Cyclist Performance Classification System based on Submaximal Fitness Test

S. Sudin[1, 2], A.Y. M. Shakaff[1, 2], A. Zakaria[1, 2], A. F. Salleh[1], F. S. A. Saad[1, 2] and A. H. Abdullah[1]
[1]*School of Mechatronic Engineering, Universiti Malaysia Perlis, Kampus Tetap Pauh Putra, 02600 Arau, Perlis, Malaysia.*
[2]*Centre of Excellence for Advanced Sensor Technology, Universiti Malaysia Perlis, Lot 16-21 Taman Muhibah, Jejawi-Permatang, 02600 Arau, Perlis, Malaysia.*
sukhairi_sudin@yahoo.com

***Abstract*—Performances among cyclist always measured by time traveled from start to finish line and then the winner in cycling event also decided by time or who crossed the finish line first. On the other hand, cyclist performance can be measured through cardiorespiratory and physical fitness, and this performance can be enhanced by proper training to increase fitness and skill without burden. A wireless sensor network (WSN) system developed by combined various sensing element to capture physiological and bicycle's kinetics feedback. Physiological data such as heart rate variability (HRV) and kinetic data such as paddling power and cadence used as input in Astrand-Ryhming and PWC_{150} submaximal test to classify the performance group among cyclist. Developed HRV system using Photoplethysmography (PPG) provides the significant output with R^2 value was 0.967. A group of 15 cyclists from three different backgrounds was used as a subject in this study. Maximal oxygen intake (VO_{2max}) produced by Astrand-Ryhming test correlated with estimated paddling power produced by PWC_{150} test with P<0.01 and the R^2 value was 0.8656. Discriminant analysis was 88.3% successfully classified cyclist into 3 group and group of trained and untrained cyclist clearly separated.**

***Index Terms*—Astrand-Ryhming; Cyclist; Performance Monitoring; PWC.**

I. INTRODUCTION

Performance in cycling today is not just about physical training but also depends on technology support during the training program and competition itself [1]. Typically, technology in cycling sport is about sensing the current cyclist physiological, kinetic and kinematic condition. These feedbacks are important to provide information about cyclist condition while structuring their training routine to increase their performance and capability to maximum and preventing injury [2].

Physiological information such as heart rate variability (HRV) can be used as an early indication of cardiovascular condition. HRV is one of the non-invasive ways that widespread commonly to extract heart beat-to-beat variation. Heartbeat modulated by the human automatic nervous system (ANS) produced low-frequency component during sympathetic and parasympathetic nature that will change blood volumetric inside the vessel [3,4]. Besides fitness, abnormalities in heart electrical waveform pattern in a normal person with a symptom like dizziness, presyncope, palpitation, angina, nausea, and syncope turn to be a predictor of heart diseases [2,5]. HRV is normally estimated from the electrocardiogram (ECG); which require sensor electrodes to be attached to the chest rendering it unsuitable for a condition that requires a considerable amount of movement. Therefore, Photoplethysmography (PPG) technique was considered to be used in this system to estimate HRV from cyclist's finger [6,7].

When it comes to cycling, cyclist performance is always related to how fast he is able to move from one point to another point. Pedaling power, cadence and suitable gear ratio are the main factors that affect cycling speed. Paddling power has been used to determine performance in a sport such as a cyclist rather than looking at the heart rate due to it more directly coupled to cyclist's performance and is related to the cyclist's will in winning the race[8]. However, usage of physiological and kinetic data such as HRV and paddling power together in submaximal fitness test provide useful information to coach and physician in assessing cyclist's fitness, performance and condition. Cyclist fitness can be derived indirectly from cardiorespiratory fitness that reflected by maximum oxygen intake (VO_{2max}) value and physical fitness which response from paddling power output [9–12]. Cardiorespiratory fitness also known as aerobic fitness is very important especially for endurance activity.

In order to measure cyclist aerobic fitness for endurance activity, the test must be conducted for aerobic intensity which VO_{2max} consider as a major factor that widely used for the athlete and non-athlete by the researchers. Most accurate VO_{2max} value can be gathered using direct maximal laboratory test. VO_{2max} values involve the measurement of the maximum amount of the oxygen consumed per unit of time while performing different exercise intensity [13]. However, the direct maximal test consumed very high cost in equipment and the procedure which it required special equipment that operated by the professional operator must be involved in the medical field because the unsupervised maximal test can drive subject to over-trained state which can cause a fatal. More or less accurately, the submaximal test can be used as an indirect method which it predicts or estimates cyclists VO_{2max} without burdening their hearts [13–15]. Astrand-Ryhming test is one of the famous submaximal tests to predict VO_{2max} in cycling condition that uses a steady-state exercise heart rate at single power output as its calculation method [16–18].

Furthermore, the Astrand-Ryhming test focused on intensity which estimates cyclist VO_{2max}. On the other hands, physical working capacity (PWC) test is the submaximal test that focused on estimated aerobic power output. The aerobic power output from PWC also can be extrapolated from VO_{2max} that estimated from Astrand-Ryhming test [9, 19]. The measurement of the PWC involves with HRV and cycling workload parameters which can be obtained from continues time series data. Then, the aerobic power will be estimated based on certain heart rates such as 130bpm (PWC_{130}), 150bpm (PWC_{150}), 170bpm (PWC_{170}) and 75% ($PWC_{75\%}$) from maximum HRV.

II. SYSTEM DESIGN

The monitoring system for track cyclists was developed based on a combination of various sensing elements and method in order to generate cyclist's condition and performance profile. Physiological, kinetic and kinematic data was transmitted wirelessly from cyclist and bicycle to the base station for monitoring and logging purposes. Figure 1 illustrates the overall system architecture. A combination of off-the-shelf and specially designed devices and software were used in the system.

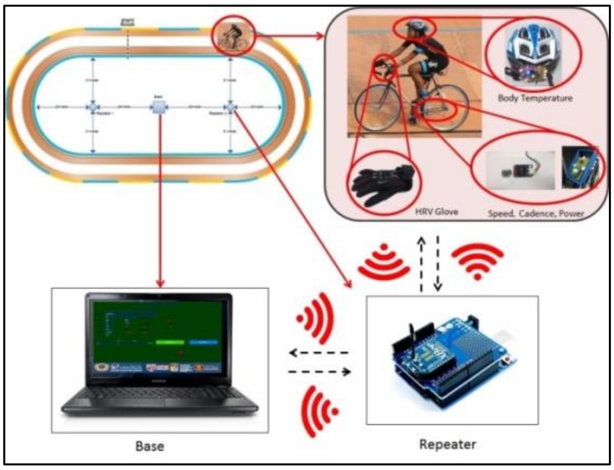

Figure 1: Overall system overview

A. *Physiological Sensor*

Heart rate variability (HRV) sensing elements were placed inside the cyclist's glove. HRV based on Photoplethysmography (PPG) is different from others methods like ECG and bipolar ECG that use electrodes which are attached to the human body to detect HRV. PPG concept is based on light absorption or reflectance on human skin specifically at the fingers. The HRV detector was designed using APDS-9007 low powered light photo sensor which receives a green light reflected from a cyclist's finger. The green led produces 530nm wavelength was the most suitable wavelength to react with blood melanin inside the microvascular bed of tissue which provides better waveform [7, 20]. Low pass filter with 2Hz cut-off frequency was applied to raw PPG signal to remove outliers signal before it is amplified in the pre-processing stage. This conditioning or acquisition circuit was built on a single board with 10mm diameter to fit under the finger skin. A Nova microcontroller with Arduino Leonardo bootloader was chosen as a controller due to its compact size and low power consumption. The system can last for 4 hours of continues operation when powered with 90mAh LiPO Battery.

The comparative method was used in maximum peak finding process by comparing each sampled signal received to find the highest value that declared as peak as illustrated in Figure 2. HRV estimated by the time difference between each peak and times by 60. HRV for each individual is not exactly the same, and there are many formulas to calculate maximum HRV for different categories. However, for standard users, Karvonen formula in Equation (1) still can be used to determine maximum HRV based on age [14, 21–23].

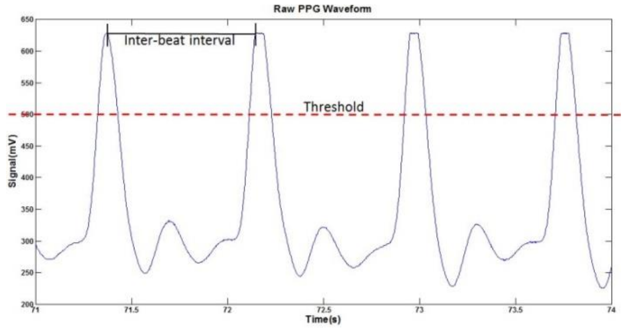

Figure 2: PPG signal waveform

B. *Bicycle Kinetic and Kinematic*

Paddling power, cadence, and speed are considered as kinetic and kinematic elements that are measured from a bicycle. Cadence and speed information are extracted by counting the number of rotation that is produced by the front sprocket and rear wheel in 60 seconds. The magnetic Hall Effect sensor used in this application counts triggering edge each time magnet placed on wheel and front sprocket pass through it. Paddling power is derived by multiplying cadence and torque. In this study, torque is measured at paddle by using off-the-shelf Garmin Vector paddle.

Sensor nodes used on cyclist and bicycle attached with a wireless communication system to meet cyclist comfort level to wear without distracting their performance like illustrated in Figure 3.

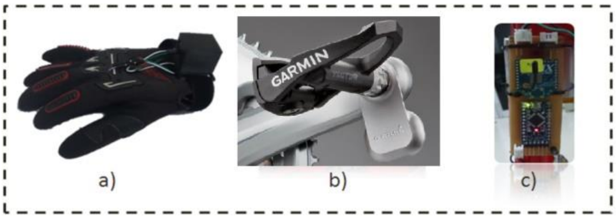

Figure 3: Three sensing nodes: a) PPG attached to the glove; b) Garmin Vector paddle; c) Cycling speed and distance measurement unit

C. *Wireless Communication*

Wearable devices in moving applications are incomplete without the implementation of the wireless network. XBee series 2 with ZigBee protocol was attached to each Arduino based microcontroller as end device to transmit processed data to base station. These 2.4GHz low cost and low powered wireless communication devices have better range compared to ANT. This module comes with sleep function on the end device side which is useful to reduce power consumption. It has an on-chip antenna to strengthen transmitted and received signal. XBee communication signal strength was measured based on Receive Signal Strength Indicator (RSSI) PWM output [24]. This module operated at 12MHz with 2400 total counts on PWM referring to 200μs period. PWM reading in decimal from the analog port can be converted to signal strength percentage.

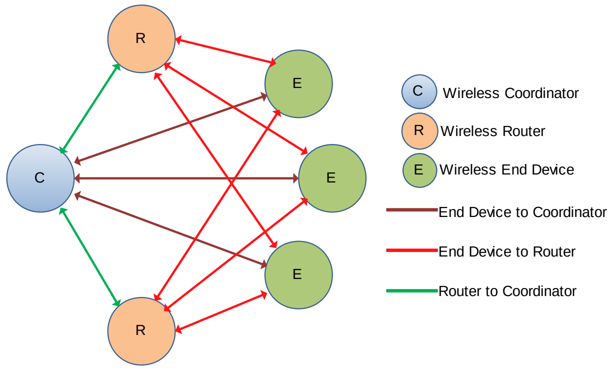

Figure 4: Wireless network connection

Data packet from the end device at sensor node will be transmitted directly to the coordinator at a base as this will reduce the transmitting time. However, if the connection between the end device and coordinator failed, end device will transmit to the router as a signal repeater to pass data to the coordinator. Figure 4 illustrates a wireless network connection between end device, router, and coordinator. This network connection reduces dropped data packet and each packet is assigned with message count header to avoid data duplication and identify packet drop.

III. EXPERIMENTAL PROCEDURE

This study conducted indoor using Tacx Vortex virtual reality electromagnetic brake trainer attached to a bicycle to provide likely load cycling on the track as illustrated in Figure 5. Room temperature remained between 22°C to 24°C for cyclist comfort. Each cyclist required to sit on the chair and relax for 5 minutes to record cyclist resting heart rate (rHR) before each session. Experiments were done on fifteen participants aged 24±6 from various backgrounds: five healthy well-trained cyclists, five healthy normal people that are occasionally cycling and five healthy people that are rarely cycling. The participant declared free from any serious disease and under good health condition to do some related test. Well-trained cyclists consist of a cyclist from Malaysia Junior Team under Malaysia Sports Council and normal cyclists consist of normal people who live in the active and healthy lifestyle. The electromagnetically brake equipment has provided nearly same condition as in real road cycling due to applied resistance on the wheel during cycling activity. Participant comfort during cycling activity was taken into account by adjusting the saddle height depends on each cyclist leg length using LeMond saddle height method. Optimal saddle height when pedal crank positioned at 6 o’clock position that provides knee flexion at 30°±5°. With this setting can minimize fatigue and reduce the likelihood of injury to the knee [25,26]. LeMond method provides 65% accuracy of knee flexion at 30°±5° which it considerably well for cyclist [27].

Figure 5: Indoor experimental setup

One of the factors that can affect participant result comes from their lifestyle; a standard procedure must be applied to each participant. In order to perform a cycling fitness test, each cyclist was set to follow some standard pre-test regulation as below:

i. Cyclist must be free from any cycling tournament or physical work hard for at least two days before the test.
ii. Cyclist must have enough sleep at least 6 hours
iii. Smoker requested to abstain for minimum 2 hours before the test
iv. Cyclist cannot take any meal minimum 2 hours before the test
v. Cyclist do not take any drug or medicine
vi. Cyclist do not take any drink or food that contain caffeine in prior 24 hours before the test
vii. Cyclist require maintaining a constant cadence all the time
viii. Repeatable test must be done at the same time another day

Participant maximum heart rate (HR_{max}) and exercise heart rate intensity zone predicted and calculated using Karvonen formula which is commonly used in physical training, rehabilitations, and another related field[21]. By using the Karvonen formula, participant reserve heart rate (HRr), target heart rate (HRt) and rHR will be a set of important information to avoid the overtraining situation by a participant that may harm their self, especially for the normal participant. rHR obtains by recording the participant HR after woke up in the morning or 30 minutes after lying down in relax mode. The exercise heart rate intensity, divided into several zones between HRr to HR_{max}. Equations (1) – (3) below shows how HR_{max}, HRr, and HRt were obtained from Karvonen formula. In the physiological study, heart rate training zone was dividing into six stages like listed in Table 1[22] and for this study; participant was monitored to keep their heart rate between recovery and aerobic zone which in the range 60% to 75% exercise intensity.

$$\mathrm{HR_{max}} = 220 - \mathrm{age} \tag{1}$$

$$\mathrm{HRr} = \mathrm{HR_{max}} - \mathrm{rHR} \tag{2}$$

$$\mathrm{HRt} = \mathrm{HRr} \times \mathrm{intensity} + \mathrm{rHR} \tag{3}$$

where: HR_{max} = Maximum heart rate
HRr = Reserve heart rate
rHR = Resting heart rate
HRt = Target heart rate

Table 1
Heart Rate Training Zone

Training zone	Intensity
Recovery	< 65% HR_{max}
Aerobic	65% - 75% HR_{max}
Extensive Endurance	75% - 80% HR_{max}
Intensive Endurance	80% - 85% HR_{max}
Anaerobic Threshold	85% - 90% HR_{max}
Maximum Aerobic	> 90% HR_{max}

A. Astrand-Ryhming Cycle Test

Maximal heart rate and exercise heart rate intensity is much easier and cheaper to measure compared to oxygen intake (VO_2). The relationship between HRV and VO_2 in Equation (4) show that HRV also can be used indirectly as a substitute to VO_2 in determined the fitness by using arteriovenous oxygen difference ($AVDO_2$) and stroke volume (SV), which is the volume of blood on ventricle each time heart beat[21,23]. However, fitness predicting accuracy more reliable by measure VO_2 and VO_{2max}; which, in this study, we considered to perform submaximal cycling test. Cyclist VO_{2max} estimated using Astrand-Ryhming 6 minutes cycling test that known as of the submaximal test that introduced by Per-Olof Astrand from Sweden in 1956 will be used in this experiment. Prior study has been proved that VO_2 and power output relationship is linear up to about 50-60% VO_{2max} which makes Astrand-Ryhming was a reliable test for determined cyclist VO_{2max}[28].

$$VO_2 = HRV \text{ x } AVDO_2 \text{ x } SV \tag{4}$$

where: VO_2 = Oxygen intake
HRV = Heart rate variability
$AVDO_2$ = Arteriovenous oxygen difference
SV = Stroke volume

The cyclist will start to warm up for 5 minutes with 50W braking load. After finished warm up, cyclist gave 5 minutes rest before starting with the actual test. Actual ride test workload was set to 100W. Astrand-Ryhming 6 minutes cycling test required the cyclist to cycle just for 6 minutes with maintaining cadence at 60rpm. HRV recorded at last 15 seconds on each minute and took the average for first 5-minutes. HRV from the fifth minute to the sixth minute was recorded and take the average as steady-state heart rate (HRss). An average of total cycling workload (W) was taken and converted to kilogram per-minutes by Equation (5). Equations (6) - (7) used to estimate VO_{2max} in liter per minutes for female and male respectively. Cyclist age also will affect the VO_{2max} value for each individual; Table 2 shows an age correction factor that needs to multiply with calculated VO_{2max} before it converted to VO_{2max} per kilogram using Equation (8).

$$\text{workload (kg/min)} = \text{watt x } 6.12 \tag{5}$$

Astrand equation for female:

$$VO_{2max} = \frac{(0.00193 \text{ x workload} + 0.326)}{(0.769 \text{ x HRss} - 56.1)} \text{x}100 \tag{6}$$

Astrand equation for male:

$$VO_{2max} = \frac{(0.00212 \text{ x workload} + 0.299)}{(0.769 \text{ x HRss} - 48.5)} \text{x}100 \tag{7}$$

$$VO_{2max} \text{per kg} = \frac{\text{VO2 max x } 1000}{\text{weight}} \tag{8}$$

where: VO_{2max} = Maximum oxygen intake in l/min
HRss = Heart rate steady state
weight = Cyclist weight in kg

Table 2
Astrand-Ryhming Age Correction Factor

Age(Years)	Factor(x)
≤15	1.2
16	1.1
17-34	1.0
36-39	0.87
40-44	0.83
45-49	0.78
50-54	0.75
≥55	0.71

B. PWC Test

PWC was a submaximal test like Astrand-Ryhming which it used powers at low HRV to estimate aerobic power certain HRV. This experiment conducted for PWC_{150} that estimated the power output at 150bpm of HRV using Equation (9). Participants were required starting cycling at 50watt of workload and it will increase by 20watt every 2 minutes. Average of HRV and power recorded at the end 15 seconds on every 2 minutes until HRV archive first 150bpm. First 150bpm of HRV recorded as HR_2 and power simultaneously with this HRV recorded as P_2 while lowest HRV and it simultaneous power recorded as HR_1 and P_1 respectively. Estimated aerobic power at 150bpm HRV can be converted to watt over kilogram by dividing it with participant weight and rate using Table 3.

$$PWC_{150} = \left(\frac{(P_1 \text{ x } HR_2) - (P_2 \text{ x } HR_1)}{HR_2 - HR_1}\right) + \left(HRt \text{ x } \left(\frac{P_1 - P_2}{HR_1 - HR_2}\right)\right) \tag{9}$$

where: PWC_{150} = Estimated aerobic power at 150bpm
HR_1 = Lowest HRV
HR_2 = Highest HRV after reach 150bpm
P_1 = Paddling power simultaneous with HR_1
P_2 = Paddling power simultaneous with HR_2
HRt = Target heart rate

Table 3
Relative Performance (watt/kg) for PWC 150

	Weak	Moderate	Average	Good	V.Good	Excellent
Men	<1.5	1.5-1.99	2.0-2.49	2.5-2.99	3.0-3.49	>3.5
Woman	<1.2	1.2-1.59	1.6-1.99	2.0-2.49	2.5-2.99	>3.0

IV. Results and Discussion

A. Developed HRV system

The developed HRV system using PPG technique in this study was found to produce 3% error compared to Sigma PC10.1 commercial heart rate monitor belt and the coefficient of determination (R^2) of HRV was 0.967. The strong linear relationship between the developed device and off the shelf device state how effective the developed model in measure HRV.

The difference between proposed HRV monitoring device that using PPG method with off the shelf device that used bipolar ECG method was normally distributed shown by Bland-Altman plot in Figure 6(b). Bland-Altman plot is one of the effective ways to validate the two measurements techniques by combined graphical and statistical interpretation[29,30]. The center line in Bland-Altman plot shows the means difference between both HRV measurements with 0.1 biases corresponding to 0 differences. This small bias gap proves that developed device is reliable to measure HRV. The outer line indicates 95% limits of agreement (LOA) for HRV difference. The 95% limit of agreement was defined as the mean difference ±1.96 standard deviation of the difference in value for lower and upper limits were -1.924 and 2.0528 respectively.

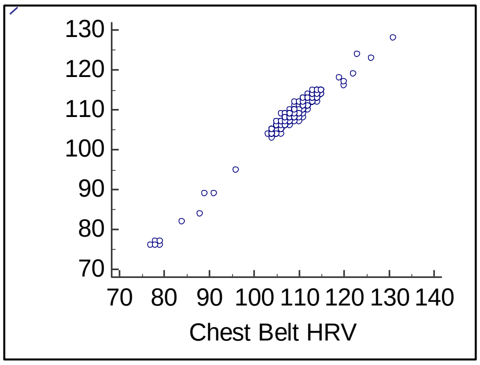

Figure 6(a): The scatter diagram for HRV relation between the established device and the developed device

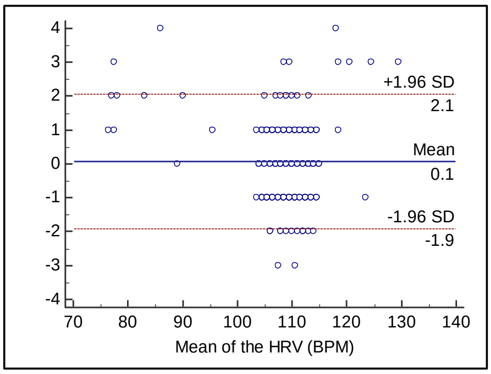

Figure 6(b): The Bland-Altman plot for HRV

B. Performance Classification

Regression analysis was performed to estimate the relationship between cardiorespiratory fitness using VO_{2max} from Astrand-Ryhming submaximal test and physical fitness using paddling power from PWC_{150} submaximal test as illustrated in Figure 7. Astrand-Ryhming and PWC_{150} test significantly correlated ($p<0.01$) with each other and coefficient of determination (R^2) between both tests were 0.8656. This strong linear relationship shows that cardiorespiratory fitness and physical fitness related each other in cyclist performance estimation.

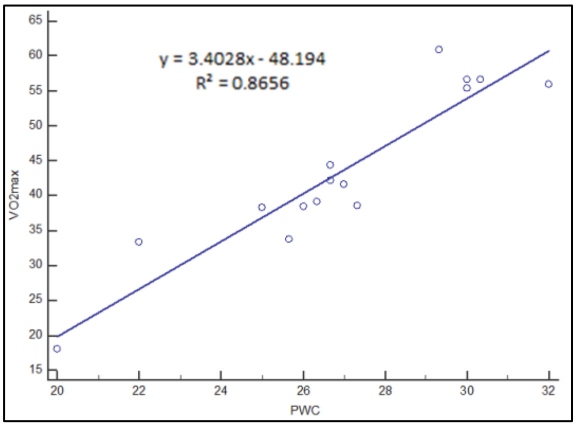

Figure 7: The scatter diagram relation between the Astrand-Rhyming and PWC_{150}

Discriminant analysis has been done through collected data both Astrand-Ryhming and PWC_{150} test. As illustrated in Figure 8, group 1 which represents trained-cyclist from Malaysia Junior Cyclist Team clearly separated from group 2 and 3. Group 2 represents active untrained cyclist while group 3 represents non-active untrained cyclist.

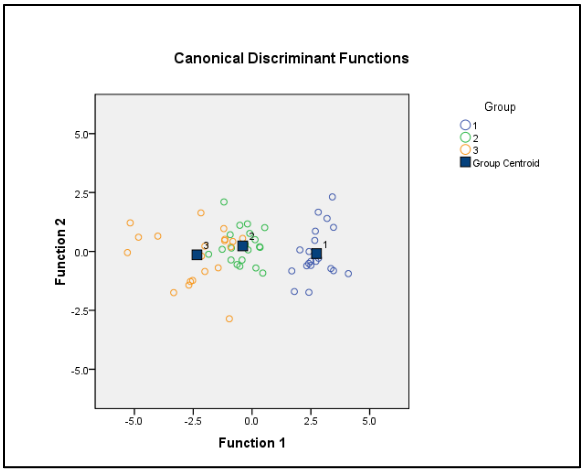

Figure 8: Group classification using discriminant analysis

From the analysis, 88.3% was successfully classified into three performance level. Cross-validation between groups mostly occurs between an active untrained cyclist and non-active untrained cyclist. However, the system successfully classified and separated between trained and untrained cyclist.

V. Conclusion

The developed HRV system provides good performance with different minimum value compared to off the shelf product. The developed system was able to operate together with off the shelf system from TACX Vortex and Garmin Vector under the same wireless network. Cardiorespiratory fitness and physical fitness have a strong bond together in order to estimate the cyclist's performance. Both cardiorespiratory and physical fitness obtained from Astrand-Rhyming and PWC submaximal test can classified cyclist performance level group. Besides fitness, the large classified gap separated between cyclists was help by cycling technique and skill. This can be proven when there is a little overlap between group 2 and 3 which both are an untrained cyclist with active and non-active in exercise while group 1 clearly separated from other two groups.

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