Assessing the physical capabilities of sportsman using wearables and machine learning

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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 possibly in some healthy indivituals, 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 Fysiological function of the heart

2.3.1 Nerval stimulation

The human body is a complex balancing act of various electrical and/or hormonal impulses.

The nerval system is can be split up in hierarchy: Starting from the full nerval system we can split 2 subsytems based on their location; the central nervous system in the brain and spinal cord, and the peripheral nervous system in the rest of the body. The peripheral nervous system can again be split up into 2 subsystems based on the control that we have over it: the somatic nerval system which handles voluntary signals and the autonomic nerval system which handles involuntary signals. The autonomic nerval system can again be split up based on the context in which signals are sent: the sympathetic nerval system which handles “fight-and-flight” reactions and the parasympathetic nerval system which handles “rest-and-digest” reactions.

Nervous control starts with two paired centers in the brainstem. The cardioaccelerator regions stimulate activity via sympathetic stimulation, and the cardioinhibitory centers decrease heart activity via parasympathetic stimulation. During rest, both centers provide stimulation to the heart, with a slight predomination for cardioinhibitory stimulation as the SA node left to its own devices would initiate a sinus rhythm of approximately 100 bpm. This means that simply stopping parasympathetic stimulation would let the heart rate to increase to approx. 100 bpm, but a further increase requires sympathetic stimulation.

These (para-)sympathetic stimulations are fired upon various sensoric impulses, which are summed up in table 2.1 and table 2.2

(Betts et al. 2013)

Table 2.1: Major Factors decreasing Heart Rate and force of contraction. (Betts et al. 2013)

Factor	Effect Trigger
n. Cardioaccelerator	Release of norepinephrine by cardioinhibitory nerves
Proprioreceptors	Increased firing rates of positional sensors
Chemoreceptors	detection of decreased levels of O2
Chemoreceptors	detection of increased levels of H+, CO2 and lactic acid
Baroreceptors	falling blood volume/pressure
Limbic system	Anticipation of physical exercise or strong emotions
Catecholamines	Increased epinephrine and norepinephrine release
Thyroid hormones	Increased T3 and T4 in the blood (released by thyroid)
Calcium	Increase in calcium ions in the blood
Potassium	Decrease in potassium ions in the blood
Sodium	Decrease in sodium ions in the blood
Body temperature	Increase in body temperature
Stimulants	Presence of nicotine, caffeine or other stimulants

Table 2.2: Major Factors decreasing Heart Rate and force of contraction. (Betts et al. 2013)

Factor	Effect Trigger
n. Cardioinhibitor	Release of acetylcholine by cardioaccelerator nerves
Proprioreceptors	Increased firing rates of positional sensors
Chemoreceptors	detection of increased levels of O2
Chemoreceptors	detection of decreased levels of H+, CO2 and lactic acid
Baroreceptors	rising blood volume/pressure
Limbic system	Anticipation of relaxation by the limbic system
Catecholamines	Increased (nor-)epinephrine release by the adrenal glands
Thyroid hormones	Decreased T3 and T4 in the blood (released by thyroid)
Calcium	Increase in calcium ions in the blood
Potassium	Increase in potassium ions in the blood
Sodium	Increase in sodium ions in the blood
Body temperature	Decrease in body temperature
Tranquilizers	Presence of opiates, tranquilizers or other depressants

2.3.2 Heart Rate

The maximum heart rate that a healty individual can attain is around 220 bpm. This maximum heart rate is a hard limit due to physiological phenomena (the maximum throughput of the SA node) and will remain constant for a subject, regardless of increased/decreased fitness level or other factors. Due to age this maximum heart rate will slowly deteriorate and can be approximated by taking this 220 bpm maximum and subtracting the age of the subject.

The lowest heart rate that a healthy individual can attain is called the Resting Heart Rate. It is the heart rate of the subject when it is at complete rest, relaxed but awake, with no external stress factors such as recent exercise, environmental temperature,... For an average person this lies within the interval of 60 to 100 beats per minute, but a few exceptionally trained aerobic athletes demonstrate resting heart rates in the range of 30–40 beats per minute. This is lower for fit individuals because the body has adapted to maintain basic functionality on these lower heart rates.

Performing any kind of movement will place a circulatory demand on the heart, and the heart rate will change to meet this demand. If demand is higher than what HR_{max} allows, the heart rate will plateau at HR_{max} until the body can no longer sustain the exercise. For a constant exercise that doesn't reach this boundary the demand will also remain constant, so an equilibrium will be reached at a certain heart rate. An important distiction to make is that of the lactate threshold. Lactate is a substance in the blood that increases in concentration when performing heavy exercise.

Heart rate will quickly reach the equilibrium as described as long as blood lactate levels remain under a threshold (the value of which depends on the individual). At higher levels of exertion blood lactate levels will rise but plateau after 10-20 minutes above the resting lactate levels. This means that the heart rate equilibrium will only be reached after 10-20 minutes of sustained exercise; this is called the slow component of cardiovascular kinetics. At severe levels of exercise lactate levels will not plateau but rise steeply until the subject is too exhausted to continue, no equilibrium will be reached.

(Zakynthinaki 2015)

2.3.3 Heart Rate variability

TODO: de paper (Shaffer & Ginsberg 2017) is heel uitgebreid, later terugkeren om de relevante informatie uit te filteren

The time between heartbeats (the RR interval) is not constant but fluctuates ever so slightly between beats. The difference between these intervals is not random but is the result of a multitude of complex interactions between various organs of the body and is best described as “mathematical chaos”. HRV dimishes with age and is a marker for parasympathetic activity, with a higher value being in general considered “more healthy”. Lower HRV values have been linked to Myocardial Infarction and Myocardial Dysfunction, while raising HRV through exercise to battle cardiovascular mortality risk has been proven beneficial. (Malik et al. 1996)

2.3.3.1 Time domain

A way to measure HRV is in the time domain, meaning that we look at the time in between heart beats and derive metrics from the difference.

- SDNN
- SDRR
- SDANN
- SDNNI
- RMSSD
- HTI

Therefore, 60 seconds appears to be an acceptable recording time for lnRMSSD data collection in col- legiate athletes. (Esco & Flatt 2014)

2.3.3.2 Frequency domain

Various oscillations have been measured with a frequency ranging from seconds to >24 hours and can be roughly grouped into different bands (see table 2.3). The LF and HF bands are significant because their oscillations can be affected by breathing rythm. More specifically, the LF band is affected by slow breaths (3 to 9 per minute) and the HF band is affected by fast breathing (9 to 24 per minut)e

Table 2.3: frequency bands of Heart Rate variability.

Name	Period	Actors
Ultra Low (ULF)	5 min - 24 hrs	
Very Low (VLF)	25 sec - 300 sec	
Low (LF)	7 sec - 25 sec	
High (HF) or Respiratory band	<7 sec	

- LF/HF ratio

2.3.3.3 Contextual Factors

2.3.3.4 Subject Variables

2.3.4 Heart Rate Recovery

After cessation of exercise, the return of heart rate towards its baseline is modulated by the ANS. The resulting speed at which the baseline is reached is called Heart Rate Recovery (HRR). As mentioned before, Heart rate is influenced by the two distinct nervous sub-systems; parasympathetic (PNS) and sympathetic (SNS). This balancing act has a significant effect on HRR, because the impulses of these systems are delivered independently from each other. At first the PNS, responsible for reducing heart rate, will kick into gear resulting in a sharp decrease in HR. The SNS, responsible for increasing heart rate, reacts slower and winds down the impulses given to the heart gradually.

The combination will result in Heart Rate Recovery Curve, split into a fast phase and a slow phase. The transition between these phases denotes the border where the SNS takes over the mediation of HR from the PNS (Bartels et al. 2018). Studies show that this curve becomes steeper as the subject transition to adulthood, so a window of at least 2, preferrably 3 minutes between measurements is recommended for achieving age-independent HRR metrics (Suzic Lazic et al. 2017) (Molina et al. 2016)

2.3.5 Cardiac Output

In the context of fitness, one of the most important factors is Cardiac Output (CO). CO is the measurement of the volume of blood pumped by each ventricle per minute, and is calculated by multiplying Heart Rate with Stroke Volume (the amount of blood pumped by each ventricle). It is fairly easy to conclude that an increase in CO means an increase in oxygenated blood reaching the muscles, which increases the potential maximum energy output of a muscle. Note that SV is not the same as the volume of a ventricle. There is always a certain volume of blood (the so-called End Systolic Volume or offload) present in the ventricles. During the cardiac cycle the ventricles fill up to a maximum volume (called the End Diastolic Volume or preload) after which the SV is ejected to return to the ESV. An average heart at rest has approx 130 mL EDV and 50-60 mL ESV, which result in an SV of 70-80 mL.

It is clear that a higher heart rate will result in a higher Cardiac Output, but its not just a matter of multiplying Heart Rate with Stroke Volume. SV will initially be able to keep up with an increase in HR, but at around 120 bpm there is not enough time between contractions for the ventricles to fill up with blood. Up until 160bpm the rate at which SV decreases is lower than the rate at which HR increases, so CO will continue to increase. As HR rises above 160 bpm, this balance shifts and CO starts to decrease. Therefor individuals performing aerobic exercises are cautioned to monitor their HR to ensure they stay within the target heart rate range. The target HR is loosely defined as the range in which both the heart and lungs receive the maximum benefit from the aerobic workout and is dependent upon age.

(Betts et al. 2013)

2.4 Measuring heart rate

2.4.1 Phonocardiogram (PCG) measurement

The phonocardiograph will measure heart pulse data by listening to the sound of the beating heart. In a normal, healthy heart, there are two distinctly 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 as a consumer wearable (Sharma et al. 2019) (Abbasi-Kesbi et al. 2018).

2.4.2 Electrocardiogram (ECG) measurement

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 rudimentary electrocardiographs.

2.4.3 Photoplethysmogram (PPG) measurement

Various biological tissue types (bone, blood, pigments in the skin,…) reflect and absorb light in different ways. The pumping action of the heart has a large effect on the pressure and corresponding presence of blood in the arteries. The peak of this pressure wave is called “systole” and the valley is called “diastole”. Note that this pulse is very strong in the arteriers, being directly connected to the output of the pump. Deeper inside the system this pulse gradually weakens to a static pressure in the veins. The pulsing of blood flow and blood pressure can be determined easily using a pulse rate monitor. The principle behind PPG sensors is the optical detection of this pulse using a sensor system consisting of a light source and a detector. The sensor monitors changes in the light intensity via reflection from or transmission through the tissue. The changes in light intensity can be mapped to the diastole and systole to provide information on the pulse rate of the heart. (Tamura et al. 2014)

PPG sensors are fairly simple devices and have found their way to various wrist-based wearables, where they measure the pulse rate of the arteries in the wrist.

2.5 Physical fitness

To model our fitness coach we need to know the distint differences between a fit and unfit subject. We also have to make the distiction between a trained and untrained subject, because these concepts are inherently linked but are not synonyms. To be “fit” is to have a large aerobic capacity, the body has adapted to be able to deliver more oxygen to the muscles which improves aerobic ability. To be “trained” is having the extra muscle and nerval impulses te be able to use this oxygen, converting it into more power than an untrained subject.

Another aspect that is closely linked to “fitness” is cardiovascular health. It is common knowledge that being more fit results in a lesser change to contract cardiovascular problems such as infarcts, but being in good cardiovascular health doesn’t necessarily imply being fit. Attempting to alleviate poor cardivascular health through fitness training is however a widely acknowledged and applied therapy.

2.5.1 Fitness metrics

Due to the large amounts of ways to parametrize “fitness”, calculating a fitness score involves carefully selecting which metrics to incorporate and which to ignore.

2.5.1.1 Baeke Score

The Baeke Score is a tried and tested (Florindo & Latorre 2003) self-administered questionaire to evaluate the activity level of the subject. It is a quick way to determine a rudimentary score for the fitness level of an individual, but requires validation from measurements to be a reliable metric.

2.5.1.2 VO_{2max} & Aerobic capacity TODO

Aerobic capacity is the ability to take in oxygen and deliver it to skeletal muscle during exercise. It uses VO_{2max} (or Peak Oxygen Uptake), the maximum rate of oxygen consumption in mL/(kg*min) - volume of oxygen delivered per minute, per kilogram of body mass - , as a measure because it reflects the capabilities of the circulatory and respiratory systems. It is a gold standard measure for comparing individual subjects and training methods because it correlates with cardiorespiratory fitness and endurance capacity. Erythropoietin (EPO) can significantly increase VO_{2max}, so it is no surprise that it has been used extensively as a Performance-Enhancing Drug in aerobic sports such as cycling. Note that higher VO_{2max} doesn't necessarily mean a higher volume of oxygen in the blood. In fact, most VO_{2max} increases can be attributed to a higher capacity of the body to extract the oxygen already present in the blood.

Accurately measuring VO_{2max} is difficult/impossible without specialized medical equipment, but a meta-study revealed that VO_{2max} may be stimulated/extrapolated from Rating of Perceived Exertion (RPE) during a Perceptually Regulated Exercise Test (PRET) test. RPE is a standardised 6-20 scale with 6 meaning no exertion at all and 20 meaning maximal exertion. These ratings can informally be described as "exercise resulting in a heartrate of rating times 10". Furthermore, performance during a Cooper test (maximum distance covered by foot during 12 minutes) can be extrapolated to VO_{2max} using the formula

$$VO_{2max} \approx \frac{dist - 504.9}{44.73}$$

Where $dist$ is the distance covered in meters in 12 minutes.

2.5.1.3 Blood Lactate levels

Fatigue has an apparent impact on the slow phase of the blood lactate level increase, the higher the intensity that can be sustained without a significant presence of the slow component, the better the prospects for endurance. Endurance training will have the effect of elevating the value of lactate threshold of an individual and thus eliminate the slow com- ponent for some exercise intensities. This way exercise intensities which were initially severe for the particular person might become heavy or even moderate following training (Zakynthinaki 2015)

2.5.1.4 Heart Rate variability

Heart Rate variability is the variation in time between each heartbeat. This variation is affected by the autonomic nervous system and will increase from parasympathetic/rest-and-digest activity and decrease from sympathetic/fight-or-flight activity. A healthy ANS is one that can quickly activate or deactivate either stimuli, so being able to quickly change from low to high variation and vice-versa is a measure of good physical and mental health and high stress resilience (Dong et al. 2018). Habitual aerobic exercise appears to aid the maintenance of higher HRV in active subjects when compared with age- and weight-matched sedentary subjects (De Meersman 1993), and correlates with VO_{2max} (Buchheit & Gindre 2006).

Not all HRV measures are created equal; HF, SDNN and RMSSD were statistically significantly higher in athletes than in controls, but other resting HRV parameters were not statistically different between groups (Danieli et al. 2014). It is equally important to compare HRV measures not in a vaccuum but from longitudinal monitoring. In the case of elite athletes training for an upcoming event, another study found weekly and 7-day rolling averaged Ln rMSSD and the Ln rMSSD to R–R interval ratio as practically useful to represent a meaningful change in fatigue and/or fitness. In the same study, increasing HRV values were shown to be a possible sign of positive adaptation and/or coping with training load, while reductions in HRV in the week/days before pinnacle events may represent increasing freshness and readiness to perform (Plews et al. 2013).

2.5.1.5 Heart Rate Recovery

HRR has become a significant, non-invasive measure of cardiovascular-parasympathetic influence and general cardiovascular health. A large number of studies suggest that slowed HRR is an independent predictor of all-cause mortality (Qiu et al. 2017). Fast HRR is statistically significantly faster in athletes (Danieli et al. 2014), and is associated with cardiac adaptation to physical activities of various durations and intensities (Durmić et al. 2019). HRR differs alot from subject to subject, depending on the type of sport the subject is trained in, his/her age, the intensity of the training regime, etc. (Durmić et al. 2019) It is important to use the change in HRR over time as a measure of increased fitness, instead of using it as a baseline fitness metric.

HRR has a fast phase and a slow phase (see also section 2.3.4). Analysis revealed that the fast phase accounts for almost all of the HR decay after a intermediate intensity sessions (98%), remaining only a minor portion of the decay falling in the slow phase (2%). On the other hand, slightly different contributions are observed in High Intensity sessions (91% and 9%). For these reasons, percentage values of slow and fast phase might provide complementary information when comparing different exercise intensities. This same study also demonstrated that high-intensity exertion delays both parasympathetic reactivation and sympathetic withdrawal, resulting in a flatter curve (Bartels et al. 2018). The fast phase HRR correlates with parasympathetic modulation (Danieli et al. 2014)

Studies have shown no correlation between HRR and HRV (Esco et al. 2010) (Molina et al. 2016), but a correlation exists between HRR and Baeke score (Buchheit & Gindre 2006), which means that having an active lifestyle results in faster HRR. Fast phase HRR (specifically, the Heart Rate Index, being HR_max minus Heart rate after 1 minute of recovery) also correlates with VO_{2max}. As VO_{2max} is primarily influenced by sympathetic activity, this means that an incread in fitness not only means higher parasympathetic modulation, but also enhanced sympathetic activity. In general, HRR can be used as a measure of Autonomic Nervous System adaptation (Durmić et al. 2019).

2.5.2 Hoe wordt fitheid getrained TODO

- 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
- The development of functional overreaching is associated with a faster heart rate recovery in endurance athletes

Fitness training is based on three principles (Powers & Howley 1995): - a training effect occurs when the tissue is stressed at a level beyond it is accustomed to (overload) - a training effect is limited to the tissue involved in the activity (specifity) - the effect of training is quickly lost when training is stopped (reversibility)

These principles aren't limited to muscular tissue, but can also be applied to aerobic capacity. VO_{2max} increases after consistent training sessions of 20 to 60 minutes, at an intensity of 50% to 85% VO_{2max}. Recall that VO_{2max} is measured as volume over time (per kg of body mass), which means that an increased Cardiac Output (due to higher preload and lower afterload) accounts for 50% of the VO_{2max} increase. The remaining 50% is due to an increased oxygen intake by organ tissue, resulting from a greater capillary density in the trained tissue (Powers & Howley 1995).

If an amount of muscle fibers are insufficient to accomplish a task, more fibers will be recruited, which increases the sympathetic nervous response, heart rate response and ventilation response to sustain the metabolic rate of these extra fibers. Fitness training results in an increased presence of mitochondrial cells in the muscle, which means that overall less muscle fibers need to be recruited which decreases the aformentioned responses (Powers & Howley 1995).

2.5.2.1 Detraining

Detraining is the rapid declination of the benefits gained from training. A fast decrease of

2.5.2.2 functional overreaching

HRR is geen metriek voor f-OR (Aubry et al. 2015)

2.5.2.3 overtraining syndrome

2.5.3 MUSCLE FATIGUE

2.5.3.1 neural fatigue

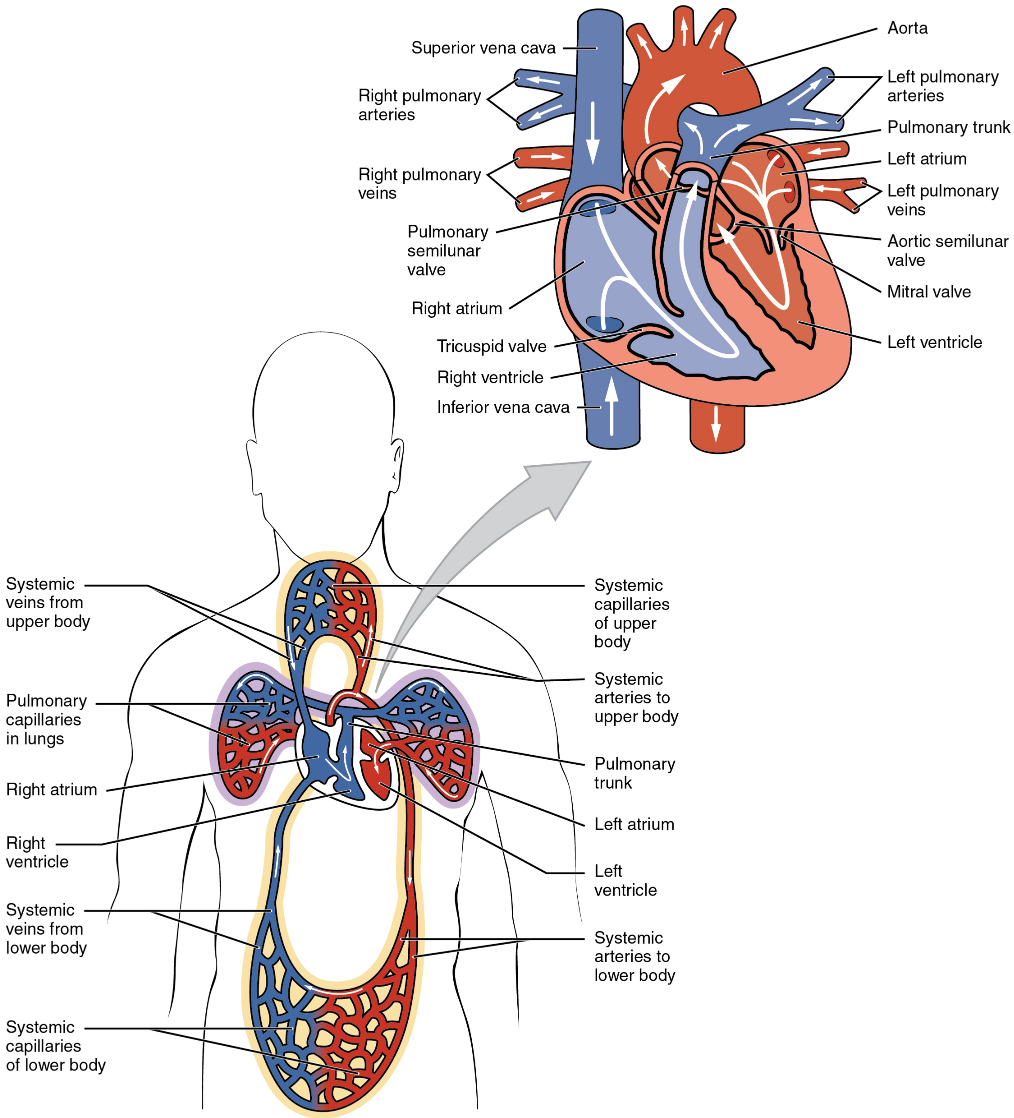

Figure 2.1: An anatomical overview of the heart

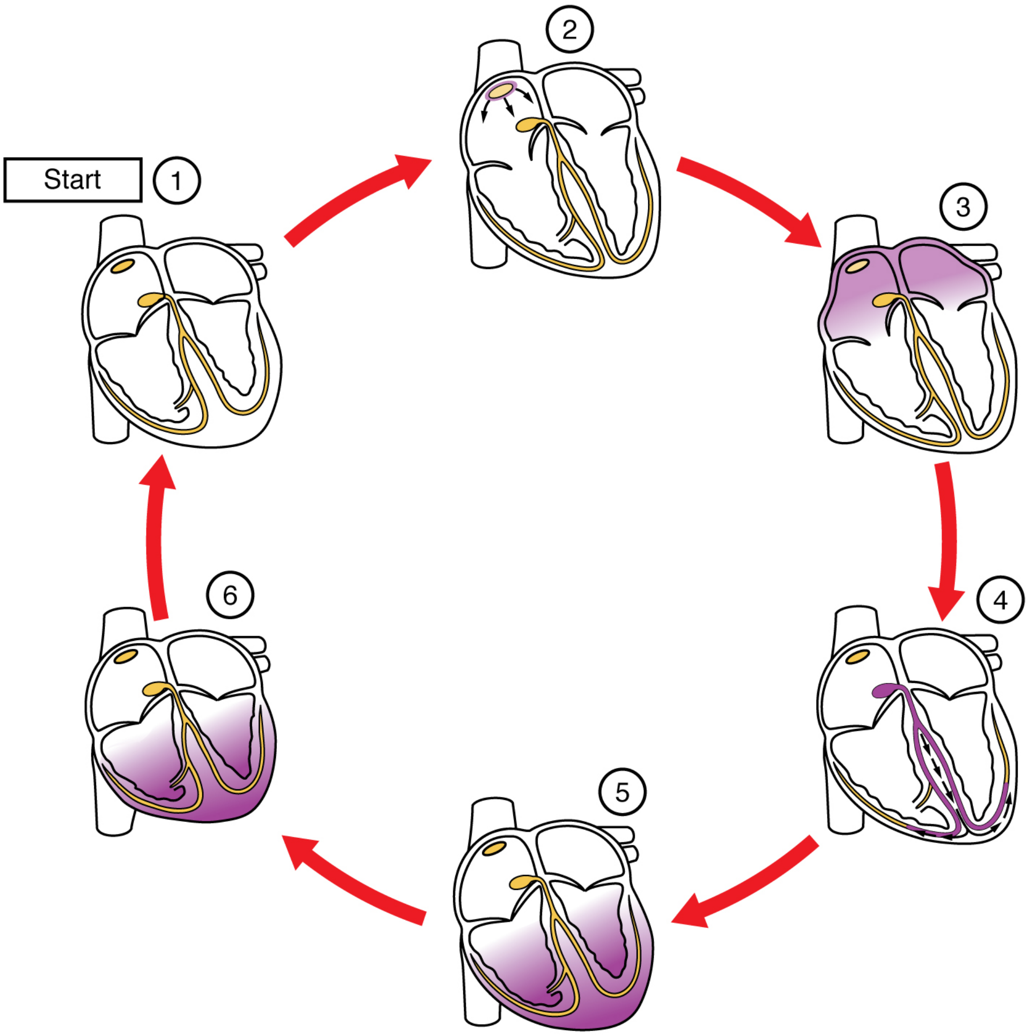

Figure 2.2: the innervation and pumping mechanism of the heart

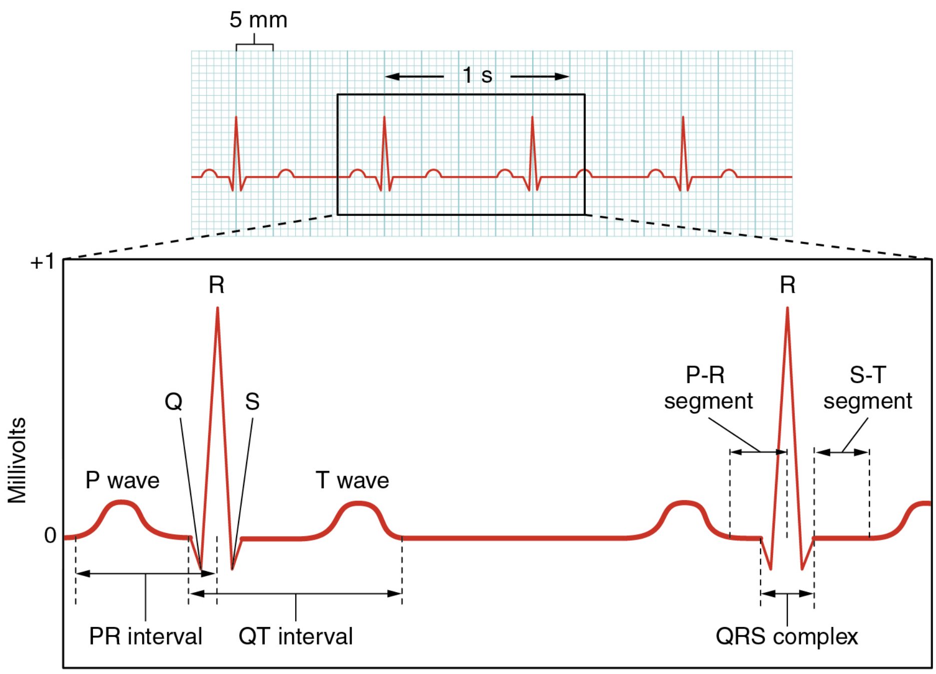

Figure 2.3: an example ECG tracing

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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