

COMPARISON OF TWO ALGORITHMS TO DETECT CHANGE IN AEROBIC CAPACITY OVER TIME.

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ABSTRACT.

Many people struggle to quit smoking and start running since the chance on relapse is very high amongst self-quitters. That is why Roessingh research and development, University of Twente and other partners designed the Perfect Fit program. The program uses a virtual coach that gives the participants a personalised training plan based on the change in aerobic capacity over the time. In this research two algorithms to estimate the change in aerobic capacity over time were designed and analysed.

The first algorithm is based on the algorithm used by Garmin in their wearables and uses the positive linear relation between heart rate and VO_2 to estimate the VO_{2max} of the runner. The second algorithm uses the positive linear relation between heart rate and speed to calculate the heart rate-speed ratio. Both VO_{2max} and the heart rate-speed ratio are a quantification of the aerobic capacity. A data set with 888 running trainings and two VO_{2max} measurements is used to analyse and validate the designed algorithms. The measured change in aerobic capacity is an improvement of 25 ml/kg/min (53 %) between the two VO_{2max} measurements.

The change estimated by the Garmin algorithm is an improvement by only 11 ml/kg/min (19,64 %), where the heart rate-speed ratio algorithm also calculated an increase by only 1,68 bpm/(km/h) (11,38 %). Therefore both algorithms underestimated the change in aerobic capacity over time. The underestimation could be due to the low amount of runs containing heart rate data and to unknown external factors such as cold or hilly terrain.

To conclude, it was not possible to accurately predict the change in aerobic capacity over time with the use of an algorithm for this data set. However it is not clear if the algorithms would work on data sets containing more VO_{2max} measurements and more consistent training. Overall more validation and calibration needs to be done to use the algorithms in the Perfect Fit program.

Veel mensen hebben moeite om te stoppen met roken en te beginnen met hardlopen omdat de kans op terugval erg groot is. Daarom hebben Roessingh Research Development, de Universiteit Twente en andere partners het Perfect Fit programma ontworpen. Het programma maakt gebruik van een virtuele coach die de deelnemers een gepersonaliseerd trainingsplan geeft op basis van de verandering in aërobe capaciteit over de tijd. In dit onderzoek zijn twee algoritmes ontworpen en geanalyseerd om de verandering in aërobe capaciteit in de tijd te schatten. Het eerste algoritme is gebaseerd op het algoritme dat Garmin in hun wearables gebruikt en maakt gebruik van de positieve lineaire relatie tussen hartslag en VO_2 om de VO_{2max} van de loper te schatten. Het tweede algoritme gebruikt het positieve lineaire verband tussen hartslag en snelheid om de hartslag-snelheids ratio te berekenen. Zowel VO_{2max} als de hartslag-snelheids ratio zijn een kwantificering van de aërobe capaciteit. Een dataset met 888 looptrainingen en twee VO_{2max} metingen wordt gebruikt om de ontworpen algoritmen te analyseren en te valideren. De gemeten verandering in aërobe capaciteit is 25 ml/kg/min (53%) tussen de twee VO_{2max} metingen. De door het Garmin-algoritme geschatte verandering is een verbetering met slechts 11 ml/kg/min (19,64 %), terwijl het algoritme voor de hartslag-snelheids ratio een toename met slechts 1,68 bpm/(km/h) (11,38 %) berekende. Beide algoritmes onderschatten dus de verandering in aërobe capaciteit over de tijd. De onderschatting zou te wijten kunnen zijn aan het geringe aantal lopen met hartslaggegevens en aan onbekende externe factoren zoals kou of een heuvelachtig terrein. Concluderend kan worden gesteld dat het niet mogelijk is om met behulp van deze algoritme de verandering in de aërobe capaciteit over de tijd te bepalen bij deze data set. Het is echter niet duidelijk hoe de algoritmes werken bij het gebruik van een andere data set die meer VO_{2max} metingen en consistente training bevat. Uiteindelijk zal er meer validatie en kalibratie met behulp van een andere dataset moeten plaatsvinden om de algoritmes in het Perfect Fit programma te kunnen gebruiken.

1 Introduction

Roessingh research and development, University of Twente and other partners, are designing a program to get people to quit smoking and start running, named Perfect Fit [1]. The developed program acts as a virtual coach that gives a specific training plan for the participant. The training plan is based on the participant's current aerobic capacity.

Aerobic capacity is a measure of the ability to perform oxidative metabolism, in which the pulmonary, cardiac, vascular and musculoskeletal systems are involved [2]. During the training the participant adjusts to the new workloads imposed by the training plan. The training intensity needs to progressively and systematically increase [3] to increase the aerobic capacity. The training must contain training variation, for example a variation in volume or frequency of the training, to maximize the adaptation to the training plan. The training plan could also be used by athletes outside the Perfect Fit program who want to improve and or monitor their aerobic capacity.

The change in aerobic capacity can be used as motivation for the participants of the Perfect Fit program [4]. The participants are in the activated stage of their behaviour change. This means that they have made the decision to change their life style in the coming month [5]. Reminding the participant of the development in their aerobic capacity will act as motivation and it will encourage the new healthy behaviour. Without any personal help, relapse occurs in 95 to 98 percent of people who try to quit smoking [6]. The most common causes for relapse are the positive or negative events in their personal environment and cigarette dependence [7]. Relapsing itself can also cause a lot of stress, however running is already used to improve the mental and physical health of people who quit smoking [8, 9].

The early effects of training take place in the mitochondrial and capillary density, the oxidative fibre types and the muscles mass [3]. Because of the adaptations in the muscles, the extraction rate of oxygen is improved, therefore the need to deliver oxygen to the muscles increases [10]. To increase the oxygen flow to the muscles, a rise of the blood flow (cardiac output) is necessary. That is where the next adaptation to aerobic training occurs. The cardiac output is increased by an increase in stroke volume [11]. Because of this increase, more oxygenated blood can reach the muscles and because the extraction of oxygen by the muscles is improved as well, the aerobic power can be enlarged up to 50 %.

In athletes it is seen that the heart rate after a period of training is lower than the heart rate of their runs before the period of training, measured at the same intensity. The change in heart rate at the same intensity can be explained by the increase in stroke volume, the increased volume of red blood cells and the increased blood volume in general [12, 13]. The same amount of oxygen in the muscles is needed, but because the stroke volume has increased, the heart rate can be lower to deliver the same amount of oxygen. The increased volume in red blood cells also increases the amount of oxygen that can be delivered since the same blood volume contains more red blood cells with oxygen.

Since the change in heart rate and speed can be measured by a heart rate monitor and a GPS-tracker, the aerobic capacity can be estimated. In the current study, two algorithms are developed and compared to determine the changes in the aerobic capacity of the participants. It is preferred that both algorithms can estimate the aerobic capacity without the help of a protocol during the training. For example, the already existing Coopertest can predict the maximal oxygen uptake (VO_2max), in litre per kilogram per minute, of the athlete with no significant difference (a correlation of 95 percent) to a portable spirometer [14, 15]. However a protocol is needed during the Coopertest, which can form a threshold for an athlete to determine their aerobic capacity.

The first algorithm is based on the algorithm used by Garmin in their wearables [16, 17]. This algorithm is based on the positive linear relation between heart rate and speed and the positive linear relation between speed and oxygen uptake (VO_2) during submaximal exercise. The algorithm determines the mean speed at different heart rates and calculates the VO_2 corresponding with this speed [17]. Since there is a delay in heart rate response when the intensity of the run changes, the heart rate and speed in steady state are preferred [18]. When the maximum heart rate of the participant is known, the VO_2max can be estimated as seen in figure 1.

The second algorithm is based on the positive linear relation between heart rate and speed during submaximal exercise seen in figure 2 [3, 19, 20, 21]. As mentioned before, the heart rate and speed in steady state are preferred. And it is also expected to see a decrease in the heart rate-speed ratio (HR-SP ratio) over the time the participant is enrolled in the Perfect Fit program.

Both algorithms stated above will be validated using the same data set. Since there

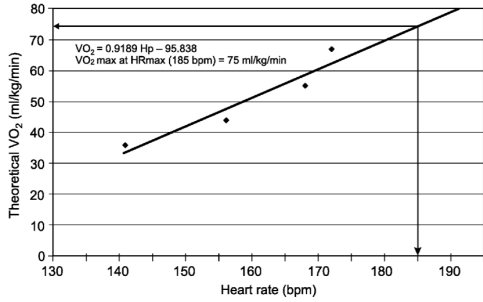


Figure 1: Calculation of VO_{2max} [17]

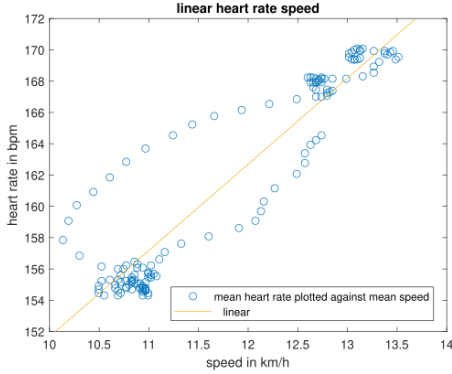


Figure 2: linear heart rate-speed ratio training 31-03-2020

was no available data set of a participant who quit smoking, the data set of a non-smoking, male triathlete is used. The data set contains 1.667 recorded swimming, cycling and running trainings. The data set also contains manually entered trainings (so not recorded with GPS or containing the exact training time). Those trainings are therefore not reliable and do not contain heart rate, so they are not included in the overview. Table 1 shows an overview of the content of the data set. The data set includes two VO_{2max} measurements executed on a cycle ergometer. For this research only the running data is of interest because the Perfect Fit program focuses on running. All kinds of running training (long steady runs and interval runs) are included in the study.

The aim of this research is to determine the possibility to detect change in aerobic capacity over time using an algorithm. This algorithm should be able to be used during a free training and must provide a parameter which can be used to quantify aerobic capacity [22].

Type of training	Running	Swimming	Cycling	Indoor cycling	Total
Total number of trainings	888	28	721	30	1.667
Number of trainings containing heart rate	603	0	367	30	1000

Table 1: Overview of recorded trainings

Since the accuracy of the estimation of the aerobic capacity can change per run, due to the variability in heart rate because of for example cold weather (where the increase in energy consumption causes the heart to beat faster), this research will focus on change in aerobic capacity per week [19].

2 Methods

2.1 Data quality assurance

Before a run is processed it needs to be evaluated to assure the run is suitable for the algorithms. Runs without heart rate data present will be excluded since both the VO_{2max} value and a heart rate-speed ratio are based on heart rate. Once this criterion is met, the run will be analysed by the algorithms.

2.2 Algorithm based on Garmin

For the algorithm based on Garmin, runs require a minimum length of twelve minutes. The first ten minutes can be considered as the warming up [23]. The warming up is used to increase muscle and tendon suppleness, to stimulate blood flow to the muscles (dilation of the arteries), and to increase muscle temperature [24]. Due to this, changes the heart rate response do not match the intensity changes. The duration of the warming up depends on the athlete, but in this research a mean length of ten minutes is used [23]. Because of the warming up, the first ten minutes of a run will be excluded from the VO_{2max} estimation. Runs shorter than twelve minutes will then not produce an accurate VO_{2max} .

The heart rate, speed and number of data-points (to predict the length of the run) will be extracted from the run since the VO_{2max} value will be estimated using those parameters. After excluding the first ten minutes of the run (warming up), segments with length T_{seg} are made. The standard deviation of the speed and the heart rate are calculated for every segment.

The length of the segments (T_{seg}) is determined after comparison of the estimations of the algorithm with the known VO_{2max} measurement in 2017 (72 mL/kg/min) from the

data set. The segment length for which the error between the measured VO_2 max and the mean VO_2 max is the smallest is used in the algorithm, in this case 26 seconds. For the comparison the runs a month prior to and a month after the VO_2 max measurement were used. Figure 11 in appendix 1 shows the mean VO_2 max and standard deviation per segment length. Table 3 highlights some of the considered segment lengths. Segment lengths between twenty seconds and four minutes are considered since this is the preferred segment length according to Garmin [17].

After making the segments, they are placed in bins depending on the mean heart rate in the segment. These bins have a range of ten heartbeats per minute. For example, the first bin contains segments with a mean heart rate between 90 and 99 bpm and the second bin contains segments with a mean heart rate between 100 and 109 bpm and so on. The segments are evaluated per bin. The segment with the lowest standard deviation in the group is labelled 'best segment'. The lowest standard deviation is preferred because of the delay in heart rate response mentioned in the introduction. Segments with a speed lower than seven km/h are dismissed as only segments with running are analysed. If the segment is dismissed, the segment with the next lowest standard deviation becomes the new best segment. This process continues until a segment is found with a mean speed higher than seven km/h. The best segment also needs to differ 26 seconds with respect to the best segment of the previous bin. With this criterion it is made sure that no overlapping segments are used to determine the VO_2 max of the run. Overlap-

ping segments would cause data points close to each other, which would influence the linear heart rate- VO_2 line (Figure 1), with the consequence that an error occurs in the VO_2 max estimation.

After every bin's best segment is determined, the VO_2 per best segment will be calculated with

$$VO_2 = 3.6 * \text{meanspeed}[17]$$

When all values of VO_2 are known, regression analysis is done if there are more than four groups with a best segment. With the equation of this trend line and the maximum heart rate of the athlete, the VO_2 max and correlation between heart rate and VO_2 per run are estimated. To qualify the run for further analysis (week and year overview), the correlation (R^2) needs to be higher than 0.75 to qualify as a very strong correlation [25]. Runs where the correlation between VO_2 and heart rate is less than 0.75 are excluded from further analysis because they are not qualified as a very strong correlation. If, due to one of the criteria above, it was not able to calculate the VO_2 max, the activity is disqualified from further analysis.

The algorithm is summarised below in Pseudo code.

```

1 Algorithm based on Garmin
2 IMPORT single file
3 EXCLUDE warming up
4   DIVIDE activity into overlapping
5   26 second segments
6   CALCULATE standard deviation
7   of speed per segment
8   CALCULATE mean heart rate
9   per segment
10
11 SORT all segments in groups
12 matching their mean heart rate
13

```

Segment length in seconds	Mean VO_2 max value one month prior and one month after measurement in 2017 in mL/kg/min (including standard deviation)	Mean error with respect to the measurement in 2017 in mL/kg/min
20	63.27 ±3.75	-8.72
26	67.33 ±3.24	-4.67
28	63.54 ±9.45	-8.46
30	63.56 ±9.07	-8.44
32	63.07 ±8.77	-8.93
48	62.26 ±7.96	-9.74
60	64.08 ±5.65	-7.92
90	60.33 ±7.34	-11.67
120	62.78 ±7.44	-9.22
150	64.16 ±7.08	-7.84
180	59.44 ±6.45	-12.56
210	60.02 ±6.84	-11.98
240	59.47 ±3.37	-12.53

Table 2: Important segment lengths from figure 11

```

14 FOR all groups
15     FIND segment with lowest
16     standard deviation
17     CHECK IF speed in this segment
18     is higher than 7 km/h
19         IF NOT
20             FIND next best segment
21
22     CHECK IF chosen segment does
23     not overlap with previous
24     best segment
25         IF NOT
26             FIND next best segment
27
28 IF more than 4 best segments
29 are found
30     CALCULATE VO2 per segment
31     CALCULATE R^2 value of points
32     to the trend line
33     IF R^2 < 0.75 disqualify
34     activity from further analysis
35     EXTRAPOLATE data to find VO2max
36     to the line

```

2.3 Heart rate-speed ratio

The heart rate and speed are extracted per run and used for the determination of the heart rate-speed ratio. In contrast to the estimation of the $VO_2\max$, the heart rate speed ratio (HR-SP ratio) uses the last five minutes of the warming up. To determine a consistent HR-SP ratio it is necessary to use the same heart rate range for every run, for example the range between 160 and 170 bpm. When such a small window is considered, linearity between heart rate and speed can always be assumed to be the same. If a small abnormality exists in the linearity between heart rate and speed in this range it will always be the same abnormality if the same range is used. It is not possible to use such a range in all the runs since this range is not always achieved in long, steady runs and is only achieved in the acceleration or deceleration during an interval training. The assumption is made that most runners use the same warming up for every run, so these heart rates and speed can be considered constant and can be used to determine the HR-SP ratio. Therefore the length of the run needs to have a minimum length of ten minutes.

In the last five minutes of the warming up, segments of 26 seconds are made the same way as described in the algorithm based on Garmin. For those segments the standard deviation of the speed and heart rate are calculated. Since the most constant segment is preferred for analysis, the segment with the lowest standard deviation in both speed and heart rate, the 'total' standard deviation, is determined. To determine the ratio between the standard deviation (SD) in speed and heart rate the next formula is used:

$$Ratio = \frac{\text{mean SD of heartrate}}{\text{mean SD of speed}}$$

With this ratio, the total standard deviation per segment is calculated by using the formula:

$$SD_{total} = SD_{heartrate} + SD_{speed} * Ratio$$

The three segments with the lowest total standard deviation are chosen for further analysis. For those segments the same criteria as in the Garmin algorithm apply. This means that the mean speed in the chosen segments needs to be higher than 7 km/h and that there is no overlap between segments.

As final step the heart rate over speed ratio is calculated per segment. Since there are three segments, the mean of the three ratios is determined to be the ratio of the run. The algorithm is summarised below in Pseudo code.

```

1 HR-SP ratio algorithm
2 IMPORT single file
3 INCLUDE minute 5 till 10
4 DIVIDE activity into 26 second
5     segments
6     CALCULATE standard deviation
7     of speed per segment
8     CALCULATE mean heart rate
9     per segment
10
11 CALCULATE ratio of standard difference
12 CALCULATE total standard difference
13     per segment
14 FIND 3 best segments
15 FOR 3 segments
16     CHECK if speed in this segment
17     is higher than 7 km/h
18         IF NOT
19             FIND next best segment
20     CHECK if chosen segment does
21     not overlap with previous
22     best segment
23         IF NOT
24             FIND next best segment
25
26 IF 3 best segments are found
27     CALCULATE heart rate-speed ratio
28     per segment
29     CALCULATE mean ratio

```

3 Results

Figure 3 shows the mean training time per month. The duration of all types of training (running, cycling and swimming) is included. It can be concluded that the athlete made more training hours during the summer (May til August).

3.1 Algorithm based on Garmin

Figure 4 shows the $VO_2\max$ estimates of the algorithm based on Garmin. In total 217 of the 888 running training's (24,43 %) passed all the conditions and were analysed.

Figure 5 shows the $VO_2\max$ data points from the data set (47 mL/kg/min on 27-03-2014 and 72 mL/kg/min on 15-06-2017) and the $VO_2\max$ estimations from the runs five months

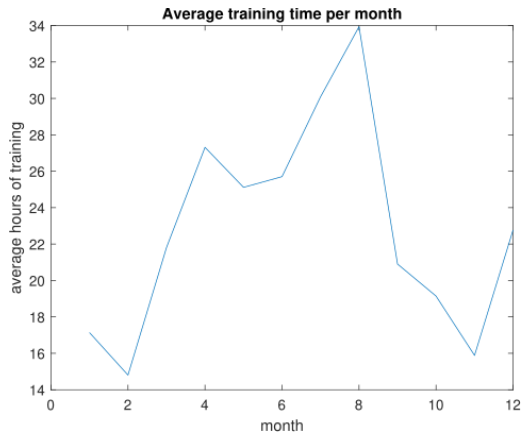


Figure 3: Sum of training effort per month (including running, swimming and cycling)

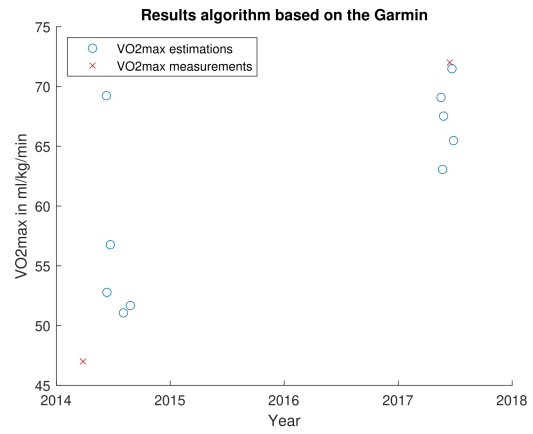


Figure 5: VO_2 max estimations made by the algorithm based on Garmin around the time of the VO_2 max measurements.

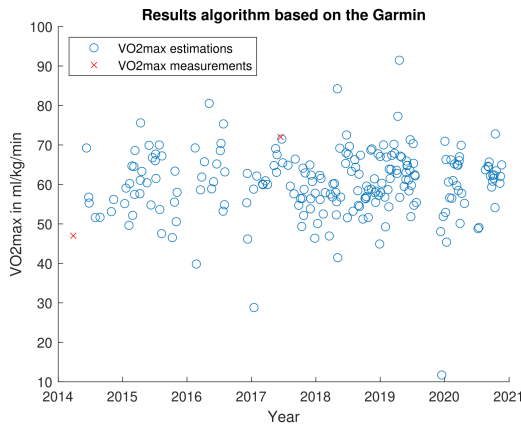


Figure 4: VO_2 max estimations made by the algorithm based on Garmin

prior to and five months after the VO_2 max measurement in 2014 and the runs a month prior to and a month after the VO_2 max measurements in 2017. Those windows were chosen to include at least five runs with heart rate data present. It is seen that the measured VO_2 max value improved by 25 mL/kg/min (53 %). To determine the change in the estimated VO_2 max value, the mean of the VO_2 max values around the VO_2 max measurement are compared. The mean value in 2014 equals 56 mL/kg/min and in 2017 67 mL/kg/min, this means that an increase of 11 mL/kg/min (19,64 %) is detected. Due to the low number of runs containing heart rate data in 2014, it was necessary to lower the correlation requirement of R^2 to 0.5 (a strong correlation) [25]) to detect data points around the VO_2 max measurement.

In figure 6 an overview of the VO_2 max (blue line) per week for 2018 is shown. This figure shows that a difference in VO_2 max per week can be detected.

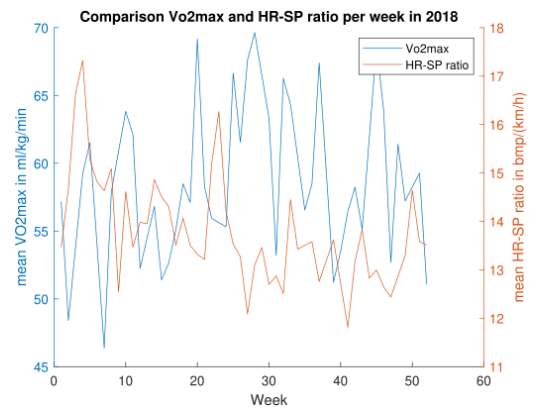


Figure 6: VO_2 max and HR-SP ratio per week in 2018

3.2 Heart rate-speed ratio algorithm

Figure 7 shows an overview of all calculated heart rate-speed (HR-SP) ratios made by the heart rate-speed ratio algorithm. In total 459 of the 888 running trainings (51,68%) passed all the conditions and are shown in the figure.

To calculate the change in the HR-SP ratio, the runs five months prior to and five months after the VO_2 max measurement in 2014 and the runs a month prior to and a month after the VO_2 max measurements in 2017 are used. Those windows were chosen to include at least five runs with heart rate data present. Figure 8 shows the calculated HR-SP ratios in those months. The mean value in 2014 equals 14,76 bpm/(km/h) and in 2017 13,08 bpm/(km/h), this means that a decrease of 1,68 bpm/(km/h) (11,38 %) is detected.

The orange line in figure 6 shows that the change in HR-SP ratio can also be detected per week.

Figure 9 is zoomed in on the year 2016 to show the decrease in HR-SP ratio in the period towards the summer. Table 3 summarises of the results of this research.

	Aerobic capacity in 2014	Aerobic capacity in 2017	Change in aerobic capacity over time
Vo2max measurement	47 mL/kg/min	72 mL/kg/min	25 mL/kg/min (53%)
Estimation algorithm based on Garmin	56 mL/kg/min	67 mL/kg/min	11 mL/kg/min (19,64 %)
HR-SP ratio	14.76 bpm/(km/h)	13.08 bpm/(km/h)	1.68 bpm/(km/h) (11.38%)

Table 3: Summary of the results

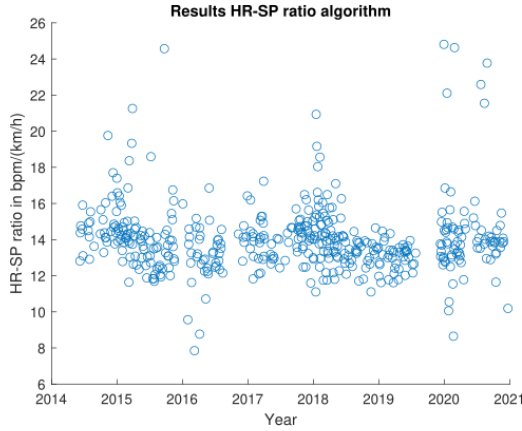


Figure 7: Calculated heart rate-speed ratios by the HR-SP ratio algorithm

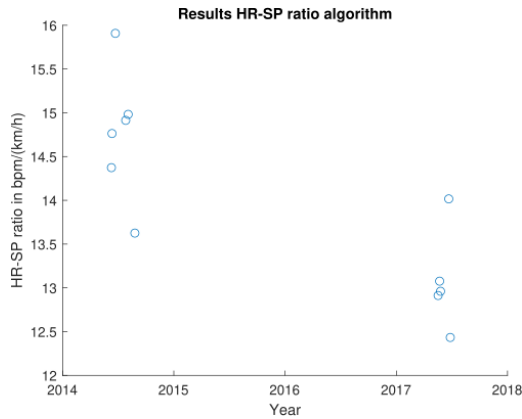


Figure 8: HR-SP ratios made by the HR-SP ratio algorithm around the time of the Vo2max measurements.

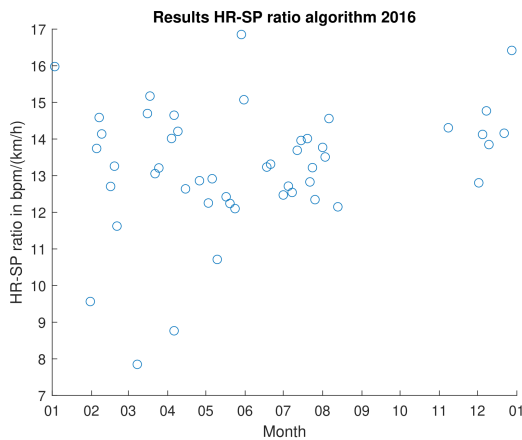


Figure 9: HR-SP ratios made by the HR-SP ratio algorithm in 2016

4 Discussion

4.1 Algorithm based on Garmin

The purpose of this research was to find and compare two algorithms to detect change in aerobic capacity over time. For the algorithm based on Garmin there is found that the estimated change in aerobic capacity does not match with the change in the VO₂max measurements. Where the measured change over time equals 53 %, the estimated change over time by the algorithm based on Garmin is only 14 %.

The first cause for the difference in change over time might be that the algorithm based on Garmin could not be reconstructed from the Garmin-patent correctly [17]. In the original patent, a different method is used for rating the reliability of the segments. In the patent every segment gets a reliability value based on the combination of the length of the segment and the standard deviation in speed in that segment. A long segment with a low standard deviation in speed is rated as highly reliable, where a shorter segment with the same standard deviation is rated as less reliable (as shown in figure 10). In this research, segments which all had the same length were used due to the difficulty of programming varying segment lengths into Matlab. Since the segments are all of the same length it was not possible to use the reliability coefficients seen in figure 10 in the algorithm based on Garmin. Therefore the segments with the lowest standard deviation in speed are chosen to be used for further analysis.

In addition to the difference in reliability rating, J. Anderson et al [26] found that the commercially available Garmin Fenix 5x Wrist-Worn Optical Sensor, which uses the Garmin algorithm, underestimates the VO₂max of the test subjects with 2.16 ml/kg/min. This is within the manufacturers estimated error range of 3.5 ml/kg/min, but this possible difference which was not included in the analysis of the algorithm based on Garmin. N. Snyder et al [27] also found that there can be a difference in the accuracy of VO₂max prediction for men and woman. The Garmin Forerunner 230 can predict the VO₂max accurately for both genders, however the Polar V800 overestimates the VO₂max value for men but not for woman. The difference between genders is also not included in the algorithm based on Garmin. This difference is not included in the HR-SP ratio ei-

Standard deviation of successive 10 sec heart rate values (beats per minute)	Duration (min)					
	less than 0.5 min	0.5- 1.0 min	1.0- 1.5 min	1.5- 2.0 min	2.0- 2.5 min	2.5- 3.0 min
	Reliability coefficient (%)					
more than 3.0 bpm	3%	6%	8%	11%	14%	17%
2.5-3.0 bpm	6%	11%	17%	22%	28%	33%
2.0-2.5 bpm	8%	17%	25%	33%	42%	50%
1.5-2.0 bpm	11%	22%	33%	44%	56%	67%
1.0-1.5 bpm	14%	28%	42%	56%	69%	83%
less than 1 bpm	17%	33%	50%	67%	83%	10%

Figure 10: Reliability coefficient Garmin Patent[17]

ther, however this will not form a problem because the HR-SP ratio cannot be validated with known values from the data set, whereas the algorithm based on Garmin can be compared with the VO_2max measurements from the data set.

4.2 Heart rate-speed algorithm

For the HR-SP ratio algorithm it is found that the estimated change in aerobic capacity does not match with the change in the VO_2max measurements. Where the measured change over time equals 53 %, the estimated change over time by the HR-SP ratio algorithm is only 7,11 %. One of the reasons for the difference in change over time could be the use of the last five minutes of the warming up. As mentioned in the method it is necessary that the most steady part of the run is used for the analysis and that it is also more convenient if the heart rate range for which the HR-SP ratio is calculated is the same for every run. In this research it is assumed that the warming up is a constant factor of the runs and that the warming up is the same for every run. Since the precise warming up is not known for the runs, it is not clear if the assumption that is made is reasonable. To validate the model it is necessary that the warming up for every run is the same or that runs are carried out on a steady heart rate or speed.

It was not necessary to use the value R^2 between heart rate and speed for the HR-SP ratio algorithm. Due to the focus on a small part of the heart rate domain, a linearity between heart rate and speed can always be assumed. It was also found that the heart rate-speed ratio decreases in the begin of the year until the summer. This result is clearly seen in the years 2016 and 2017, for the other years this is less clear. The decline can be explained by the increase in training effort. Due to the training effort the aerobic capacity increases, so the HR-SP ratio decreases because of the increased cardiac output, blood volume and red blood cells as described in the introduction. Another explanation for the unexpected results

is the occurrence of deflection in the heart rate during a run. A deflection occurs when the athlete trains at higher speeds [28]. At this point the heart rate will stabilize at a steady state but the speed at which the athlete runs still increases. When the speed increases but the heart rate is at a steady state, the HR-SP ratio is disturbed. An analysis of this phenomena is not included in this research so the HR-SP ratio algorithm should be corrected for this phenomena in further research.

4.3 General factors

Overall it was found that a lot of runs were not analysed by the algorithms due to the unavailability of heart rate data of the runs. This could be the result of the fact that this data set was not generated with the aim to be used for research. Therefore a lot of runs did not contain heart rate data and only two VO_2max measurement were performed over the course of eight years. The algorithms are calibrated on this data set so it is not known how well they work with other data sets.

Since both of the algorithms rely on the linear relation between heart rate and speed and between heart rate and VO_2max , the linearity of the heart rate is very important. However heart rate is manipulated easy by the smallest external factors [19]. The mental state of the athlete can for example increase the heart rate [29] and also daily factors such as dehydration, where the blood volume decreases so the heart needs to beat faster, medication and environmental elements, such as cold weather which increases the energy consumption causing the heart to beat faster, influence the heart rate [19]. Because of these daily changes in heart rate or even changes during the run (surface of the run or hilly terrain), an error can occur in the VO_2max estimation and the HR-SP ratio. It is therefore advised to look at the weekly changes in physical capacity instead of the change per run.

Another influence can be the state of fatigue of the athlete. Fatigue is the inability to maintain a certain muscle tension over time [10]. Since fatigue is a complex phenomenon where different factors and mechanisms in the body interact and contribute to, it is not yet clear what exactly causes the inability to maintain muscle tension over time [30]. But if an athlete is fatigued, his heart rate will not react the same on a stressor [30]. Some athletes experience a higher heart rate in a normal training while others experience a lower heart rate due to fatigue. This will also affect the calculation of the VO_2max and HR-SP ratio and causes an error in the estimation of the VO_2max and the HR-SP ratio.

For further research it is advised to only use data sets of runners with more known VO_2max points. In this way, fatigue due to other sports (such as cycling and swimming) will be ruled out, the algorithms can be validated on more VO_2max data points and the length of the segments can be improved.

To compare the change estimated by the algorithms with the measured change, the change in the mean of five VO_2max estimations around the VO_2max measurements is used. A better statistic way to do this would be to use the two-sample t-test [31]. But to use this test, more data sets are needed. It is advised to use the two-sample t-test in further research.

The last point of interest is the method of VO_2max determination. The VO_2max tests in the data set were done on a cycle ergometer. A lot of studies were performed on the difference between a VO_2max test on an ergometer or on a treadmill. For example, J. Kohrt [32] found that a VO_2max executed on a cycle ergometer resulted in a VO_2max value of 57.9 ± 5.7 mL/kg/min and a VO_2max test executed on a treadmill, with the same participants, resulted in a VO_2max value of 60.5 ± 5.6 mL/kg/min. In contrast, O'Toole [33] found that there is no significant difference in VO_2max values measured on a cycling ergometer or on a treadmill. P. Millet [34] combined all those studies and found that no conclusion can be drawn. In this research the VO_2max outcomes of the algorithm based on Garmin (so found for running) are compared to the VO_2max test executed on a cycle ergometer. The algorithms were also calibrated on those cycling VO_2max tests. This could result in an error in the VO_2max prediction for running.

5 Conclusion

For the participants of the Perfect Fit program, the improvement in their aerobic capacity can act as a motivation to keep running and continue quitting smoking. So the aim of this research was to compare and analyse two algorithms designed to quantify, and estimate the change in the aerobic capacity of the participants of the Perfect Fit program.

In general it can be concluded that it was difficult to quantify the aerobic capacity with this data set. A lot of runs did not contain heart rate data and there were only two known VO_2max data points to compare with the estimations of the algorithms.

For the algorithm based on Garmin, very varying VO_2max estimations were found and due to the criterion of a very strong correlation a lot of runs were disqualified for further use in the week and year overview. Overall the algorithm

based on Garmin underestimated the improvement in aerobic capacity over time.

For the heart rate speed ratio algorithm, it was necessary to analyse warming up instead of the run which can be a reason of the varying ratio's that were found. This algorithm also underestimated the improvement in aerobic capacity over time.

Overall it can be concluded that more research needs to be done since heart rate and speed can indicate the change in aerobic capacity, but both algorithms do not work accurately. To make the algorithms work more accurately, it is necessary to acquire a data set with the aim to be used for this research. This data set should contain data from a runner with at least one known VO_2max point per week and all runs should contain heart rate data. This data set would allow the algorithms to be calibrated and validated.

Concluding, it was not possible to accurately predict the change in aerobic capacity over time with the use of an algorithm for this data set. However it is not clear if the algorithms would work on data sets containing more VO_2max measurements and more consistent training. Overall more validation and calibration needs to be done to use the algorithms in the Perfect Fit program.

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6 Appendix

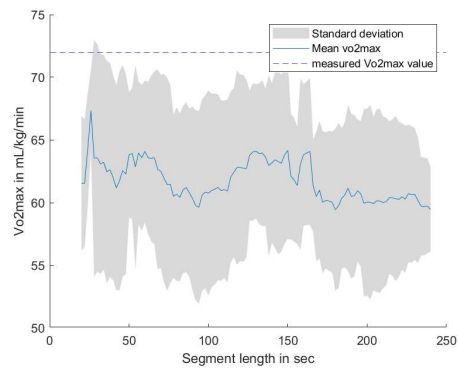


Figure 11: VO₂max per segment length including standard deviation