Influence of physical fitness and exercise intensity

- Post-exercise heart-rate recovery correlates to resting heart-rate variability in healthy men
- The relationship between resting heart rate variability and heart rate recovery
- Estimation of heart rate recovery after stair climbing using a wrist-worn device

Ectopic beat

3.1.3 Zuurstofopname

- Prediction of maximal or peak oxygen uptake from ratings of perceived exertion
- Submaximal, Perceptually Regulated Exercise Testing Predicts Maximal Oxygen Uptake: A Meta-Analysis Study
- Heart rate and exercise intensity during sports activities. Practical application.
- Exercise and the autonomic nervous system.

Dit is een andere belangrijke meting, die we helaas niet rechtstreeks kunnen meten. Deze sectie onderzoekt het nut van de zuurstofopname af te leiden uit hartslag (en user input?), maar dit zal waarschijnlijk geen uiteindelijk deel worden van de fitnesscoach. de opgedane kennis is waarschijnlijk wel nutig voor `Physical Load Level` beter te bepalen.

3.1.4 Physical Load Level

- Prediction of Physical Load Level by Machine Learning Analysis of Heart Activity after Exercises
- Heart rate and exercise intensity during sports activities. Practical application.
- Exercise and the autonomic nervous system.

Het uiteindelijk doel van alle metrieken en metingen. Een maat voor de inspanning die een gebruiker aan het leveren is. We willen dit nauwkeurig kunnen voorspellen, aangezien de fitnesscoach een specifiek trainingsregime zal aanbevelen op basis van de verwachte load level die dit regime teweeg brengt. Duidelijk de distinctie maken tussen absolute load level en de relatieve load level (hoeveel energie een regime vraagt vs hoeveel de gebruiker zich moet inspannen om deze energie te besteden)

Chapter 4

Research containing a figure

4.1 smartwatches in context plaatsen

https://www.qualcomm.com/products/wearables - Accuracy of smartphone application to monitor heart rate. - Comparison of Polar M600 Optical Heart Rate and ECG Heart Rate during Exercise - Enabling Smartphone-based Estimation of Heart Rate - Can Wearable Devices Accurately Measure Heart Rate Variability? A Systematic Review - Improving heart rate variability measurements from consumer smartwatches with machine learning

Het probleem moet opgelost worden in de context van wearables. Er wordt een marktonderzoek gedaan naar de huidige markt, waar de processing power en accuraatheid van sensoren onderzocht. In de verdere secties wordt er dieper ingegaan op de gevolgen van deze limitaties.

Het is vrij onrealistisch om een volwaardig ML algoritme puur op de chip van een smartwatch te draaien. Er wordt dus ook onderzoek gedaan naar de mogelijkheid om deze berekeningen te offloaden naar een gepaarde smartphone, een eigen server (SaaS), of exotischere mogelijkheden om dit op te lossen.

4.1.1 OMGAAN MET MINIMALE COMPUTATIONELE KRACHT

Zelfs als de berekeningen offloaded worden, gaat er nog steeds rekening gehouden moeten worden met minimale computationele kracht. Er wordt onderzocht welke ML subcategorien bestaan die functioneel blijven met weinig berekeningen.

4.1.2 OMGAAN MET INACCURATE METINGEN

- Heart rate variability estimation in photoplethysmography signals using Bayesian learning approach
- Can PPG be used for HRV analysis?
- Stressing the accuracy: Wrist-worn wearable sensor validation over different conditions

wearables zijn niet altijd even accuraat en kunnen een niveau van onzekerheid in de metingen bevatten. (specifiek, niet accuraat genoeg voor HRV en RR-interval te meten tijdens fysieke inspanning). Om dit te vermijden wordt de abstractie gemaakt naar “ideale” gesimuleerde hartmetingen, en doen we een onderzoek naar de verschillen tussen deze ideale simulatie en de reele metingen. Zo is de uiteindelijke fitnesscoach tevens futureproof aangezien het niet onrealistisch is dat toekomstige wearables wel deze accuraatheid bevatten.

Chapter 5

Probleemstelling

- Measurement, prediction, and control of individual heart rate responses to exercise-basics and options for wearable devices

Enerzijds een optimate hartslagsimulator vinden of aanpassen aan de noden van het onderzoek (niet te complex maken, moet enkel complex genoeg zijn zodat de fitnesscoach geanalyseerd kan worden)

anderzijds een fitnesscoach die in staat is om op basis van verschillende metrieken, gedriveerd van enkel en alleen hartslag en user input, een fitnesscore toe kan wijzen. Het hoofddoel is om op basis van de historiek van deze fitness-score een adequaat trainingschema op te stellen, rekening houdend met de voorkeur die de gebruiker ook ingegeven heeft (aanbevelingsysteem)

5.1 Overzicht van de Hartslag-simulator

https://archive.physionet.org/challenge/2002/generators/ https://archive.physionet.org/physiol
https://physionet.org/content/ecgsyn/1.0.0/

init waarbij we parameters geven aan een commanda, die dan een persoonprofiel kan creeren. Dit profiel geeft een lijst van bpm-metingen terug. we kunnen met commandos dit profiel ook verschillende niveaus aan fysieke intensiteit laten beleven, en het profiel fitter of minder fit maken.

5.2 Overzicht van de fitnesscoach

5.2.1 BASE LEVEL FITNESS BEPALEN IN DAGDAGELIJKS LEVEN

- Long Short-Term Network Based Unobtrusive Perceived Workload Monitoring with Consumer Grade Smartwatches in the Wild

Streamed, labeled data voor te initialiseren. Streamed, unlabeled data voor de rest

met behulp van permanente monitoring en andere variabelen zoals besproken in onderdeel `metrieken`. Dit onderdeel moet in staat zijn om het *verbeteren* van de Base Level Fitness te detecteren.

5.2.2 DETECTIE VAN HUIDIGE STATUS

- Implicit Context-aware Learning and Discovery for Streaming Data Analytics
- Detection of functional overreaching in endurance athletes using proteomics
- On the physiological and psychological differences between functional overreaching and acute fatigue

in rust, actief, hoge fysieke inspanning, (slapen?)

Streamed, unlabeled data. Machine Learning classificatie-probleem met context

In geval van hoge fysieke inspanning zou de gebruiker de optie moeten krijgen om te laten tellen als trainingssessie

5.2.3 TRAININGSPLANNING OPSTELLEN (AANBEVELINGSYSTEEM)

Het systeem weet de volgende dingen: - de huidige fitheid van de gebruiker - de hoeveelheid rust dat de gebruiker heeft gehad recentelijk - welke trainingsessies en de intensiteit van de voorbije trainingsessis van de gebruiker - welke impact ieder type trainingsessie heeft - een optimaal trainingschema dat in optimale omstandigheden zo dicht mogelijk gevolgd wordt

Aanbevelingsysteem gebruiken om een top n mogelijke trainingsessie samen te stellen (bvb intensief interval-sprinten, langdurig lopen, hoge-intensiteit cardio-sessie, rustdag, gewichtheffen,...). De gebruiker kan hieruit een kiezen.

5.2.4 REALTIME FEEDBACK TIJDENS TRAININGSESSIE

- MiLift: Efficient Smartwatch-Based Workout Tracking Using Automatic Segmentation
- The Multimodal Nature of High-Intensity Functional Training: Potential Applications to Improve Sport Performance
- Modelling the HRV response to training loads in elite rugby sevens players
- Effects of varying training load on heart rate variability and running performance among an Olympic rugby sevens team

Classification probleem: gestreamde hearbeat met een rolling window zegt of de inspanning te hoog of te laag is om het doel van de sessie te bereiken. Machine Learning classificatie-probleem

5.2.5 ANALYSEREN VAN EEN TRAININGSESSIE

- Heart rate recovery after exercise: Relations to heart rate variability and coplexity
- Ultra-short-term heart rate variability indexes at rest and post-exercise in athletes: Evaluating the agreement with accepted recommendations

Na afronden van een trainingsessie wordt de intensiteit van de sessie berekend en wordt bijgehouden in de historiek zodat er rekening gehouden mee kan worden in het aanbevelingsysteem

5.2.6 gebruikte technieken

Chapter 6

Validation of the model

Chapter 7

Conclusion

7.1 Thesis summary

In summary, pellentesque habitant morbi tristique senectus et netus et malesuada fames ac turpis egestas. Nunc eleifend, ex a luctus porttitor, felis ex suscipit tellus, ut sollicitudin sapien purus in libero. Nulla blandit eget urna vel tempus. Praesent fringilla dui sapien, sit amet egestas leo sollicitudin at.

7.2 Future work

There are several potential directions for extending this thesis. Lorem ipsum dolor sit amet, consectetur adipiscing elit. Aliquam gravida ipsum at tempor tincidunt. Aliquam ligula nisl, blandit et dui eu, eleifend tempus nibh. Nullam eleifend sapien eget ante hendrerit commodo. Pellentesque pharetra erat sit amet dapibus scelerisque.

Vestibulum suscipit tellus risus, faucibus vulputate orci lobortis eget. Nunc varius sem nisi. Nunc tempor magna sapien, euismod blandit elit pharetra sed. In dapibus magna convallis lectus sodales, a consequat sem euismod. Curabitur in interdum purus. Integer ultrices laoreet aliquet. Nulla vel dapibus urna. Nunc efficitur erat ac nisi auctor sodales.

Abbreviations

API	**A**pplication **P**rogramming **I**nterface
JSON	**J**ava**S**cript **O**bject **N**otation

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