Modelling and Regulating of Cardio-Respiratory Response for the Enhancement of Interval Training

By

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Certificate of Original Authorship

I, Azzam Haddad, certify that the work in this thesis has not previously been submitted for a degree nor has it been submitted as part of requirements for a degree except as fully acknowledged within the text.

I also certify that the thesis has been written by me. Any help that I have received in my research work and the preparation of the thesis itself has been acknowledged. In addition, I certify that all information sources and literature used are indicated in the thesis.

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ABSTRACT

Nowadays, interval training method becomes a well known exercise protocol which helps strengthen and improve one's cardiovascular fitness. It was first described by Reindell and Roskamm and was popularized in the 1950s by the Olympic champion, Emil Zatopek. Swedish physiologist Per Oløf Astrand's study in 1960 was the first scientific study on interval training. Since then, it has been the basis for athletic training programs for many years.

This thesis aims to develop an effective training protocol to improve cardiovascular fitness based on modeling and analysis of Heart Rate (HR) and Oxygen Consumption Rate (VO_2) dynamics. VO_2 and HR are key indicators of functional health status. Thus, investigating VO_2 and HR is important when building an effective training protocol because observing these two factors can help predict the amount of energy spent during training protocols which mainly used to determine goals such as fat burning or cardiovascular system improvement.

The first part of this thesis has considered conducting a certain number of experiments to investigate the dynamic characteristics of cardio-respiratory responses to the onset and offset exercises. The key device for this study is a portable gas analyzer ($K4b^2$,

Cosmed). This versatile portable device can measure HR and oxygen consumption both in field and lab environments.

Two different training protocols have been established for two different age groups. Each protocol has been tested separately. Observing the original data for each subject has clearly helped us to identify some important facts about HR and VO_2 profiles. It has been concluded that for each individual subject, steady state gain of offset is smaller than steady state gain of onset for both HR and VO_2. Based on the modelling results, it can be seen that the time constant of offset is larger than the time constant of onset for both HR and VO_2 in each group.

The second part of the thesis was all about building sensible interval training protocol based on the experimental results. Determining an actual HR_{max} is the key to constructing a well-designed training program. Our training protocol has targeted the aerobic zone which aims to develop the exercisers cardiovascular system. The third part in this thesis is to use the identified time constants and the steady state gains of VO_2 and HR for both the onset and offset of exercises to build a model to simulate the VO_2 and HR responses to the proposed interval training protocol. A switching RC circuit has been constructed to simulate the proposed interval training protocol.

The proposed interval training protocol is based on the established average model. However, for an individual exerciser the proposed protocol might need to be adjusted in order to achieve the desired exercise effects. A hybrid system model has been presented to describe the adaptation process and a multi-loop PI control has been developed for the tuning of interval training protocol. This thesis showed under modest assumptions that the special hybrid system can be simplified as a simple discrete time system. Based on that, we show how we can design a discrete time multi-loop PI controller to adjust the duty cycle and the period of the proposed square wave type exercise protocol.

We believe that the self-adaptation feature in the controller gives the exerciser the opportunity to reach his desired setpoints after a number of iterations. It should be emphasized that the proposed multi-loop PI control algorithm only performs one time between two training experiments. Therefore, it is very easy to be implemented in low cost portable devices which have limited computation power, and that is the final phase of this thesis. The control technique has been implemented and tested on eZ430 Texas Instrument programmable watch. Although further investigation is required and more subjects need to be recruited for the validation of this study, we believe that it will be useful in the modeling and regulation of interval training exercise in free living conditions.

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Chapter 1

Introduction

Regular exercises and physical trainings are great ways of maintaining long term health and well being [2]. Given the fundamental role that exercise plays in improving general health status, it is very important to establish an exercise protocol based on the attributes and properties of different parts and phases of the training protocol.

Any regular exercise or physical activity structure has at least three crucial phases, warm up, exercise and cool down or recovery, taking into account a scientific approach in building these three different phases is considered to be essential for optimum improvement.

Warm up is widely used as a technique in regular exercise and physical activity preparation [3][4]. Almost all studies have reported the potential of warm up to improve the physiological responses and performance [5][6][7][8][9][10][11][12]. However, few studies have investigated the changes in performance following warm up [13][14][15].

Warm up techniques can be classified into two major categories [4]; passive warm up and active warm up. Active warm up is defined as any kind of exercise which may induce great metabolic and cardiovascular changes. On the other hand, passive warm up is defined as an increase in muscle temperature or core temperature by any external means or effects such as hot showers, saunas and heating pads.

Active warm up has been used in this study, five minutes of an active warm up (low speed walking) has been reported to increase the muscles temperature and therefore decrease the stiffness of muscles and joints [16] as well as reduce injury risk [17][18].

Exercise phase is the second period in the training protocol structure; the main characteristics of this phase include the intensity, duration, frequency and mode of exercise [19]. 2006 American College of Sports Medicine (ACSM) guidelines has prescribed exercise intensity for developing and maintaining the cardiorespiratory fitness for adults. It suggests performing at 70-94 % of the maximum heart rate to achieve the desired cardiovascular fitness targets.

However, [20] has recommended an 80% of the maximum heart rate for unfit people and for those with respiratory or cardiac risks. Accordingly, a speed of 9 km/h for group A and 8 km/h for group B was examined and set to be the highest level in the testing training protocol, each participant, at varying times, reached a reading of 80% of his HR_{max} at this speed.

A smooth transition from exercise to resting state is achieved through the last phase of the protocol which is the cool down phase. It shares the same structure with the warm up but with different targets. Cool down phase has a tremendous influence on an exerciser's overall health [21].

The exercise intensity at this phase has been proposed to match 40-50 % of maximum heart rate of the exerciser. This will help in decreasing the heart rate back to original resting level, which allows the cardiorespiratory system to respond effectively to lower demands. Moreover, it ensures that blood does not pool to the lower extremities, leading to dizziness and fainting [22].

The current literature has effectively demonstrated different ways in building regular exercises [23][24][25]. However, it totally neglects observing as well as using the dynamic characteristics of the cardiorespiratory system to do so. Combining the knowledge of how to build a training protocol with the information about the impacts of training on cardiorespiratory system led us to construct an effective training protocol for observing the dynamic characteristics of the regular running exercise.

The training protocol that we are aiming to build in this study is the interval training protocol; it will be built based on the dynamic characteristics of the cardiorespiratory indicators, heart rate and oxygen consumption. Interval training was first described by Reindell and Roskamm. This new training approach was presented to the public in the 1950s by the Olympic champion Emil Zatopek [26]. However, Swedish physiologist Per Oløf Astrand provided the first scientific study on interval training in the 1960s [27].

Interval Training is a good strategy for enhancing the BODE index and the functional capacity in patients with Chronic Obstructive Pulmonary Disease (COPD), it is recommended for the rehabilitation process of these patients. Furthermore, patients with COPD exercise more comfortably with lower symptoms of dyspnea and leg discomfort [28][29]. Study [30] shows that a two-week interval training program can help increasing the walking distance in patients with stage two peripheral arterial disease (PAD). To date, this study is considered to be the best provider of a first type of rehabilitation training for PAD patients.

Paper [31] has investigated an eight-week interval training program and its effects on total lung capacity; the study shows that the program made a significant difference in the total lung capacity. It increases the total lung capacity level due to the influence of such a program on the respiratory muscles [32][33]. In addition, it makes a significant difference in the expiratory reserve volume. Based on the study results, an eight-week interval training program is proved to be efficient in both decreasing the total body fat and increasing the resistance of expiratory respiratory muscles [34][35].

An interval training program has also been studied in patients with chronic heart failure [36][37]. The studies showed that a rehabilitation program with high intensity interval training considerably improves the physical capacity of these patients.

High intensity interval training program improves aerobic and anaerobic energy supplying systems in male soccer players [38]; it causes positive changes on physiological parameters and oxidative status of combat sports athletes [39]. Many studies showed that interval training may cause significant changes in body mass index, body fat mass as well as blood lipids [40]. Generally, interval training has been the basis for athletic training programs for many years.

While the above studies provide valuable information regarding the importance of interval training, caution needs to be considered before proposing a general form of interval training protocol aiming to improve the cardiovascular system for a specific age range. It may therefore be advantageous to investigate building, simulating and controlling an effective training protocol based on the experimental results to achieve the best and optimum performance of the cardiorespiratory system.

1.1 The objectives of the study.

The first primary objective of this study is to build an effective training protocol which will aim to improve the exerciser's cardiovascular fitness. The first step to achieve this objective is to investigate HR and VO_2 response dynamics to running exercises, as they are very important when building an effective training protocol, because observing these two factors can help predict the amount of energy spent during training protocols which are mainly used to determine goals such as fat burning or cardiovascular system improvement.

An embedded or specific objective within the previous one is concerned about combining incorporated variables in building an appropriate interval protocol with experimental results to create a proper interval training protocol to bring upon some of the benefits that have been mentioned before. The target here is to build two different training protocols for two different age groups.

The second primary objective of this study is to propose a switching electrical model, a switching RC circuit, to interpret the variations of time constant and steady state gain during onset and offset of treadmill exercise, which will be applied to simulate interval training protocol in Matlab Simulink.

Creating an adaptation process of our proposed interval training protocol is considered as a third primary or main objective of this study, the aim is to find a system model which combine discrete events and continuous responses and represent them as a complete model. The adaptation process aims to propose a multiloop PI control scheme which is responsible for tuning of the interval training protocol.

The goal of this adaptation process will be tuning the duty cycle as well as the period of the interval training protocol to achieve desired training effects.

The final objective of this study is to implement the created interval training protocol as well as the designed control scheme in one portable device. Interval training protocol and PI controller will be implemented and tested in low cost device which has limited computation power.

Our concerns will be improving the controller design to effectively adjust the training protocol structure to quickly reach the exerciser's desired setpoints with a minimum number of exercise sessions.

1.2 The methodology of the research.

To meet the objectives outlined in the previous section, the research efforts were divided into eight individual categories. These were:

1. A comprehensive literature review to identify the most accepted definitions of interval training and current construction techniques.

2. A stretched research to point out the benefits as well as the advantages of interval training compared with regular and constant training protocols.

3. Construction of practical experiments and identification of measurement techniques closely related to the common beneficial training exercises.

4. Organization of frameworks for collecting data from the subjects chosen for cardio respiratory dynamic characteristics investigation.

5. Equipment setup.

6. Data collection, analysis and evaluation of the data collected.

7. Construction of system models capable of modelling and simulating the exercise profiles based on selected assessment techniques.

As most scientists are aware, recruiting subjects to do experiments particularly when the research requires achieving many exercising sessions is extremely difficult. Fortunately, by convincing the participants that the research would be beneficial to them, that it was to help them improving their cardiovascular systems, we were able to apply the selected exercises in two major different age groups.

The data collection technique was carried out so as to have a minimal effect on both the participants and environment. We did not confine ourselves to the data collection and analysis; attempts were made to establish new methods of constructing, simulating and controlling training protocol based on specific purposes.

Relying on observation and experiment is the traditional methodology employed by scientists; however, experiments under laboratory conditions are sometimes difficult to conduct and control due to the impact of many exogenous variables. Simulations, on the other hand, allow for assessing the impact of changes in operating factors on the model. These previous techniques were devised with the thesis' objectives in mind.

1.3 An outline of the thesis.

This section of the study shows the order of the topics, their importance and relationship to each other. This study is organized as follows. Chapter 2 presents a general definition of cardiovascular fitness and shows how it reflects the capacity of the respiratory system. Section 2 and 3 provide the associated measurements of the fitness level as well as pointing out some indicators of the human cardiovascular fitness.

Two important indicators (heart rate and oxygen consumption) are well presented and explained in section 4 and 5 of this chapter, because these two important factors will be heavily used throughout this study.

Chapter 3 moves to another level of definition, it starts with defining the concept and nature of interval training. Section 2 as well as 3 demonstrate the health benefits due to the contribution of interval training and the advantages and disadvantages of such a training regime. Variables of interval training protocol are presented in section 4, to show how these variables can control different variations based on different needs and requirements.

Coming to the equipment and tools that have been used in this study, Chapter 4 gives a full description of them. Starting with the motor-driven treadmill and finishing with the programmable watch that has been used in the last part of this study.

Chapter 5 concentrates on the subjects participated in the experiment sessions, section 1 presents the characteristics of each subject. However, section 2, 3 and 4 illustrate the physiological and environmental factors that may have an impact or influence on the experiments results. These three sections also provide the preparation procedures as well as the experiment location conditions.

Experiments results are presented in chapter 6; the first two sections determine the protocols setup and the first order process structure. Raw data for both HR and VO_2 are presented in section 3, section 4 and 5 evaluate the results through a detailed discussion. Nevertheless, modelling results as well as dynamic characteristics are also investigated in this chapter.

In chapter 7 we demonstrate different approaches to creating the interval training protocol setup. Section 1 mentions the training zones and exercise intensity levels in addition to the maximum heart rate equation. New interval training based on the experiment results has been built in section 2, and in section 3, the interval setup has been developed to serve the cardiovascular system improvement.

Chapter 8 on the other hand, shows how to construct a simple RC circuit to simulate the proposed interval training protocol. Two new subjects participated in this part of the study to show the similarity between simulation data and experiment data.

Chapter 9 determines the adaptation framework, a hybrid system model has been presented to describe the adaptation process and a multi-loop proportional and integral controller has been proposed for the tuning of interval training protocol. The simulation results of the controller have been presented in section 5 showing that the output of the controller has reached the desired references or setpoints after 12 iterations.

In chapter 10, a new device or tool has been used to examine the functionality of the proposed controller that has been designed in chapter 9. A new experiment setup has been constructed to show that the controller itself can work under different environemnet once the parameters have been set in the right way. Section 3 presents the new experiment results. Finally, chapter 11 gives the conclusions.

1.4 Thesis contributions.

The significant of this study is characterizing the importance of training protocol and how it can be helpful in improving general health status. The contributions of this thesis are presented as follows:

Firstly, models of the dynamic characteristics of heart rate and oxygen consumption are built in a new setting by applying a technique in a new context. These constructed models help us evaluating the effects of a change in the regular training protocol parameters. The new models give us the ability to compare two important characteristics of each profile, the steady state gain and the time constant.

For better understanding, two models for each profile are built, onset and offset models, these two models demonstrate how different phases of exercise can affect the outcomes of the experiment results. The modelling information will be used in creating the second contribution of this thesis.

Another significant contribution of this study is to demonstrate a concept of an interval training showing that it is easier to implement and has more benefits as well as advantages than the regular training protocol. In addition to the experimental results, the modelling results are used to constructing the new proposed interval training protocol.

By combining the average values of heart rate and oxygen consumption characteristics with the maximum heart rate values, a new interval training protocol is created to improve the cardiovascular system performance. This new approach provides a technique for creating an interval training protocol for special purposes. It has been shown how it can be applied in practice and what its limitations are.

Thirdly, an existing principle such as an RC circuit is introduced to simulate the experimental model of the interval training protocol.

Simulation results give us the ability to understand in depth the switching behavior between different training segments within the training protocol.

Fourthly, a novel multi-loop integral control based approach has been presented for the adjustment of the proposed Interval Training protocol in order to handle the inter and intra differences of exercisers. The whole adjustment process is first treated as a hybrid system, and then has been simplified as a purely discrete problems [41][42].

The simplified discrete system has been further reduced as a two-input two-output static system. Then, a multi-loop integral controller is designed to regulate the key parameters of the Interval Training protocol. The general frame work of the proposed adjustment procedure can be applied to describe and adjust the characteristics of various exercise.

Lastly, the new interval training protocol and the PI controller are implemented on eZ430 Texas Instrument reprogrammable watch. This system implementation which is done on an easy to use and cheap programmable watch provides a freedom to the exerciser to get the benefits of his or her exercise by conducting a certain number of exercise sessions.

A set of experimental studies on the new implementation were conducted. These were conducted using the new proposed interval training protocol but with different exercising environment. Stairs climbing is used instead of running on a controlled treadmill. Results of these experiments provided useful information about interval training in free-living conditions, the validity of the controller designed and the hints for future work following this study.

Chapter 2

Cardiovascular Fitness

2.1 Definition of cardiovascular fitness.

Cardiovascular fitness is an indication of physiological status; it is defined as the maximal oxygen capacity measured during a strenuous exercise effort and is mostly determined by physical activity participation and genetic contributors [43]. Cardiovascular fitness reflects the capacity of the respiratory system and the ability to carry out prolonged exercise and has been considered a health marker at all ages [44]. One of the main purposes of this study is to build up an interval training protocol which can improve the cardiovascular system for two different age groups.

Cardiovascular fitness, also known as cardiorespiratory fitness, describes the ability of the heart, lungs as well as organs to deliver and consume oxygen during sustained physical activity. Regular exercise can increase the cardiovascular fitness as the heart becomes more efficient at pumping oxygen-rich blood to working muscles and body tissues [45].

Cardiovascular fitness is known to decline with advancing age [46]. However, this decline is variable among individuals. Studies have shown that older individuals present a lower cardiovascular fitness than younger ones with differences ranging between 12 and 30% [47]. Undoubtedly, cardiovascular fitness is associated with improved health status; improving cardiovascular fitness has a great impact on various health outcomes including cardiovascular diseases, cancer, diabetes and problems associated with aging.

2.2 Levels of fitness measurements.

Some common professional uses of the terms " physical activity ", " exercise " and " physical fitness " reveal a need for clarification in order to assess the fitness level. By defining the previous terms we can provide a framework in which this study can be interpreted and compared [48].

In general, physical activity is defined as any bodily movement produced by skeletal muscles that results in energy expenditure and positively correlated with physical fitness [49], it can be categorized into sports, household or other activities.

Accomplishing an activity requires a certain amount of energy which can be measured in kilojoules (kJ) or kilocalories (kcal), 1 kcal is equivalent to 4.184 kJ. Energy expenditure can be measured by either scales and varies continuously from low to high. The total amount of caloric expenditure associated with physical activity is determined by the amount of muscle mass producing bodily movements and the intensity, duration, and frequency of muscular contractions [50].

The amount of energy is subject to personal choice and may vary from person to person as well as for a given person over time. The most commonly used approach to categorize physical activity is to segment it on the basis of the identifiable portions of daily life during which the activity occurs [51].

The following general formula can be used to express the caloric contribution to the total energy expenditure due to physical activity [52]:

$$kcal_{\text{sleep}} + kcal_{\text{occupation}} + kcal_{\text{leisure}} = kcal_{\text{total daily physical acitivity}} \tag{2.1}$$

Leisure-time physical activity can be further subdivided into categories such as sports, conditioning exercises, household tasks and other activities [53].

Exercise as a term has been used interchangeably with physical activity [54], and they have common elements because both result in energy expenditure, vary continuously from low to high and are very strongly and positively correlated with physical fitness as the intensity, duration, and frequency of movements increase. However, exercise is a physical activity that is planned, structured, repetitive and purposive to improve and maintain physical fitness components.

The following formula is relating physical activity and exercise:

$$kcal_{\text{exercise}} + kcal_{\text{nonexercise}} = kcal_{\text{total daily physical acitivity}} \tag{2.2}$$

From the previous equation we can conclude that exercise is a subset of physical activity and may constitute all or part of each category of daily activity except sleep. Tasks regularly performed to develop muscular strength or to burn up calories are considered exercise.

In contrast with the previous two terms, physical fitness is a set of independent attributes that people have to achieve, some components such as cardio-respiratory fitness, muscular endurance, muscular strength and flexibility are closely related to health, while others such as coordination and body balance are more related to performance.

Being physically fit has been defined as "the ability to carry out daily tasks with vigor and alertness, without undue fatigue and with ample energy to enjoy leisure-time pursuits and to meet unforeseen emergencies" [55]. Maintaining high or moderate level of physical fitness is one of the most important protective factors against development of chronic diseases. Physical fitness can be assessed by number of field tests, however, our aim in this study is not to assess or measure the level of physical fitness, but to develop a training protocol which aims to improve the general fitness for different age groups taking into consideration the validity, feasibility and predictive value of physical fitness.

2.3 Indicators of human cardiovascular fitness.

VO_2 and HR are key indicators of functional health status; their measurements can aid early detection of cardiac diseases [56] [57]. Furthermore, these cardio respiratory endurances have long been recognized as one of the fundamental components of physical fitness. The more intense the activity, the faster your heart will beat and the larger oxygen volume will be consumed.

It is well known that HR is a valid measure of exercise intensity only if it reflects the metabolic rate which can be measured by c; this is because the increase in HR is directly related to the increase in oxygen consumption. It is the increase in oxygen delivered to the muscles during exercise that is related to improving aerobic capacity.

The relationship between HR and VO_2 has been used to predict maximal oxygen consumption and also used to estimate energy expenditure during physical activities. Both HR and VO_2 can give a fair reflection of the intensity of work that is being performed [58]. It is important to mention that HR and VO_2 are linearly related over a wide range of submaximal intensities, which means that both VO_2 and HR increase linearly with increasing exercise intensity up to near maximal exercise. Therefore, one of them can be utilized to estimate the other during physical activities. However, the relationship between HR and VO_2 becomes non-linear during light and very highly intense activity [57].

VO_2 and HR are also important when building an effective training protocol, because observing these two factors can help predict the amount of energy spent during training protocols which mainly used to determine goals such as fat burning or cardiovascular system improvement. This study aims to develop an effective training protocol to improve cardiovascular fitness based on modeling and analysis of HR and VO_2 dynamics. Both HR and VO_2 were monitored and recorded using a portable gas analyzer $K4b^2$.

2.4 Heart rate.

Hear rate can be expressed as how fast the heart is beating; it is the number of heartbeats per unit of time. The measurement unit of heart rate is beats per minute (bpm). Heart rate or HR can be measured manually by counting the pulse at the wrist or neck; it can be measured precisely by using a heart rate monitor which usually fits around the chest. Heart rate monitors are mainly used to determine the exercise intensity of a training session and have become a widely used training aid for a variety of sports during the last two decades. HR is easy to detect and monitor compared with other indications of exercise intensities, and heart rate monitors are relatively cheap and can be used in most situations.

For more detailed information about the heart, an ECG (electrocardiogram) can be taken. Willem Einthoven, a Dutch physiologist developed the first electrocardiograph at the start of the 20th century. ECG provides information about the electrical activity in the HR, it is composed of three sections, a P wave, a QRS wave and a T wave. These waves represent the depolarization of the atria, depolarization of the ventricles and repolarization of the ventricles respectively. The figure below shows a healthy ECG trace.

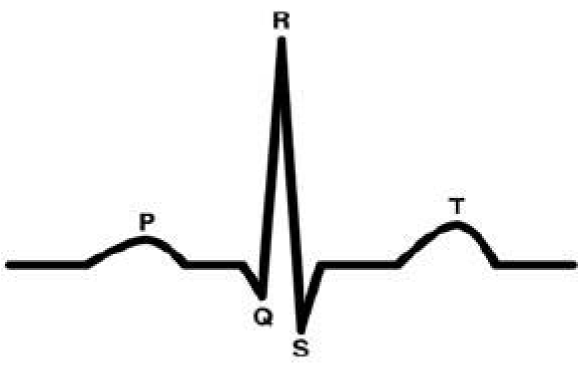

Fig. 2.1: ECG Trace.

HR has become the most commonly used method to get an indication of the exercise intensity. As mentioned before, it is easy to monitor and shows a very stable pattern during exercise. A recent study has provided a general classification of physical activity intensity based on heart rate reserve ($HR_{reserve}$) and maximum heart rate (HR_{max}) to express intensity [59].

Heart rate reserve is used to measure the intensity of the exercise, it is the difference between the maximum and the resting heart rate, a great difference leads to a large heart rate reserve and as a consequence a great range of potential training heart rate intensities, 40-85 % of $HR_{reserve}$ is recommended for exercise prescription [60]. It can be noted as:

$$HR_{\text{reserve}} = ([HR_{\text{max}} - HR_{\text{rest}}] \times Intensity) + HR_{\text{rest}} \tag{2.3}$$

Resting heart rate indicates the basic fitness level as well, and is expressed as the number of heartbeats in one minute at complete rest but awake. The typical resting heart rate in adults is 70-80 beats per minutes [61].

HR_{max} on the other hand, is the most useful tool in determining training intensities, it is the highest number of times the heart can contract in one minute and depends on age. Cardiac stress test is used to accurately measure HR_{max}.

According to [62], at this time there is no acceptable method or equation to estimate HR_{max}, and if HR_{max} needs to be estimated, then a population specific formula should be used. However, the most accurate general equation to estimate HR_{max} is that of Inbar [63]:

$$HR_{\text{max}} = 205.8 - 0.685 \times (Age) \tag{2.4}$$

Determining an actual HR_{max} is the key to constructing a well-designed training program. Therefore, Chapter 7 will provide intensive explanation about the importance of HR_{max} in building and assessing training protocols.

The table below shows the training zones and their corresponding value of HR_{max}.

Table 2.1: Exercise Intensity Levels that Coincide with HR_{max}.

Category	**%$\mathbf{HR_{max}}$**
Fat Burning (Low)	<70
Aerobic (Moderate or Vigorous)	70-80
Anaerobic (Very Vigorous)	>80

2.5 Oxygen consumption.

To carry out any kind of exercise, the body needs certain amount of oxygen. The amount of oxygen that a person uses can be easily measured; it equals the difference between the air he breathes out and the air he breathes in. VO_2 is defined as the maximal rate at which oxygen can be consumed by the body per minute [64], it is the ability to deliver and extract oxygen. VO_2 or maximal oxygen uptake is a key indicator used to measure cardiovascular fitness and efficiency. VO_2 is expressed with Fick equation; the principle is that at steady state the uptake of oxygen by an organ is the product of the blood flow through that organ and the arteriovenous concentration difference of the substance [65]. The direct Fick technique(oxygen uptake) is:

$$VO_2 = CardiacOutput(Q) \times VO_{2\ \text{Difference}} \tag{2.5}$$

Where:

$$VO_{2\ \text{Difference}} = CaO_2 - C\bar{v}O_2 \tag{2.6}$$

And:

Q: is the total volume of blood pumped by the heart per unit time.

CaO_2 : is the oxygen content of arterial blood.

$C\bar{v}O_2$: is the oxygen content of mixed venous blood.

On the other hand, the maximum amount of oxygen a person can use is called VO_{2max}; this variable measures the exercise capacity and reflects the physical fitness of the individual. How well the individual can use oxygen to produce energy is defined as fitness and it depends on many factors such as the size of the lungs and their ability to get air in, the strength, rate as well as the size of the heart, the blood volume and oxygen carrying capacity, the muscle size and its efficiency of extracting oxygen.

Maximal oxygen consumption or maximal oxygen uptake is defined as the maximum capacity of an individual's body to transport and use oxygen during exercise, it can be expressed either as an absolute rate in liters of oxygen per minute (l/min) or as a relative rate in millimeters of oxygen per kilogram of bodyweight per minute (ml/kg/min). Fitter people have a higher VO_{2max} than normal or untrained people, the average is around 35-40 ml/kg/min, but fit individuals can reach up to 90 ml/kg/min.

Accurately measuring VO_{2max} involves a physical effort and can be done via various methods. The first method is done within a laboratory and involves using treadmill or bike to measure the oxygen concentration in the inhaled and exhaled air during graded exercise test. The second method is within free environment field and in this method there is no control on the movement of the exerciser, and VO_{2max} is reached when oxygen consumption remains at steady state despite an increase in the exercise intensity.

The third method is called direct method which uses gas analyzer such as $K4b^2$ to measure the level of oxygen during exercise. Although this method is accurate, the problem is within the analyzer itself, because it is very expensive to have such equipment.

Measuring VO_{2max} can be dangerous when individuals are not considered healthy subjects. Therefore, an indirect or predicted method of measuring VO_{2max} is used in these cases. This method depends on developing protocols to estimate the VO_{2max} from another variable such as heart rate.

The tests are similar to a VO_{2max} test but they are not carried out till reaching the maximum of the cardiovascular systems and that's why they are called submaximal tests or maximal exertion tests.

The increase in HR is related to the increase in oxygen consumption. It is the increase in oxygen delivered to the muscles during exercise that is related to improving aerobic capacity. Both VO_2 and HR increase linearly with increasing exercise intensity and the relationship between each other has been used over the last 60 years to estimate VO_{2max}.

The estimation of energy can also be based on the relationship between HR and VO_2, however, the accuracy of predicting both energy and VO_2 has limitations because the relationship is curvilinear at very low and very high exercise intensities.

VO_{2max} predicted from submaximal HR is within 10-20% of the actual VO_{2max} [66], this large percentage is still suitable for measuring individuals who have difficulties in finishing or performing maximal graded test such as elderly and pregnant women.

The table below shows the relationship between VO_{2max} and HR_{max} [67].

Table 2.2: Relationship Between HR_{max} and VO_{2max}.

%HR_{max}	**%VO_{2max}**
<60	<40
60-70	41-55
71-80	56-70
>80	>70

The next table shows the training zones and their corresponding value for VO_{2max}.

Table 2.3: Exercise Intensity Levels that Coincide with VO_{2max}.

Category	**%VO_{2max}**
Fat Burning (Low)	<50
Aerobic (Moderate or Vigorous)	~50-70
Anaerobic (Very Vigorous)	>70

As mentioned before, a linear relationship between VO_2 and HR exists during moderate intense activity and that's why this study will target the aerobic zone (70-80% of HR_{max} or 50-70% VO_{2max}) which aims to develop the exerciser's cardiovascular system.

2.6 Conclusion.

Cardiovascular fitness is an indication of physiological status; it has been considered a health marker at all ages. Regular exercise can increase the cardiovascular fitness as the heart becomes more efficient at pumping blood to muscles and body tissues.

Physical activity is defined as any bodily movement produced by skeletal muscles; it can be measured by calculating a certain amount of energy required to accomplish a specific activity. Being physical fit means maintaining high level of physical fitness.

This study concentrates on two important key indicators of functional health status, HR and VO_2. The relationship between these two indicators has been used to predict maximal oxygen consumption and energy expenditure during physical activities.

HR and VO_2 are linearly related over a wide range of submaximal intensities. However, the relationship becomes non-linear during light and very highly intense activity.

HR has become the most commonly used method to get an indication of the exercise intensity, it is easy to detect and monitor compared with other indications of exercise intensities. HR_{max} is the key to constructing a well-designed training protocol. Different exercise intensity levels such as fat burning, aerobic and anaerobic can coincide with HR_{max}.

Maximal oxygen consumption or maximal oxygen uptake is the maximum capacity of an individual's body to transport and use oxygen during exercise. Direct method of measuring using a gas analyzer was used in this study to measure the level of oxygen during exercise. Different exercise intensity levels can also coincide with VO_{2max}.

Chapter 3

Concept and Definition of Interval Training

3.1 Nature and definition of interval training.

One of the most effective training regimens is called interval training which was first described by Reindell and Roskamm and was popularized in the 1950s by the Olympic champion, Emil Zatopek. However, Swedish physiologist Per Oløf Astrand's study in 1960 was the first scientific study on interval training. Since then, it has been the basis for athletic training programs for many years.

Nowadays, interval training method becomes a well known exercise protocol which helps strengthen and improve one's cardiovascular fitness. Previous researchers in this area [68][69] have investigated the effectiveness of interval training and its importance in improving factors associated with O_2 transport along with muscle uptake.

Classic interval training consists of interleaving high intensity exercises with rest periods. It alternates periods of maximal or near maximal effort with short periods of complete rest. Interval training simulates moderate to low variation in energy transfer intensity through specific spacing of exercise and rest periods. Because of frequent rest periods, interval training permits the person to perform more exercise than in continuous training.

Any interval training protocol has at least three different periods, warm-up, exercise (switching between high intensity period and recovery period) and cool-down.

Factors such as exercise interval intensity, duration, recovery interval duration and repetitions of exercise-recovery interval are needed to formulate each interval training protocol. Going from low-to-high training intensities and vice versa within the exercise zone is crucial to achieving optimum results for cardiovascular system improvement. The idea behind this approach is the ability to perform a greater volume of work at a higher intensity by breaking up a set amount of work into smaller segments.

With this protocol, the person trains at high exercise intensity with minimal fatigue that would normally prove exhausting if done continuously. By performing interval training exercise, we keep changing the status of the body movement within the exercise regime. Therefore, the heart keeps predicting and accordingly spending more energy to cope with these frequent changes. These changes place an overload on the heart, which strengthens it.

There are three general categories of interval training:

1- Anaerobic or short interval training:

This category consists of work intervals lasting 5 to 30 seconds; it is used to develop muscular strength as well as muscular power and relies on the immediate energy system. This type of exercise is performed at or above race pace and is proved to improve and develop the exerciser speed. Usually the rest periods last from 3 to 6 minutes in this category to avoid high level of lactic acid accumulation in the skeletal muscle and blood.

2- Anaerobic-aerobic or intermediate interval training:

The work intervals in this category last between 30 s and 2 minutes, the training itself performed at high intensity race pace. It relies on breaking down the polymerase chain reaction and anaerobic glycolysis for energy production.

Longer rest periods (several minutes) are needed in this category to remove the very high muscle and blood lactic acid levels.

3- Aerobic or long interval training :

This type of training consists of work intervals lasting between 2 and 5 minutes and relies on aerobic system for energy enzyme production. The changes in the oxidative capacity of muscle, especially ST and FT fibers are induced by the long intervals. Long interval training enhances lactic acid removal as well as oxidation.

The table below shows the interval training categories and their corresponding variables:

Table 3.1: Interval Training Categories and Variables.

Variable	**Short Interval**	**Intermediate Interval**	**Long Interval**
Work interval	5-30 s	30-120 s	2-5 min
Intensity/Pace	>95% race pace	90-95% race pace	60-90% VO_{2max}
Rest interval	3-5 times work interval	2-3 times work interval	1-2 times work interval

Table 3.2 below shows the interval training categories and their corresponding predominate energy system.

Table 3.2: Interval Training Energy System.

Category	**Major Energy System**
Short interval	Immediate
Intermediate interval	Anaerobic glycolysis
Long interval	Oxidative

Table 3.3 shows the interval training categories and their corresponding major effects.

Table 3.3: Interval Training Major Effects.

Category	**Major Effects On:**
Short interval	Speed and power
Intermediate interval	Speed and power, muscular endurance, lactic acid buffering and tolerance
Long interval	Cardiorespiratory endurance, muscular endurance, lactic acid removal

The three previous tables have been compiled from Rushall and Pyke 1990 [70].

3.2 Health benefits due to the contribution of interval training.

It is very well known that undertaking and participating in physical activity are associated with a reduced risk of many diseases. Researches show that for adults to attain health benefits, they should accumulate at least 30 minutes of moderate-intensity exercise on most days of the week [71].

Interval training has been proven to increase the ability to do short spurts of high-intensity aerobic activity and also to improve the aerobic fitness. This form of training may provide health as well as fitness benefits [72][73]. Furthermore, interval training has been shown to improve maximum oxygen consumption and endurance performance in active individuals [74][75][76]. It raises skeletal muscle enzyme activity [76][77], improves vascular health [78] and decreases risk of cardiovascular-disease in obese adolescents [79].

Additionally, interval training increases proteins that transport fatty acids across the mitochondrial membrane [80]. Interval training showed improvements in glycolytic and oxidative enzyme content and activity [81][82], a study showed that after one week of interval training; skeletal muscle glucose transporter 4 content has considerably increased [83].

In the same way, β-hydroxyacy1 coenzyme A dehydrogenase activity, which is responsible of catalyzing a key rate limiting step in fat oxidation has also increased after six weeks of interval training sessions [74]. A recent study reported that interval training improved peripheral vascular structure and function and showed that insulin sensitivity was increased in group of young men after two weeks of interval training intervention [84][85]. This study aims to develop an effective training protocol to improve cardiovascular fitness based on modeling and analysis of HR and VO_2 dynamics.

3.3 Advantages and disadvantages.

As mentioned in the previous section of this chapter, interval training has a number of benefits to exercisers and individuals, it improves anaerobic metabolism and can enhance maximal oxygen consumption, and it specifically teaches an endurance athlete the race pace. Interval training is an effective way to target an athlete's deficiencies. However, depending upon how this training regime's variables are manipulated, it appears to be extremely demanding and requires a reasonable fitness level.

Interval training offers several advantages over continuous training. It allows and permits the exerciser to perform more exercise than in continuous one. As a consequence, this form of exercise improves the fitness as well as the recovery time which is crucial for athletes in high-fitness demanding sports such as tennis, hockey and soccer where you need continuous stops and starts.

Research confirms that interval training improves fitness in much less time than the normal or continuous training. Risks such as overuse injury, muscle soreness and an abnormal response do not exist in interval training protocol. However, interval training sessions are longer than the continuous training ones and this due to the rest periods within the exercise regime itself.

On the other hand, interval training puts a high load on the exerciser's cardiovascular and musculoskeletal systems. Therefore, it is not recommended for anyone with lung, heart or cardiorespiratory problems. It might increase the risk of overtraining which is a major setback for most of the athletes. Symptoms such as loss of strength speed, endurance or other elements of performance may appear while participating in interval training protocol. If you decided to perform interval training without any reasonable fitness level, you might feel something unusual like loss of appetite as well as inability to sleep well. Interval training can cause chronic aches and pains and some kind of fatigue.

3.4 Variables of interval training protocol.

Any interval training protocol has at least three different periods, warm-up, exercise (switching between high intensity period and recovery period) and cool-down. Going from low-to-high training intensities and vice versa within the exercise zone is crucial to achieving optimum results for cardiovascular system improvement. The most important incorporated variables in building an appropriate interval protocol are time (or distance), intensity level (onset speed level), time of each recovery period (offset) and number of repetitions within the exercise period. This study shows how combining the previous variables with the experiments results can create proper intervals training protocol to bring upon some of the benefits that have been mentioned before. The table below shows examples of different types of interval training which have been used to improve aerobic and anaerobic capacity, where R = recovery between series; vVO_{2max} = velocity of maximal oxygen uptake; vxm = average velocity over x meters [26].

Table 3.4: Different Types of Interval Training Classification.

Intensity(% vVO_{2max})	**Anaerobic Training**	**Aerobic Training**
115-130	-6x30 sec; R=30 sec(rest); -60 sec, -45 sec, -30 sec, -45 sec, -60 sec; R=5 min(rest)	-20x10 sec; R=10 sec(rest)
105-115	-6x1 min; R=3 min(rest); -3x500m at v1500m; R=3min(rest)	-15x15 sec; R=15 sec at 50% vVO_{2max}
100-105	-3x1000m at v3000m; R=3 min(rest)	-20x15 sec; R=15 sec at 50% vVO_{2max}
95-100	-5x1000m at v5000m; R=3 min(rest)	-25x15 sec; R=15 sec at 50% vVO_{2max}; -6x3 min; R=3 min 50% vVO_{2max}
90-95		3x3000m at v10000m; R=3min(rest)
85-90		-2x20 min; R=3 min at 70% vVO_{2max}
80-85		-2x30 min; R=3 min at 70% vVO_{2max}
75-80		2x15 km; R=1 km at 70% vVO_{2max}

3.5 Conclusion.

Interval training has become the basis for athletic training programs for many years. It was firstly described and scientifically studied in 1950 and 1960 respectively. Interval training consists of interleaving high intensity exercises with rest periods, it simulates moderate to low variation in energy transfer intensity through specific spacing of exercise and rest periods.

The basic structure of interval training can be determined by three different periods, warm up, exercise and cool down. Interval intensity, duration, recovery duration as well as repetitions are needed to formulate the interval training protocol.

There are three general categories of interval training; each one has its major corresponding effects such as speed, muscular endurance and lactic acid removal.

Interval training has been proven to improve the general fitness; it offers several advantages over the continuous training. However, interval training is not recommended for anyone with lung and heart problems because it puts a high load on the exerciser's cardiovascular and musculoskeletal systems.

The most important incorporated variables in building an appropriate interval training protocol are time, intensity and number of repetitions. This study shows how combining these variables with the experimental results can create proper interval training protocol.

Chapter 4

Tools and Equipment

4.1 Motor-controlled treadmill.

The system which has been recruited in the first part of our experiments is composed of a treadmill and a computer. A Full Vision Inc MdI TMX425 motor-driven treadmill with a DC motor was used for the training protocol. The treadmill allows speed in the range 0.8-19.3 (step 0.1) km/h, gradients from 0 to + 15 %(step 0.1), and a maximum acceleration of 5 m/s^2 [86].

The treadmill is controlled by the computer via an RS-232 serial port; both speed and gradient are controllable externally via this link. The control software, programmed in Labview, used the serial port to control the treadmill. The system is complemented by a safety harness, safety siderails, and the emergency stop switch.

4.2 Portable gas analyzer K4b^2.

All laboratory analyses in this study were performed using a portable gas analyzer (K4b^2, Cosmed). The K4b^2 gas analyzer was used because it has previously been reported to be valid, accurate and reliable [87], [88]. The Cosmed K4b^2 employs a breath by breath, gas exchange measurement system. The portable unit, which is powered by a rechargeable battery attached to the back side of a harness, contains the O_2 and CO_2 analyzers, sampling pump, UHF transmitter, barometric sensors and electronics.

The O_2 analyzer has a measurement range of 7-24% O_2 and accuracy to 0.02% O_2, The CO_2 analyzer has a measurement range of 0-8% CO_2 with accuracy to 0.01% CO_2. Both analyzers with a rapid response of <150 ms per 90% full scale are flow dependent, thermo-stated as well as compensated for variations in pressure and temperature.

Before using the $K4b^2$, the system must be warmed up for at least 30 minutes. During the warm up period, the device must be powered on and calibration and/or testing procedures should never be performed until the warm up period has been completed.

Following the warm up, a calibration of both the turbine and gas analyzer is taking place. Flow and volume calibrations of the ID18 turbine are performed with a 3 liters calibration syringe, flows and volumes are measured by the bidirectional digital turbine, which offers a very low resistance to flow. Air passing through the helical conveyors causes the spiral rotation of the turbine rotor. The rolling blade interrupts the infrared light beamed by the three diodes of the optoelectronic reader. The turbine flowmeter does not require a daily calibration since it is not affected by pressure, humidity and/or temperature. However, regular calibrations should still be performed to assure that the system is acquiring reliable measurements.

To obtain accurate measurements, it is essential to configure the correct gas concentration values before beginning the analyzer calibration, and that is including setting the values of O_2 and CO_2 of the room air, the mixture contained in the gas calibration cylinder and the volume of the calibration syringe (3 liters in our case).

Analyzer calibration involves three types, room air calibration, reference gas calibration and delay calibration. The room air calibration, forced by the system before every test, consists of a sampling room air. It updates the baseline of the CO_2 analyzer and the gain of the O_2 analyzer, in order to match the readings with the predicted atmospheric values (20.93% for O_2 and 0.03% for CO_2).

The reference gas calibration, is recommended to be carried out daily, consists of sampling a gas with a known composition (i.e. 16.00% for O_2 and 5.00% for CO_2) from a calibration cylinder, and updating the baseline and the gain of the analyzers in order to match the readings with the predicted values (i.e. 16.00% for O_2 and 5.00% for CO_2). The delay gas calibration is the measurement of time required by the gas to reach the gas analyzer, it must be carried out each time some changes occur in the sampling system, i.e. when the sampling tube is changed. However, it is recommended to carry out this calibration each week in order to prevent wrong measurements.

For " Breath by Breath " analysis, it is essential that the instantaneous flow rate must be multiplied by the proper time-matched expired gas concentration. Although flow can be instantaneously measured, gas concentration measurements can be calculated with a delay related both to the time necessary for the gas to be transported to the sensor and to intrinsic characteristics of the analyzer principle.

Two factors contribute to the time alignments delay. $K4b^2$ uses a capillary sampling tube with a pump to draw a continuous gas sample into the analyzers. The gas transport time depends on the dimensions of the tube and on the pump flow rate. Additionally, the gas sensors have a response time that must be added to the above delay for calculating the total delay. The software of the $K4b^2$ - by carrying out the gas delay procedure - calculates this delay and introduces a correction to realign both flow and gas measurements.

$K4b^2$ is a versatile system. It can be used in the field or in the lab without any kind of limitation. Test can be carried out in the following three different configurations:

1- Holter Data Recorder.

This mode gives the ability to use the system in a free environment field without the receiver unit. The PU itself can store data "Breath by Breath" in high capacity memory

(1 MB). The memory allows to store up to 16 thousand breaths. All of the test results can be downloaded to the PC via the RS-232 port provided with the equipment once the tests are completed.

2- Telemetry Data Transmission.

The PU is provided with a small transmitter that allows sending data by telemetry. All data are transmitted " Breath by Breath" to the receiver unit. The receiver unit must be connected to a PC by serial port; it allows the researcher to monitor data on line both in table and graphic format. All tests are stored in the memory of the portable unit, thus in case of transmission interferences, no data will be lost.

3- Serial (Laboratory) Station.

Although $K4b^2$ has been designed for tests in a free environment field, it can also be used as a conventional laboratory station as it offers the same features of the best stand alone device. Under this operating mode, the PU is simply connected to the PC through the RS-232 serial port, and all functions are still the same and can be controlled via this serial link, exactly like any conventional laboratory device.

The serial laboratory station mode has been used in this study. However, future studies will be based on the first two modes as well. The serial mode consists of the following parts:

1- Mask and flowmeter.

2- Heart rate belt.

3- Rechargeable battery.

4- Harness.

5- $K4b^2$ unit.

6- HR probe.

7- Power cable.

8- Receiver unit.

9- RS-232 cable.

10- Personal computer.

The figure below shows the required parts in addition to the PU to operate the current study's tests.

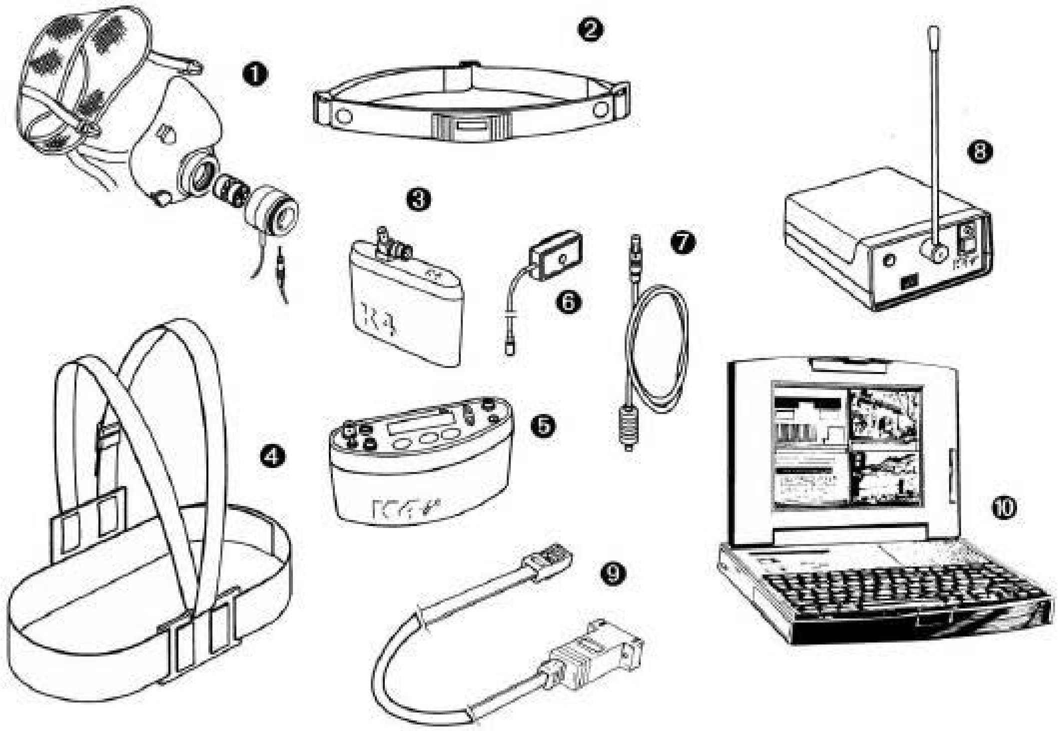

Fig. 4.1: Serial Mode Required Parts.

Before each test, the following sequence has to be followed to make sure the measurements are reliable and accurate.

Warming up the system ⇒ Connect the PU to PC ⇒ Calibrate the system ⇒ Enter participant data ⇒ Start the test ⇒ Stop the test. [1]

4.3 Monitoring and recording software and PC.

$K4b^2$ recommends the following configurations to function properly; these configurations are the minimum which assure that the monitoring software is working without any crashes or faults. [1]

- Pentium II 350 MHz.
- Windows XP, Vista 32 bit.
- 64 Mb RAM.
- HD with 50MB free space.
- CD drive.
- VGA, SVGA monitor.
- USB or RS-232 port available.
- Any mouse and printer compatible with the MS Windows™ operating system.
- PC conform to European Directive 89/336 EMC.

$K4b^2$ monitoring and recording software consists of two programs, a spirometry program and a program for ergometry. These two programs share the same archive and system calibration application. Once the installation process is complete, a Cosmed program group will be added to the Windows **Start/Programs**, and a dialog box will be automatically opened the first time the software is used.

Ergometry program which is specialized in Cardiopulmonary Exercise Testing (CPET) has been used in this study. The CPET software may display several windows at one time. The active window will always be highlighted with a different color and certain functions of this software will only be applied to the current "**Active window**". Figure 4.2 shows the CPET software user interface.

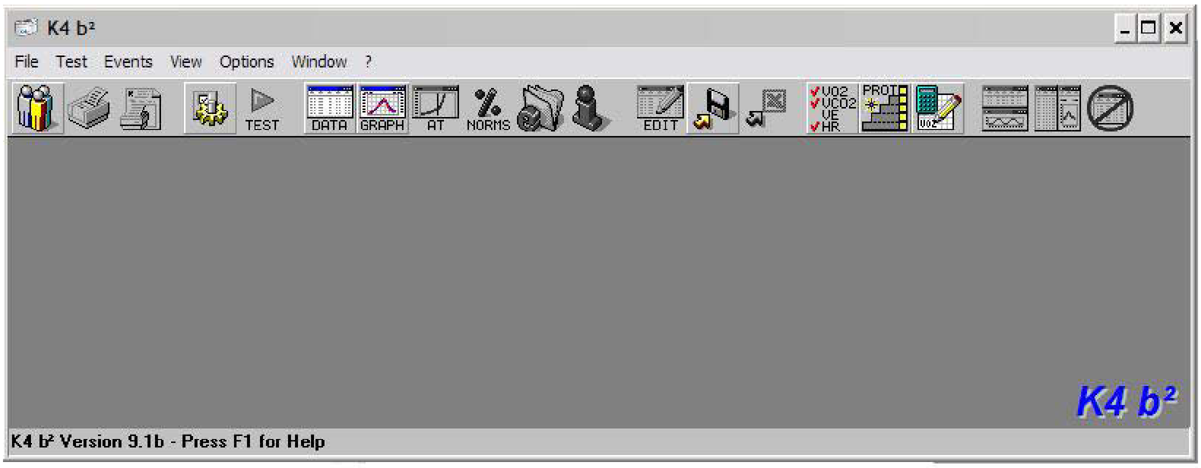

Fig. 4.2: CPET Software User Interface.

Control panel dialogue is an important and useful tool on the software user interface to check the main hardware functions of K4b^2. Using the control tabs on the control panel dialogue gives us the ability to read the signals acquired by the system both as voltages ad processed data and to activate/deactivate the valves, the sampling pump and other installed components which are considered as a good indication about the status of the hardware. The figure below shows the interface of the control panel dialogue.

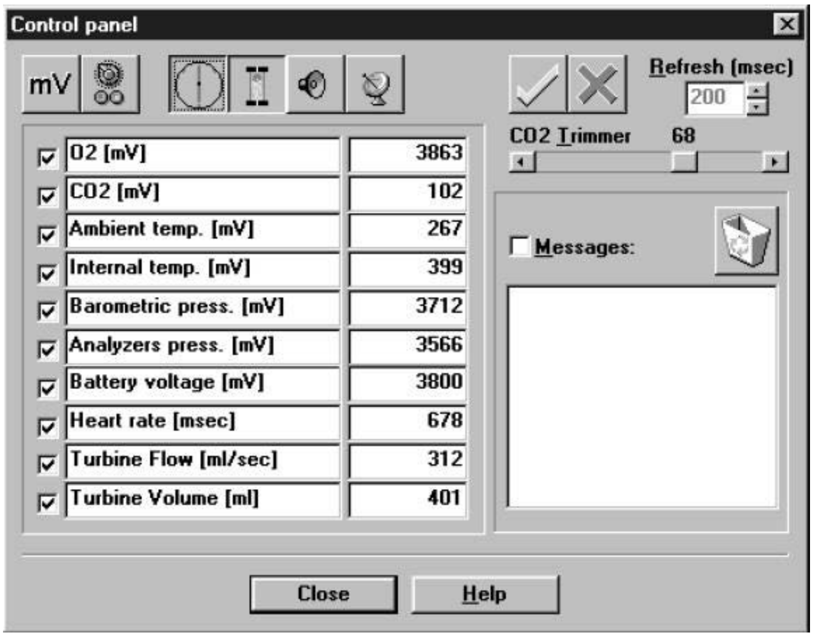

Fig. 4.3: Control Panel Dialogue.

4.4 eZ430 Texas Instrument programmable watch.

The eZ430-Chronos is a highly integrated, wireless development system that provides a complete reference design for developers creating wireless smart watch applications. Based on the CC430F6137 <1 GHz RF SoC, the eZ430-Chronos is a complete CC430-based development system, featuring a 96 segment LCD display and provides an integrated pressure sensor and 3-axis accelerometer for motion sensitive control. The eZ430-Chronos watch may be disassembled to be reprogrammed with a custom application and includes an eZ430 USB programming interface.

Code Composer Studio (CCS) v4 software has been used in this study to customize the Chronos eZ430 watch, Code Composer Studio is based on the Eclipse open source software framework. The Eclipse software framework is used for many different applications but it was originally developed as an open framework for creating development tools.

CCS v4 combines the advantages of the Eclipse software framework with advanced embedded debug capabilities from Texas Instruments resulting in a compelling feature rich development environment for embedded developers. The watch itself comes with a chest strap for heart rate monitoring from BM Innovations, it sends the measured values to eZ430 watch, which in turn will run the customized software. The figure below shows the eZ430-Chronos watch with its USB programming interface. [89]

Fig. 4.4: Texas Instruments eZ430-Chronos Watch.

The watch comes with some basic functions, such as time, date, alarm and stop watch. Four integrated sensors are embedded inside the watch, these sensors are, 3-Axis Accelerometer, pressure sensor, temperature sensor and battery/voltage sensor. The sensors are responsible for measuring and displaying the altitude, the body temperature as well as the speed of the exerciser. Some functions like the fitness functions require a compatible heart rate strap to be attached to the body of the exerciser. BM innovations heart rate strap is required to operate functions like heart rate, running speed, distance traveled and calories burned.

The watch can work in a wireless mode, three preconfigured wireless modes are implemented for this purpose, the first one is the ACC mode which is used to transmit accelerometer motion data, the second one is the PPT mode which is responsible for wireless presentation control or bind Chronos keys to PC keyboard shortcuts. The third and last mode is the Sync mode; which synchronizes time and data with PC and calibrates temperature and altitude. The figure below shows the eZ430 control center user interface, it provides a variety of demos. However, it can be used as a real-time monitoring tool for heart rate and speed in three directions.

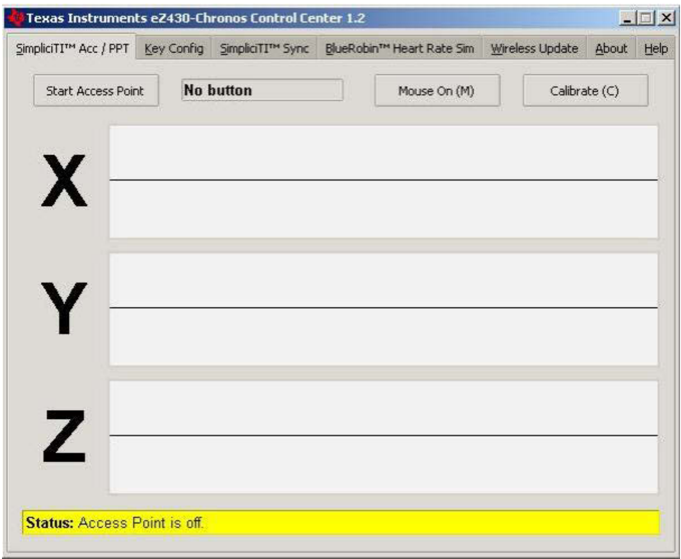

Fig. 4.5: eZ430-Chronos Control Center User Interface.

4.5 Conclusion.

A motor driven treadmill with a DC motor was used in the first part of this study. The treadmill was controlled by a computer via a serial port; both speed and gradient were controllable via this link.

All laboratory analyses were performed using a portable gas analyzer $K4b^2$, it is valid, accurate and reliable to use. The gas analyzer needs to warm up at least 30 minutes before performing any kind of calibration or test. Analyzer calibration involves three types, room air, reference gas and delay calibration. The purpose of the calibration process is to update the baseline to match the readings with predicted values.

$K4b^2$ is a versatile system; it can be used in the field or in the lab without any kind of limitations. Experiments and tests can be carried out in three different configurations. Holter data recorder; where the analyzer is used without the receiver unit, the telemetry data transmission mode; where the build-in transmitter sends data by telemetry, and the last configuration is serial or laboratory station; where the analyzer is used as a conventional laboratory station as it offers the same features of the best stand alone device.

Cardiopulmonary Exercise testing (CPET) software has been used to real-time monitoring of the recorded data.

eZ430 Texas Instrument programmable watch has been used in the controller implementation part of this study. The watch may be disassembled to be reprogrammed with a custom application and it can work in three wireless modes.

Chapter 5

Subjects Characteristics and Experiments Preparation

5.1 Characteristics of the subjects.

This section is all about pointing out the characteristics of the participants who participated in a certain number of experiments to investigate the characteristics of the key indicators. Two different age groups have been chosen: the first one is referred to as Group A (for a number of young healthy male subjects), which consists of eight healthy non-smoking males aged 29.38 ± 2.06 years, and the second one is referred to as Group B (for a number of old healthy subjects) which consists of twelve healthy non-smoking males aged 45.4 ± 5.9 years.

All participants were free from any known cardiac or metabolic disorders, hypertension, and were not under any medication. The University of Technology-Sydney (UTS) approved the study and an informed consent was obtained from all participants before each experiment.

Subjects in both groups were familiar with a motor-controlled treadmill. Group A had a mean age 29.38 year (Range 26-32 years), a mean weight 74.5 kg (Range 55-90 kg), and a mean height 173.25 cm (Range 164-180 cm). Group B had a mean age 45.4 year (Range 36-53 years), a mean weight 91.9 kg (Range 71-102 kg), and a mean height 178 cm (Range 170-186 cm).

The aim of choosing two different age groups is to expand the benefit of investigating HR and VO_2 by creating two different training protocols based on the age range to improve the cardiovascular system. The physical characteristics of the participants in each group have been recorded, presented as well as used in creating the interval training protocol setup. The physical characteristics of the participants of Group A and Group B are presented in Table 5.1 and Table 5.2 respectively, where SD is the standard deviation.

Table 5.1: Group A Physical Characteristics.

Subjects	**Age(yr)**	**Height(cm)**	**Weight(kg)**
1	27	175	55
2	32	170	87
3	29	176	90
4	29	178	77
5	32	174	79
6	29	164	64
7	31	169	67
8	26	180	77
Mean	29.38	173.25	74.5
SD	2.06	4.92	11.05

Table 5.2: Group B Physical Characteristics.

Subjects	**Age(yr)**	**Height(cm)**	**Weight(kg)**
1	40	173	102
2	45	179	97
3	45	173	101
4	37	170	71
5	53	183	99
6	45	182	98
7	36	186	92
8	53	175	89
9	45	180	94
10	43	178	100
11	50	182	86
12	53	173	73
Mean	45.4	178	91.9
SD	5.9	0.05	10.5

5.2 Experiments location.

All experiments have been performed at Center for Health Technologies (CHT), level 18 building 1, University of Technology, Sydney (UTS). Experiments were conducted in controlled laboratory environment and at the same hour of the day between 9.30 a.m. and 13.30 p.m. every day for eliminating the specific dynamic action of food for all practical purposes. The room in which experiments were performed was large enough to accommodate the necessary equipment and allow access to the participant in case of an emergency.

A thermometer and a hygrometer were presented in the experiment area and monitored regularly. The subject's heart rate and perceived exertion may rise with increased temperatures and/or humidity levels greater than 60%, which may lead to variable cardiovascular responses. An adequate temperature for testing conditions was 22° Celsius, but temperatures as high as 26° Celsius may be acceptable with efficient air ventilation.

Both treadmill and portable gas analyzer were neither operated near explosive substances nor installed near electrical or magnetic devices such as x-ray equipment, transformers or power lines. All equipment are not AP or APG units (according to EN 60601-1) and were never operated in the presence of flammable anesthetic mixtures. The room attributes did assure that all equipment were operating under normal environmental temperatures and conditions. Atmospheric pressure range was within 600 mBar and 1060 mBar.

All equipment especially the portable gas analyzer were not operating in the presence of noxious fumes or in dusty environments and they were not placed near heat sources. Adequate floor space and easy access to the exerciser during training were essential and adequate ventilation was maintained in the room where the experiments were performed.

5.3 Physiological and environmental factors.

Numerous factors may affect the response to exercise, and therefore the results of any experiment. Factors such as altering the exercise itself, altering the environment and individual responses have a big and effective impact on the experiments results. Even under controlled conditions, a study shows that changes of 2-4 beats/min are likely to occur when participants are measured on different days [90]. In addition, several physiological factors such hydration status, ability to get rid of excess heat as well as genetics influence the VO_2 and HR responses to exercise and therefore, monitoring exercise intensity will become more and more unreliable.

Both ambient and core temperatures can have a large influence on the relationship between HR and VO_2, because when exercise is performed in hot conditions, core temperature increases due to the poor efficiency of heat loss mechanisms. As a consequence, both HR and VO_2 will be different at the same exercise intensities [91][92]. Exposed to a cold environment on the other hand would have its word when exercising. Studies show that HR will be similar to that in thermo neutral conditions [93]. However, VO2 will be higher during cool conditions [94][95].

Performing an exercise at different altitudes affect HR and VO_2. At a given VO_2, HR has shown an increase while VO_2 remains the same. Because the exercise intensity will be overestimated, the relationship between HR and VO_2 determined at sea level will not be suitable to use at altitude. It is well known that many internal and environmental factors may have drastic effects on the readings during the experiment, even when all of the laboratory conditions have been set to be the same for all participants. Some environmental and undetectable factors may still affect the results. Therefore, to avoid any variance that may happen to the recorded data, the proposed training protocols were repeated twice and the data was interpolated, averaged as well as filtered [57].

5.4 Pre and post experiment preparation.

Since both HR and VO_2 can vary with time of the day, emotional state, food and caffeine intake, previous activity, fatigue, temperature, humidity, altitude and dehydration [96][97], the participants were asked to have a light meal at least two hours before the experiment and not to engage in intense or prolonged exercise for 24 hours prior to each experiment. Environmental conditions were the same for all participants. The temperature of the laboratory was set at 25° Celsius and the humidity was set at approximately 50%.

Following arrival to the experiment location, both heart rate belt and $K4b^2$ portable unit have been fixed to the subject's body. $K4b^2$ is a portable unit with a total weight lower than 1 kg. Cosmed has developed a special harness to fix the portable unit to any subject. The harness consists of a belt that can be adjusted to fit different sizes and positions. Based on the recommendations from the $K4b^2$ manual, the portable unit was located on the front and the chargeable battery was located on the back of the subject to increase comfort and to avoid any obstacles during movements. To make things easy when assembling the system, plates are provided with the harness and they can be easily removed and placed in different positions. The figure below shows the right way to assemble the analyzer together with the HR probe on the participant to obtain maximum accurate results.

Fig. 5.1: Illustration of the Equipment. [1]

After that, subjects were asked to sit and rest for five minutes prior to any exercise. Even though we asked subjects not to undertake any strenuous activity in the prior 24h, and to arrive at the lab rested, we wanted to have some seated time before subjects commenced the protocol.

The figure below shows one subject being seated to have some rest before participating in the experiment.

Fig. 5.2: Subject Being Seated to Rest for Five Minutes Prior to the Exercise.

After the five minute period, subjects were asked to stand up and walk over to the treadmill (~2m distance away) and wait there for a two minute period whilst waiting to commence the training (walk-run-walk) protocol. Obviously, going from seated to standing would induce an increase in HR/VO_2, so we waited for subjects to stand for two minutes before commencing walking to allow for bodily responses to settle down.

Figure 5.3 below shows the subject standing up for two minutes on the treadmill edges waiting to commence the training protocol.

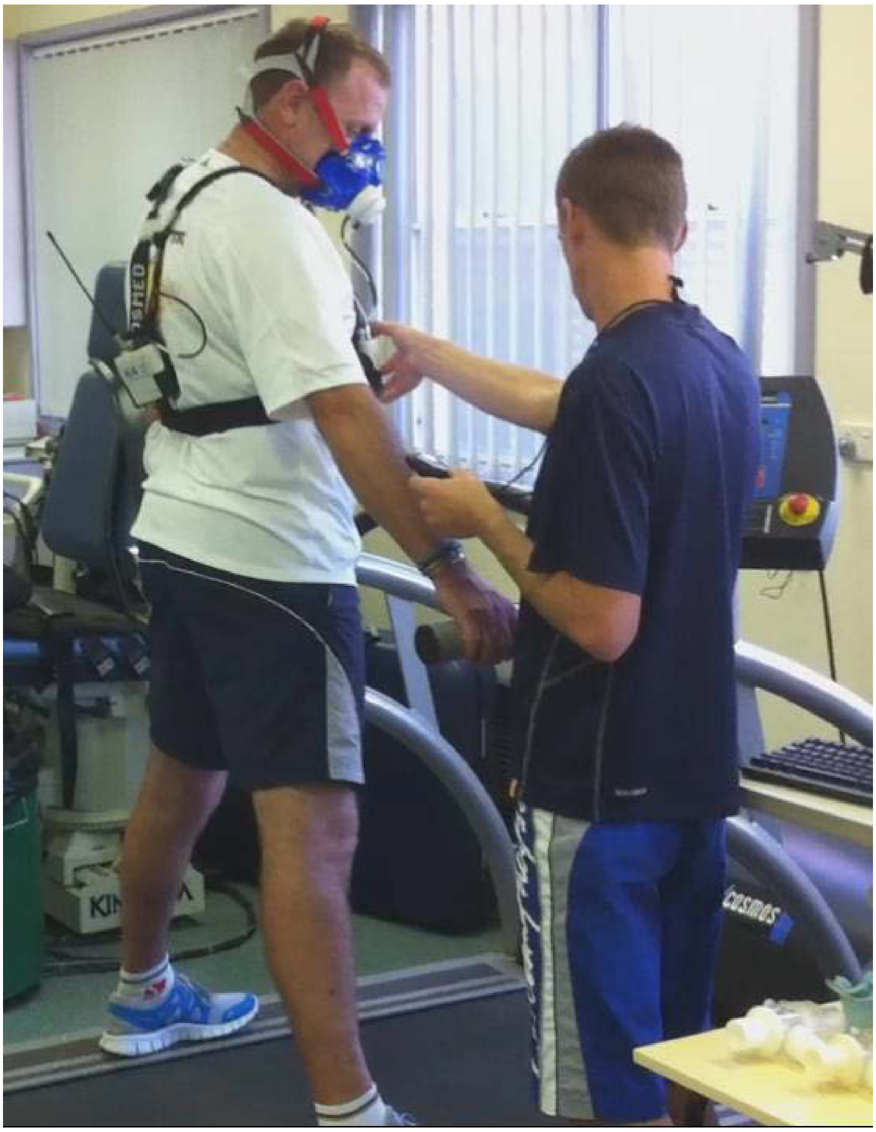

Fig. 5.3: Subject Standing up for Two Minutes on the Treadmill Edges.

Following two minutes of standing on the treadmill edges, subjects commenced walking on the treadmill. During this time we already had the treadmill started and running at the predefined speed, so subjects literally had to just step onto the treadmill and start walking. Following the specified period of walking at each protocol's speed, and within 10-12 seconds, the treadmill speed was increased (whilst subjects were walking on the treadmill). Subjects then started to run based on the speed limit of each training protocol.

Following the running period, the treadmill speed was decreased and subjects went back to walking speed. Figure 5.4 shows the subject starting to participate into the training protocol.

Fig. 5.4: Subject Starts to Participate into the Experiment.

Following the final walk, the treadmill was stopped, and subjects were escorted to a chair where they rested for five minutes. Pulmonary gas exchange was measured for five minutes of seated rest, and Cosmed measurement was then completed.

Each subject completed two running exercises on separate occasions. During experiments, a real-time HR monitor using powerful windows compatible software was observed to guarantee the safety of the subject. The figure below shows how the training protocol has been real-time monitored by one of my colleagues in order to terminate it when signs of poor perfusion, failure of HR to increase with increased exercise intensity, or noticeable change in heart rhythm were detected.

Fig. 5.5: Training Protocol Real-Time Monitoring.

5.5 Conclusion.

Two groups of participants A and B have been chosen to participate in our experiments in order to investigate the dynamic characteristics of heart rate and oxygen uptake. UTS approved the study and an informed consent was obtained from al participants before each experiment.

The aim of choosing two different age groups was to extend the benefit of investigating HR and VO_2 by creating two different training protocols based on the age variation.

All experiments have been performed at Center for Health Technologies (CHT), the room in which experiments were performed was large enough to accommodate the equipment and allow access to the participant in case of emergency.

Physiological and environmental factors may affect the response to exercise and therefore the results of any experiment. Even when all of the laboratory conditions have been set to be the same for all participants, some undetectable and unpredictable factors may still affect the results. To avoid any variance that may occur in the recoded data, each participant was asked to repeat the training protocol twice and the data was interpolated, averaged and filtered.

Each participant completed two predefined running exercises on separate occasions. However, the test was terminated when signs of poor perfusion or noticeable change in heart rhythm were detected.

Chapter 6

Modelling and Analyzing of Dynamic Characteristics

6.1 Training protocols setup.

All experiments have been done on healthy but untrained subjects. Two submaximal running protocols, that are practical and easy to apply, were implemented in the setup. They are required that the subjects where to perform at less than 80% of their maximum heart rate (HR_{max}), this is also a recommendation for unfit people and for those with respiratory or cardiac risks [98].

The relationship between HR and VO_2 becomes non-linear during light and very highly intense activity [57]. Therefore, and for the values of HR and VO_2 to remain located in the linear part, a moderate speed of 9 km/h was examined and set to be the highest level in the training protocol for group A; each participant, at varying times, reached a reading of 80% of his HR_{max} at this speed.

As mentioned before, each subject completed two running exercises on separate occasions. In each session and as a warming up interval, the subjects were requested to walk on a treadmill at 5 km/h for 4 minutes to avoid any kind of stiffness or fatiguing effect may occur during the running period. Then, they were asked to run at 9 km/h for 6 minutes, before a recovery time or cooling down period of 5 minutes at 5 km/h speed. Figure 6.1 below shows the experimental training protocol for group A.

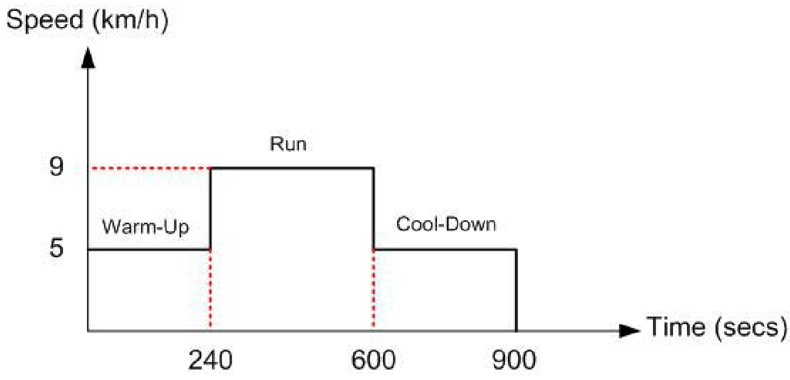

Fig. 6.1: Group A Experimental Protocol.

Also in group B, each subject completed two running exercises on separate occasions. A moderate speed of 8 km/h was examined and set to be the highest level in the training protocol, also each participant, at varying times, reached a reading of 80% of his HR_{max} at this speed in this training protocol. The subjects were requested to walk on a treadmill at 3 km/h for 4 minutes. Then, they were asked to run at 8 km/h for 8 minutes, before a recovery time or cooling down period of 8 minutes at 3 km/h speed. Setting two different training protocols in this way based on the age difference will assure two essential things, the first thing is to make sure that every participant in each group where to perform at less than 80% of his maximum heart rate, and the second one is to observe the ability of each participant to finish the whole training protocol without any extra exhaustion or fatigue just to avoid any kind of cardio risks or failures. Figure 6.2 below shows the experimental training protocol for group B.

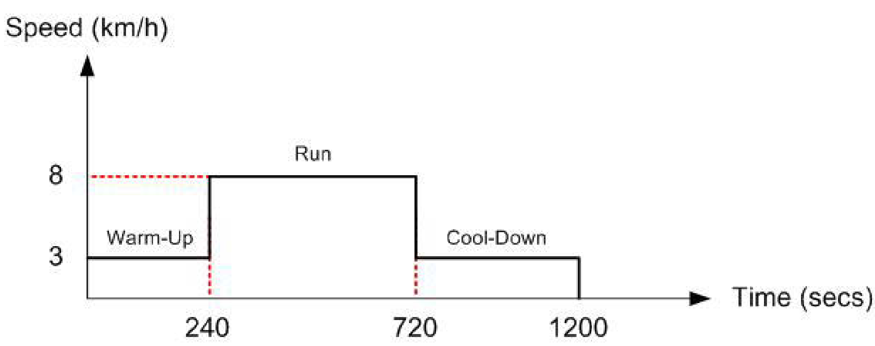

Fig. 6.2: Group B Experimental Protocol.

6.2 First-order process structure and parameters.

According to previous studies, heart rate response to exercise can be approximated as a first order linear process or system [99][100]. A first order system is that whose output is modeled by a first order differential equation. We will see in the following section that VO_2 has the same attributes and profile's shape as HR, therefore, we can depend on the similarity to create a first order process for oxygen consumption as well. A first-order linear system can be described by the following differential equation [101]:

$$\frac{dy}{dt} + p(t) \cdot y = q(t) \tag{6.1}$$

The previous equation called a first order because the highest derivative that appears in the equations is one, and it is linear because y and dy/dt appear linearly. The solution of this differential equation provides insight into the operation of the system and nature of the control problem. The general solution of the previous equation can be given by:

$$y = \frac{\int u(t) \cdot q(t)dt + C}{u(t)} \tag{6.2}$$

Where

$$u(t) = e^{\int p(t)dt} \tag{6.3}$$

And C is a constant and can be determined if an initial condition is given.

Moving from time domain to frequency domain gives us a better and easier understanding of the system characteristics. It is assumed that the system is linear time invariant at each individual stage. Then, Laplace transform is used for analysis of linear time-invariant system; it is a transformation from the time domain to the frequency domain.

Having said that, Laplace transformation (frequency domain form) of equations 6.1 can be given as:

$$Y(s) = \frac{K}{\tau s + 1} \cdot U(s) \tag{6.4}$$

The first order system is characterized by two terms, the time constant (τ) and the static gain (K). The time constant characterizes the speed of response of a first-order process, it is a measure of the time necessary for a process to adjust to a change in the input, while the static gain characterizes the sensitivity of the output to the input signal [102].

Having a step change input u of magnitude of a, where $U(s)=a/s$ will give us the following dynamic response:

$$y(t) = K \cdot a(1 - e^{-\frac{t}{\tau}}) \tag{6.5}$$

The figure below shows the transient response for a step change input.

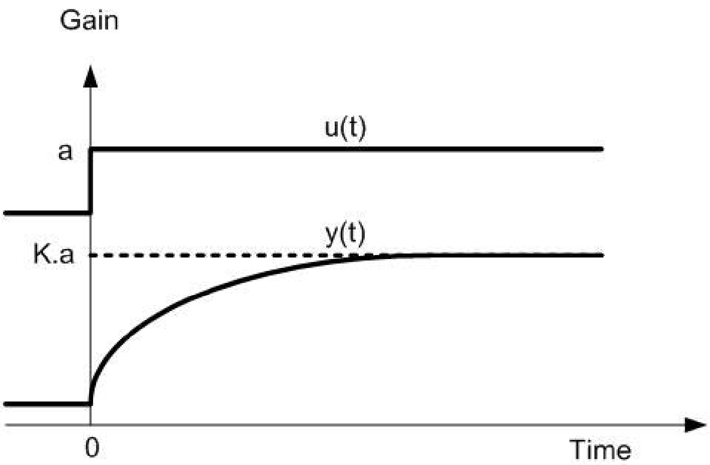

Fig. 6.3: Response of a First-Order System to Step Change in the Input.

From the previous figure, we can see that for a step change in the input, the process reaches a new steady state, the maximum value the output can reach is $K{\cdot}a$, which can be calculated using the last equation by setting $t \rightarrow \infty$. The time constant can be found by setting $t = \tau$ in the last equation which gives the output y a value of $0.632\ K{\cdot}a$.

The smaller the value of τ, the steeper is the initial response of the output. Also the larger static gain of a process, the larger steady state value of its output for the same input change.

Figures 6.4 and 6.5 show the effect of static gain and time constant on the response of first order system.

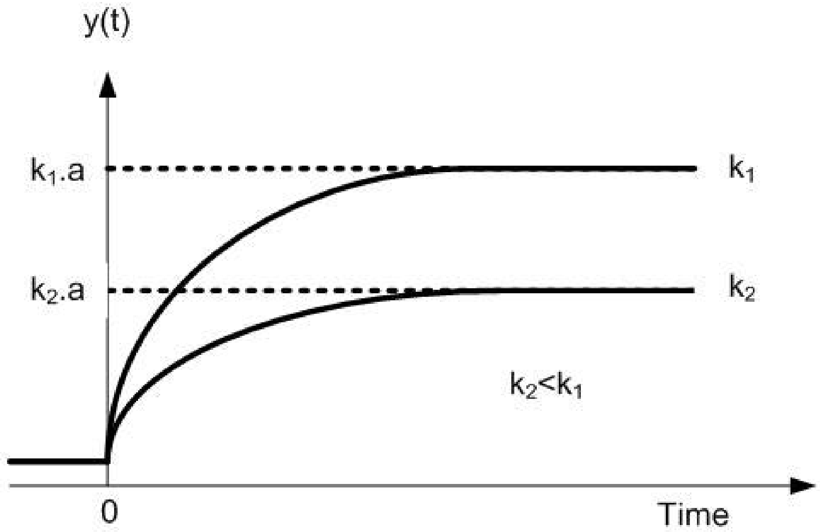

Fig. 6.4: Effect of Static Gain on the Response of First Order System.

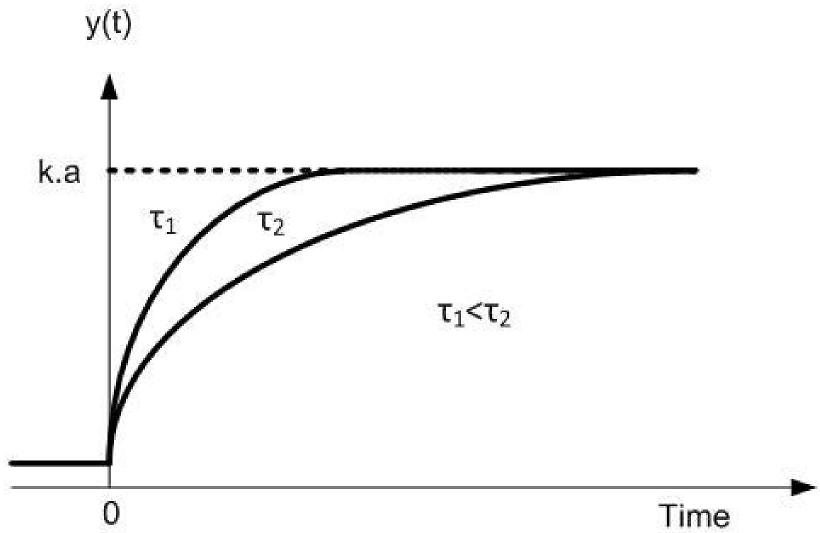

Fig. 6.5: Effect of Time Constant on the Response of First Order System.

6.3 VO_2 and HR profiles and raw data.

In this section, the profiles and raw data of HR and VO_2 for group A and B will be provided. Original signals of HR and VO_2 for all subjects in group A are shown in figures 6.6 and 6.7 respectively.

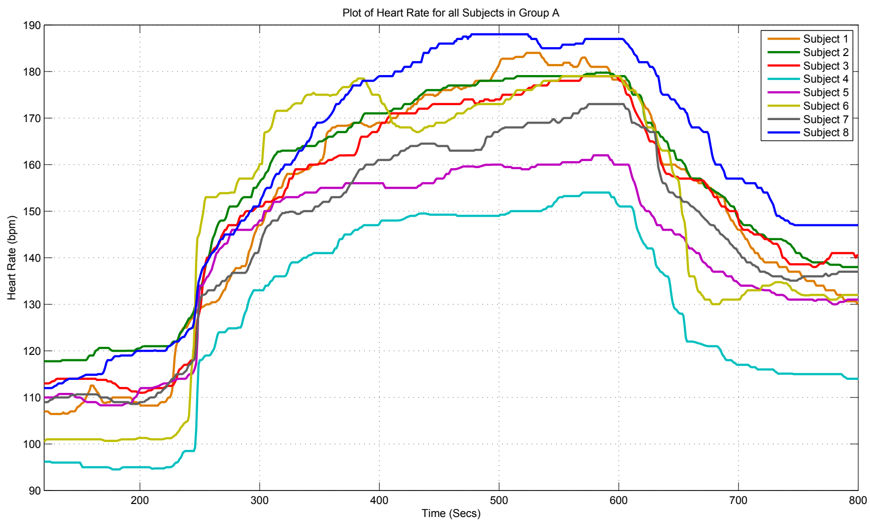

Fig. 6.6: Raw Data of HR for all Subjects in Group A.

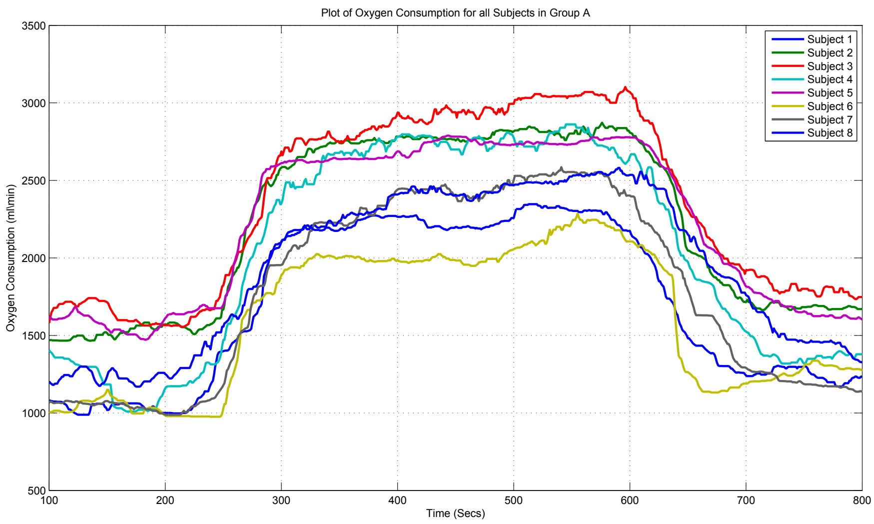

Fig. 6.7: Raw Data of VO_2 for all Subjects in Group A.

Matlab has been used to draw and establish the original signals profiles for both VO_2 and HR. Figures 6.8 and 6.9 respectively show the original signals of HR and VO_2 for all subjects in group B.

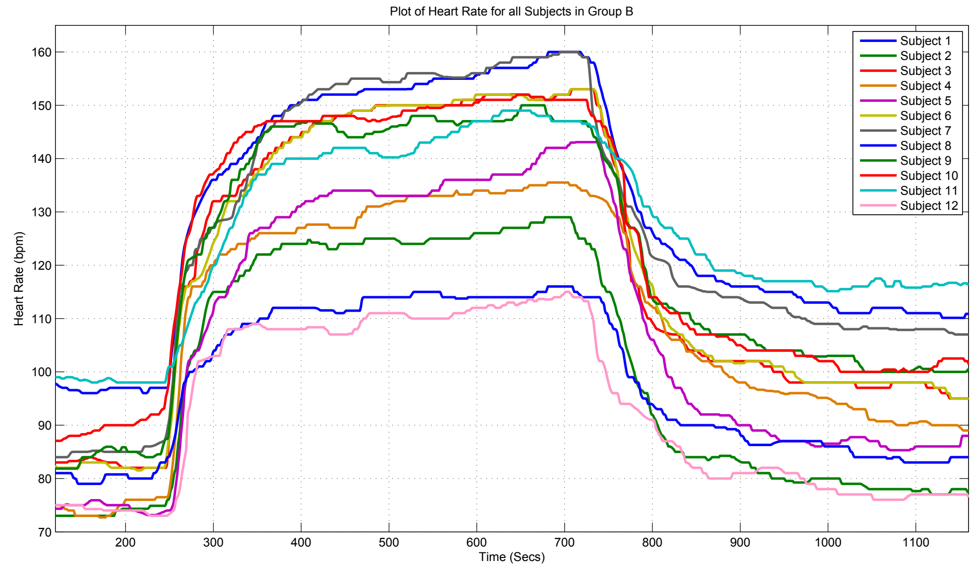

Fig. 6.8: Raw Data of HR for all Subjects in Group B.

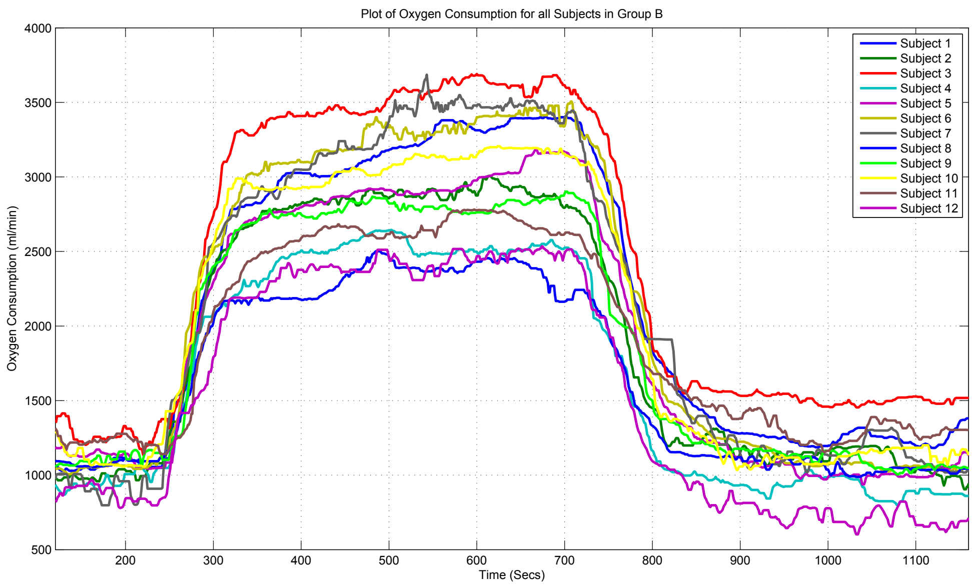

Fig. 6.9: Raw Data of VO_2 for all Subjects in Group B.

6.4 Onset and offset running protocol modelling.

As mentioned earlier, Matlab system identification toolbox has been used to establish the first-order process model for each step response data. The raw data however has been interpolated, averaged as well as filtered to be fitted into our Matlab toolbox.

From numerical analysis point of view, interpolation is known as a method of constructing new data within the range of a discrete set of known data points. From engineering and science point of view, interpolation is the ability to estimate the values of a function obtained by sampling or experimentation for a limited number of values of the independent variable.

The raw data which was collected using the $K4b^2$ did not have a fixed sampling rate, because it had been recorded breath by breath and as a matter of fact, it is not possible to synchronize our breathing process based on one fixed rate or speed, that's why we needed a function which can increase the sampling rate and gives us estimation values between each pair of data points.

interp function from Matlab signal processing toolbox has been used for this purpose. The syntax of the function is given as:

$$y = interp(x, r) \tag{6.6}$$

Which means that the function increases the sampling rate of x by a factor of r. the interpolated vector y is r times longer than the original input x.

Interpolation increases the original sampling rate for a sequence to a higher rate. **interp** performs lowpass filter interpolation by inserting zeroes into the original sequence and then applying a special lowpass filter [103].

Table 6.1 below shows a sample of data before the interpolation process, it can be seen that there is no fixed sampling rate and they are some gaps in time and accordingly gaps in values.

Table 6.1: Raw Data Before Interpolation.

Time(secs)	**VO_2(ml/min)**	**HR(bpm)**
1	383.242	72
2	240.614	71
4	1265.995	70
5	851.808	70
7	843.802	71
8	550.512	72
10	1282.329	74

Setting the sample rate as one second, the table will become after the interpolation process as follows:

Table 6.2: Raw Data After Interpolation.

Time(secs)	**VO_2(ml/min)**	**HR(bpm)**
1	120.307	35
2	311.928	70
3	466.877	70.163
4	598.457	70.327
5	660.698	70.663
6	677.484	71
7	682.959	71.5
8	709.695	72
9	743.373	72.538
10	755.185	73.123

The interpolation process has guaranteed that there are no gaps between the data and every second has been assigned to an appropriate value, it provides a means of estimating the function at intermediate points. Currently, there are many different interpolation methods such as linear interpolation, polynomial interpolation and Spline interpolation. Moreover, some forms of interpolation can be multivariate and work on more than one variable, such as bi-linear for two and tri-linear for three dimensions interpolation.

Nevertheless, it is very important to take into our considerations when choosing an appropriate method of interpolation some concerns such as the accuracy, quality as well as how many data points are needed.

Another Matlab signal processing toolbox function was applied on the raw data before getting modeled. The filtering process of the data has been done using the function **medfilt1**. The syntax of the function is given as:

$$y = medfilt1(x, n) \tag{6.7}$$

Where the medfilter applies an order n one-dimensional median filter to vector x; the functions itself considers the signal to be 0 beyond the end points. Output y has the same length as x.

The figure below shows raw data sample before and after getting filtered by the median filter, n value was 10.

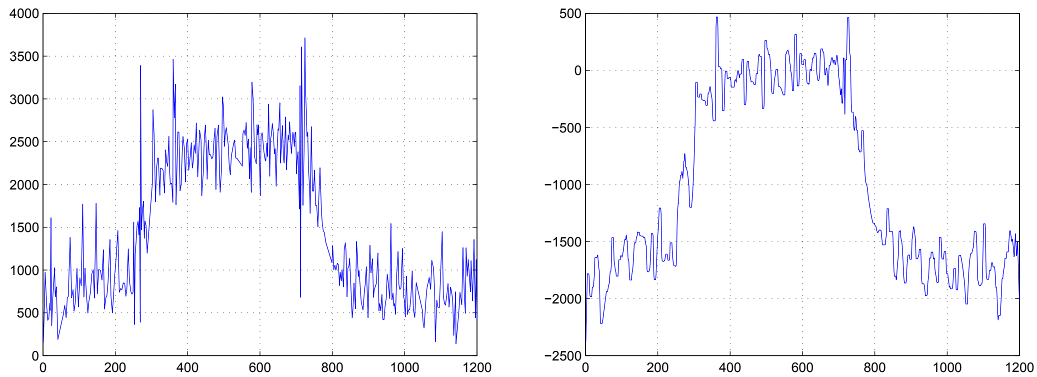

Fig. 6.10: Raw Data Sample Before and After Getting Affected by a Median Filter.

Now, as an example, curve fitting results of HR and VO_2 for subject 1 in Group A after data being interpolated, filtered and processed using the Matlab signal processing functions and toolboxes are shown in Figure 6.11 and 6.12 respectively.

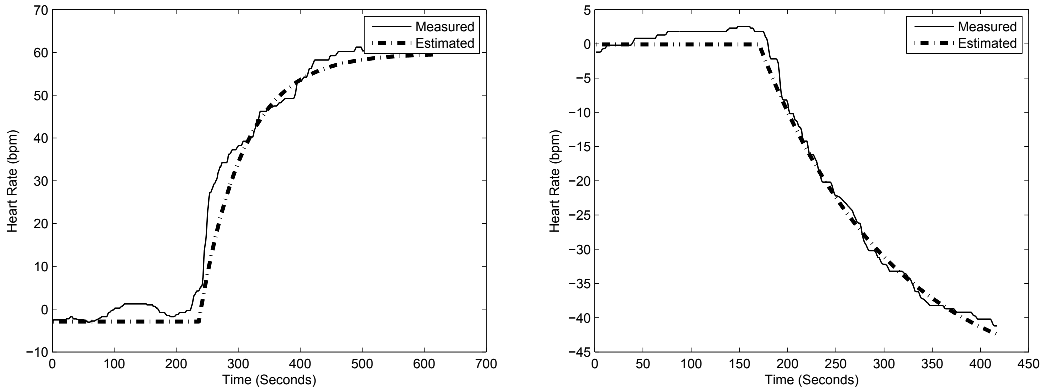

Fig. 6.11: Curve Fitting Results of HR for Onset and Offset Running Protocol for Subject No.1 in Group A.

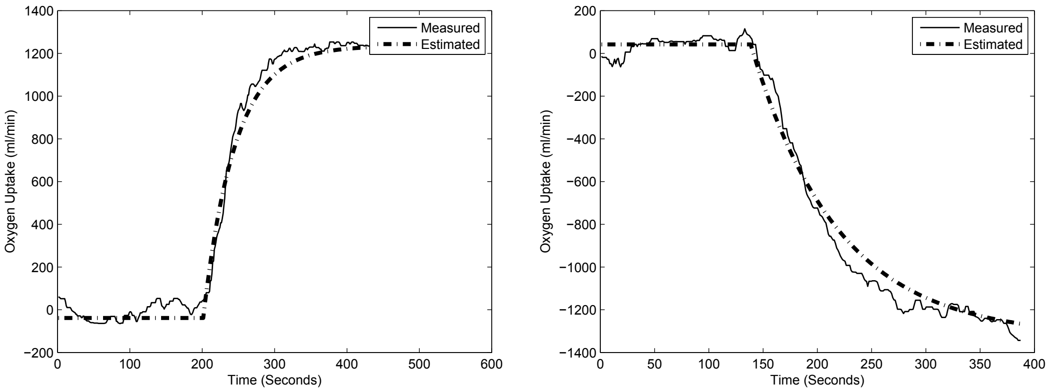

Fig. 6.12: Curve Fitting Results of VO_2 for Onset and Offset Running Protocol for Subject No.1 in Group A.

Time constants and steady state gains of HR and VO_2 for each subject in Group A are shown in Table 6.3 and 6.4 respectively.

Table 6.3: Estimated Time Constants and Normalized Steady State Gains of HR Response for Group A.

Subjects	Onset Exercise		Offset Exercise	
	Steady State Gain (K_1)	Time Constant (τ_1)(secs)	Steady State Gain (K_2)	Time Constant (τ_2)(secs)
1	17.17	89.36	14.64	117.85
2	14.32	62.73	12.38	117.42
3	15.76	65.56	10.37	90.25
4	13.62	52.87	9.71	66.58
5	11.89	36.74	7.71	69.60
6	17.94	42.43	11.66	61.12
7	14.69	82.22	9.68	96.49
8	17.48	87.10	14.09	139.64

Table 6.4: Estimated Time Constants and Normalized Steady State Gains of VO_2 Response for Group A.

Subjects	Onset Exercise		Offset Exercise	
	Steady State Gain (K_1)	Time Constant (τ_1)(secs)	Steady State Gain (K_2)	Time Constant (τ_2)(secs)
1	303.24	40.47	261.78	40.48
2	319.44	40.29	313.61	64.76
3	345.26	56.15	340.55	71.42
4	409.33	44.42	383.88	61.62
5	286.45	30.37	283.02	56.47
6	273.92	39.69	246.95	44.14
7	368.54	63.38	366.94	71.68
8	304.72	66.00	291.58	98.43

Also, curve fitting results of HR and VO_2 for subject 1 in Group B are shown in Figure 6.13 and 6.14 respectively.

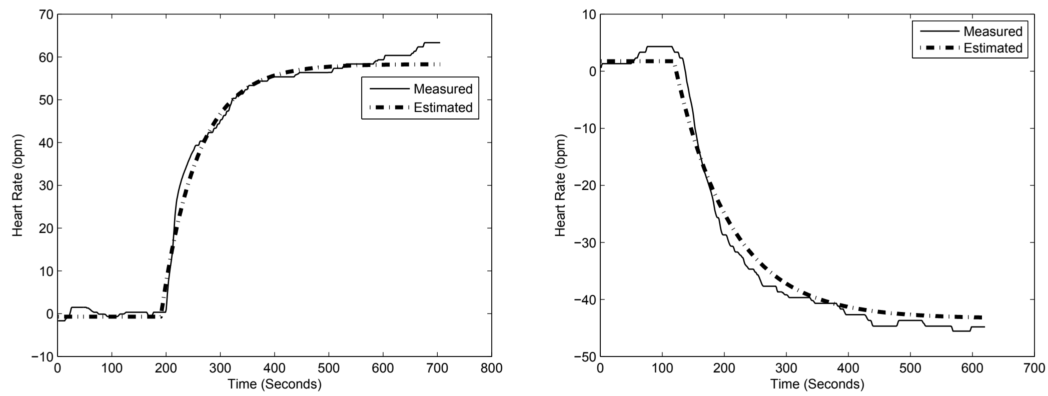

Fig. 6.13: Curve Fitting Results of HR for Onset and Offset Running Protocol for Subject No.1 in Group B.

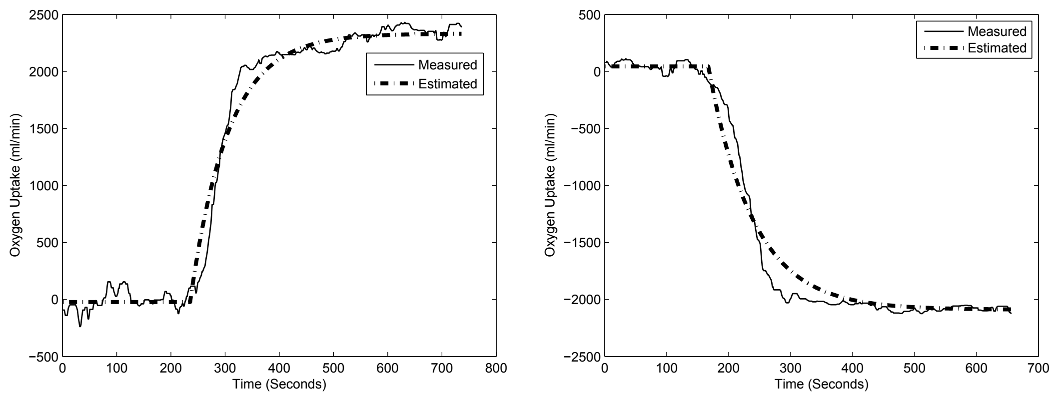

Fig. 6.14: Curve Fitting Results of VO_2 for Onset and Offset Running Protocol for Subject No.1 in Group B.

Furthermore, Table 6.5 and 6.6 show time constants and steady state gains of HR and VO_2 for each subject in Group B.

Table 6.5: Estimated Time Constants and Normalized Steady State Gains of HR Response for Group B.

Subjects	Onset Exercise		Offset Exercise	
	Steady State Gain (K_1)	Time Constant (τ_1)(secs)	Steady State Gain (K_2)	Time Constant (τ_2)(secs)
1	11.80	61.37	9.02	82.46
2	10.35	47.10	9.64	73.578
3	13.50	54.96	10.83	71.57
4	11.38	41.60	9.01	98.14
5	12.39	69.10	10.45	83.87
6	13.64	63.35	10.94	81.93
7	14.51	67.89	9.69	68.59
8	6.68	49.66	6.11	87.53
9	12.51	47.10	9.38	86.31
10	12.13	36.72	10.06	83.27
11	9.78	90.397	6.186	105.32
12	7.36	46.58	6.88	74.69

Table 6.6: Estimated Time Constants and Normalized Steady State Gains of VO_2 Response for Group B.

Subjects	Onset Exercise		Offset Exercise	
	Steady State Gain (K_1)	Time Constant (τ_1)(secs)	Steady State Gain (K_2)	Time Constant (τ_2)(secs)
1	452.58	76.01	426.71	76.32
2	379.71	54.07	361.84	57.25
3	471.10	63.65	426.78	65.90
4	323.16	52.06	321.72	52.63
5	375.62	66.10	372.81	77.18
6	457.50	63.81	449.75	78.10
7	505.12	75.10	467.67	75.89
8	260.48	60.38	255.06	59.69
9	345.16	51.78	344.39	64.55
10	414.25	53.03	396.87	69.40
11	301.11	72.698	281.80	76.14
12	352.03	59.45	329.44	65.03

6.5 Evaluating steady state gains and time constants.

By observing the original data for each subject in both groups, we can clearly identify that all subjects have similar HR and VO_2 profiles. For each individual subject, steady state gain of offset is smaller than steady state gain of onset for both HR and VO_2 and that is due to the struggle that the body undergoes in recovery in the small time duration. The difference between the onset and offset gain of VO_2 is noticeably higher than that in the case of the HR and this is due to different measurement scales for each parameter.

Based on the results listed in Tables 6.3 - 6.6, it can be seen that the time constant of offset is larger than the time constant of onset for both HR and VO_2. This is the case for all subjects in both groups, A and B except subject 8 in group B, the time constant of offset for VO_2 for this individual participant is smaller than the onset VO_2 time constant.

Subject 8 had been asked to do the predefined protocol for the third time just to neglect and avoid any errors might happen due to some internal and external factors, but the results are always noticed to be the same, the offset time constant is smaller than the onset time constant for VO_2. Emotional effects as well as physiological status may have their hands in his results; however, there is no clear reason why this is happing for this specific exerciser.

It has also been noticed that the time constant of VO_2 is smaller than time constant of HR for both onset and offset responses in group A, this important observation shows that the mechanism of oxygen consumption in human body in early ages as in group A, is responding faster than the one in HR. The muscles are younger and bigger and that's why they need fast oxygen delivery. This actually explains why oxygen consumption takes less time to reach the steady state.

The experimental results show that this is not the case in group B, on the one hand the VO_2 offset time constant is smaller than the HR offset time constant as in group A. However, on the other hand, VO_2 onset time constant is larger than HR onset time constant for most of the participants in group B.

Paper [104] had investigated the variation of onset and offset walking exercises, as well as the characteristics of the steady state of the HR responses. However, the literature shows no sign of an investigation into the variation of the dynamic characteristics of onset and offset running exercises for both HR and VO_2, nor does it investigate simulating an interval training protocol based on the value of these time constants.

For these reasons, this study investigates the variations of time constants and steady state gains for HR and VO_2 for different people under the same running exercise protocol and in the next part of the present study, a sensible interval training protocol for each group will be built based on the experimental results.

6.6 Conclusion.

Two submaximal running protocols were implemented in this part of the study, they were required that the participants where to perform at less than 80% of their maximum heart rate.

For the relationship between HR and VO_2 to remain linear, a moderate speed of 9 km/h for the first training protocol and 8 km/h for the second training protocol were examined and set to be the highest level in the training protocol for group A and group B respectively, each participant at varying times reached a reading of 80% of his maximum heart rate at these speeds.

A warm up interval of 4 minutes at 5 km/h speed was set for group A, and the same time but with different speed was set for group B. These important intervals were essential to avoid any kind of stiffness or fatiguing effect may occur during the running segment. A recovery time also was set at the end of each training setup to avoid any kind of cardio risks or failures.

Both heart rate and oxygen consumption can be approximated as a first order linear process. It has been shown that the dynamic response of HR and VO_2 is characterized by time constant as well as static gain.

Time constant is a measure of the time for a process to adjust to a change in the input while the static gain characterizes the sensitivity of the output to the input signal. The smaller the value of time constant, the steeper is the initial response of the output. On the other hand, the larger static gain of a process, the larger steady state value of its output for the same input change.

Original signals of HR and VO_2 responses for all subjects in group A and B are shown in this chapter. Also, curve fitting results of HR and VO_2 for onset and offset running protocol are presented based on the modeling results of the dynamic responses using Matlab Simulink Toolbox.

Matlab Simulink Toolbox was used to determine in details and calculate the estimated time constants and normalized steady state gains of HR as well as VO_2 response. It also helped us in evaluating some observations from the original and modeled data.

Chapter 7

Approaches to Creation of Interval Training Protocol

7.1 Training zones, exercise intensity levels and HR_{max} equation .

In this part of the present study, a sensible interval training protocol for each group will be built based on the experimental results. To build any training protocol, targets have to be set first. For instance, if the aim of a training protocol is to develop basic endurance and aerobic capacity, all running intervals should be completed at a maximum of 70% of HR_{max} while developing cardiovascular system can be done by training at a range of 70% to 80% of HR_{max}.

On the other hand, training in anaerobic zone which is 80% to 90% of HR_{max} will develop the lactic acid system. Therefore, determining an actual HR_{max} is the key to constructing a well-designed training program. As mentioned before in section 2.4, at this time there is no acceptable method or equation to estimate HR_{max} and if HR_{max} needs to be estimated, then a population specific formula should be used, and the only accurate equation which can accurately estimate the HR_{max} is that of Inbar. Therefore, Inbar HR_{max} equation will be utilized to build the interval training protocols.

$$HR_{\max} = 205.8 - 0.685 \times (Age) \tag{7.1}$$

It is well known that HR is a valid measure of exercise intensity only if it reflects the metabolic rate which can be measured by VO_2; this is because the increase in HR is directly related to the increase in oxygen consumption. It is the increase in oxygen delivered to the muscles during exercise that is related to improving aerobic capacity. Fortunately, we have the equipment to measure this variable in and outside of the laboratory.

Table 7.1 shows the relationship between VO_{2max}, HR_{max} and exercise intensity levels.

Table 7.1: Relationship Between VO_{2max}, HR_{max} and Exercise Intensity Levels.

Category	**%HR_{max}**	**%VO_{2max}**
Normal Activities	<60	<40
Fat Burning (Low)	60-70	40-50
Aerobic (Moderate or Vigorous)	70-80	~55-70
Anaerobic (Very Vigorous)	>80	>70

7.2 Interval training protocol setup.

As mentioned before, a linear relationship between VO_2 and HR exists during moderate intense activity and that's why our training protocol will target the aerobic zone (70-80% of HR_{max} or 50-70% VO_2max) which aims to develop the exerciser's cardiovascular system.

Based on equation 7.1, for Group A's average model:

$$HR_{\max} = 205.8 - 0.685 \times (AverageAge) \tag{7.2}$$

$$HR_{\max} = 205.8 - 0.685 \times (29.38) = 185.67 \approx 186bpm \tag{7.3}$$

So building an interval training which reaches a 149 bpm (80% of HR_{max}) in each interval will guarantee achieving ~70% of VO_{2max} in Group A.

Furthermore, for Group B's average model:

$$HR_{\max} = 205.8 - 0.685 \times (AverageAge) \tag{7.4}$$

$$HR_{\max} = 205.8 - 0.685 \times (45.4) = 174.7 \approx 175 bpm \tag{7.5}$$

So building an interval training which reaches a 140 bpm (80% of HR_{max}) in each interval will guarantee achieving ∼70% of VO_{2max} in Group B.

7.3 Developing exercise protocol to improve cardio-vascular system.

The experiment results of Group A show that for an average model, the exerciser exceeds an 80% of his HR_{max} at the 297^{th} second which means 57 seconds after the start of the running period, also 1 minute at speed 5km/h is considered to be the recovery period after each running interval.

Figure 7.1 shows an interval training protocol for Group A based on the previous calculations.

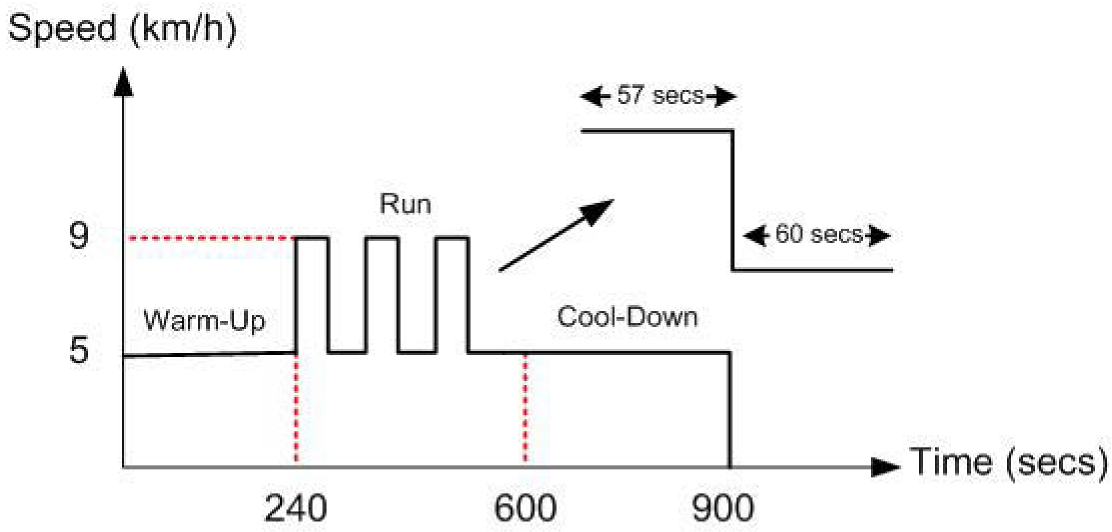

Fig. 7.1: Group A's Proposed Interval Training Protocol.

On the other hand, the experiment results of Group B show that for an average model, the exerciser exceeds an 80% of his HR_{max} at the 427^{th} second which means 187 seconds after the start of the running period, also 1 minute at speed 3km/h is considered to be the recovery period after each running interval.

Figure 7.2 shows an interval training protocol for Group B based on the previous calculations. In order to verify the new proposed interval training protocols shown in Figures

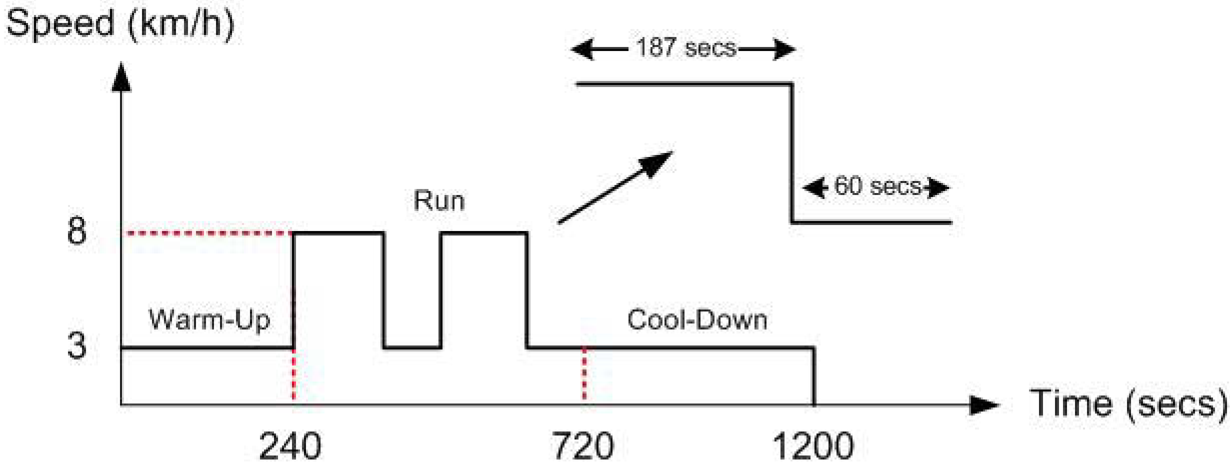

Fig. 7.2: Group B's Proposed Interval Training Protocol.

7.1 and 7.2, more subjects need to be recruited.

7.4 Conclusion.

A sensible interval training protocol for each group was built based on the experimental results. The aim was to develop basic endurance and aerobic capacity to develop the cardiovascular system, that's why all running intervals were completed at a maximum of 80% of the maximum heart rate.

Inbar maximum heart rate equation was utilized to build the interval training protocols. Average age for each group was implemented in the equation to create an average model values for each group. The interval training protocol of group A consists of three running intervals within the running segment while the proposed interval training protocol of group B contains only two running intervals. This number of intervals in each protocol was determined by the time where the exerciser exceeds an 80% of his maximum heart rate and it differs based on the age variation between the two groups.

Chapter 8

A Switching RC Circuit Model for the Simulation of Exercise Protocols

8.1 First order RC Circuit.

The series combination of a resistor and a capacitor has a great practical importance; engineers usually choose the capacitor in the coupling network of an electronic amplifier, in the compensation networks of an automatic control system, and even in the synthesis of equalizing networks.

Their choice is based on the smaller losses present in a physical capacitor, the lower cost, the better approximation which the mathematical model makes to the physical element it is intended to represent as well as the smaller size and lighter weight as exemplified by capacitors in hybrid and integrated circuits.

A first order RC circuit is the simplest type of RC circuit and is composed of one resistor and one capacitor in series [105]. The RC circuit is shown in Figure 8.1.

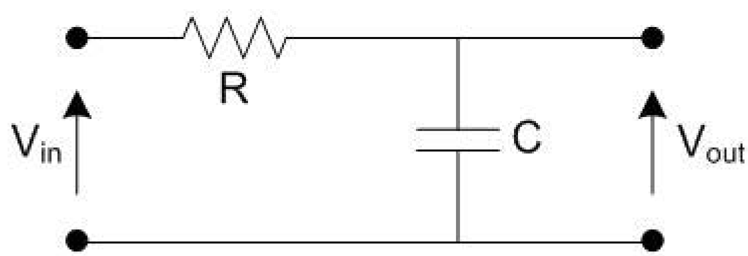

Fig. 8.1: Series RC Circuit.

In the following analysis, we will assume that there is no power or energy source in the circuit except an initial stored energy in the capacitor itself by selecting:

$$v(0) = V_0 \tag{8.1}$$

The total current leaving the node at the top of the circuit diagram must be zero, and therefore,

$$C\frac{dv}{dt} + \frac{v}{R} = 0 \tag{8.2}$$

Division by C gives us:

$$\frac{dv}{dt} + \frac{v}{RC} = 0 \tag{8.3}$$

Solving the previous differential equation gives us the response of the RC circuit:

$$v(t) = V_0.e^{\frac{-t}{RC}} \tag{8.4}$$

Where V_0 is the capacitor voltage at time t = 0 as in equation 8.1.

The time constant of the RC circuit may be found by simply noting the time at which the response has dropped (in case of no power source and the capacitor is discharging) to 36.8 percent of its initial value. In other words, it is the time required for the voltage to fall to V_0/e.

$$\tau = RC \tag{8.5}$$

Large values of C and R provide large time constants and slow dissipation of the stored energy. Large value of R is requiring a great time to convert the stored energy into heat; also large value of capacitor stores a large value of energy with a given voltage across it, again requiring a great time to lose this initial energy.

The figure below shows the voltage v(t) across the capacitor as a function of time. As mentioned earlier; the initial value of v(t) is assumed to be V_0.

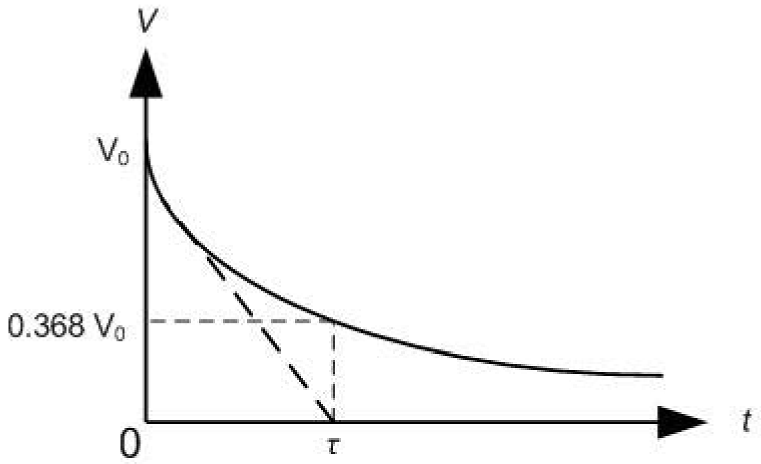

Fig. 8.2: RC Circuit Response Curve.

We can also express the circuit shown in figure 8.1 as a transfer function from the input voltage V_{in} to the voltage across the capacitor V_{out}:

$$G(s) = \frac{1}{1 + RCs} \tag{8.6}$$

Equation 8.6 leads us to a general form of a first order transfer function which can be noted as:

$$G(s) = \frac{K}{1 + \tau s} \tag{8.7}$$

Where K, τ are the steady state gain and the time constant respectively.

It has been identified that HR and VO_2 responses to exercise can be modeled as a first-order transfer function for both onset and offset exercises. In the following sections, Group A's results have been taken into our consideration in order to simulate the VO_2 and HR responses during the proposed interval training protocol. Similarly, we can apply the same techniques as well as methods on the results from Group B.

Average values of onset and offset time constants as well as steady state gains for VO_2 and HR profiles are shown below in Table 8.1.

Table 8.1: Group A's Averaged Values of Time Constants and Steady State Gains.

Profile	Onset		Offset	
	τ_1	K_1	τ_2	K_2
HR	64.88	15.36	94.87	11.28
SD	18.84	1.97	26.56	2.21
VO_2	47.60	326.36	63.63	311.04
SD	11.91	42.45	16.99	46.11

These values will be used to simulate the VO_2 and HR responses during the proposed interval training protocol.

8.2 RC simulation circuit.

However, there is no existing tool to directly simulate the switching behavior that ensures the continuity of both states and outputs during the switching period. We constructed a simple RC circuit to simulate the proposed interval training protocol.

Figure 8.3 shows a simple circuit diagram which will be used to simulate both HR and VO_2 responses after setting the parameters based on Table 8.1 in the previous section.

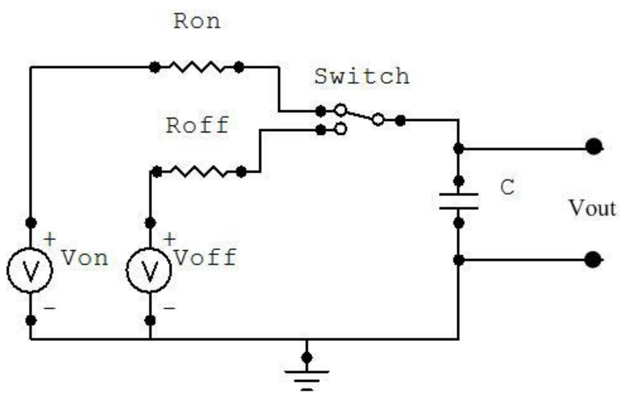

Fig. 8.3: Designed Simulation Circuit.

Coming to the analysis of the previous circuit, we can set first the following assumptions:

1. R_{On} multiplied by C (R_{On} x C) represents the time constant for the onset response.
2. R_{Off} multiplied by C (R_{Off} x C) represents the time constant for the offset response.
3. The gain value can be controlled by manipulating the voltage sources $V_{On}$and V_{Off}.
4. The switch is utilized to replicate the switching behavior between the two responses based on the training protocol segments.

Now, let us start analyzing the behavior of the circuit in Figure 8.3 and match it with what actually happens during the interval training protocol. The circuit will start representing the onset training period once the switch is connected to the upper side of the circuit. The following figure shows the circuit in an onset mode:

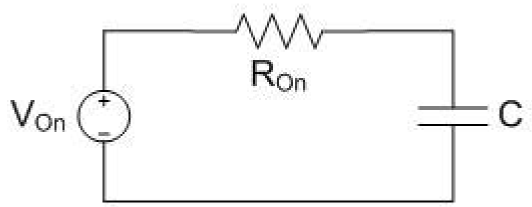

Fig. 8.4: RC Circuit in Onset Mode.

In this mode and once the switch is connected, the current will start flowing through the resistor R_{On} as well as the initially uncharged capacitor C. This actually represents the exerciser starting to run. As time goes on, the capacitor voltage will get bigger and the voltage across the resistor will get smaller.

Having said that, we can represent the voltage across the capacitor as a function of time as follows:

$$V_C(t) = V_{On}.(1 - e^{\frac{-t}{\tau}}) \tag{8.8}$$

Where V_{On} represents the maximum voltage the capacitor will see or "can possibly see", and τ is the onset time constant as stated in the assumptions before.

If we leave the capacitor connected to V_{On} for a long time, the capacitor will reach the steady state and the voltage drop across it will be exactly the same as V_{On} and therefore, the current will no longer flow through the circuit.

The figure below shows $V_C(t)$ as a function of time.

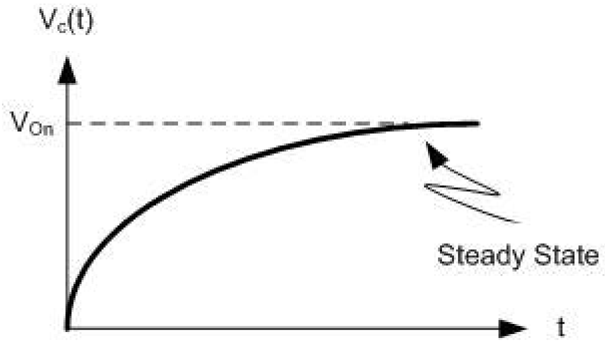

Fig. 8.5: Voltage Across C in the Onset Mode.

Reaching to V_{On} is not the case of the interval training protocol, because we need to switch the behavior of the exerciser before reaching the steady state to guarantee the maximum improvement .

As mentioned before, we did switch the behavior when reaching 80% of the maximum heart rate, and the following circuit represents the case when we switch from running to walking within the interval training segment in the running protocol. Now the switch is connected to the lower part of the circuit as follows:

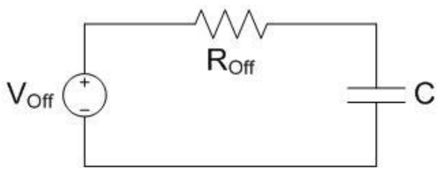

Fig. 8.6: RC Circuit in Offset Mode.

In this mode, the capacitor has already been charged to a certain amount (while being connected to the Onset Circuit), and we suddenly connect it to another voltage source which has smaller voltage value than the one that the capacitor already has.

In other words, once the switch is connected to the lower part of the circuit, $V_{Off} < V_C$. This actually represents the exerciser going from running to a recovery mode within the running segment in the training protocol itself.

Now, the voltage of the capacitor will start to change. If the capacitor is left connected to V_{Off} for a long time, then the voltage across the capacitor will drop from it is initial value to reach to V_{Off} at the steady state. How fast the capacitor will charge or discharge is depending on the time constant for both onset and offset modes.

The voltage across the capacitor as a function of time can be represented as follows:

$$V_C(t) = V_{Off} + (V_{On} - V_{Off}).e^{\frac{-t}{\tau}} \tag{8.9}$$

Where V_{Off} represents the minimum voltage the capacitor will see or ”can possibly see”, V_{On} is the initial value of the capacitor, and τ is the offset time constant as stated in the assumptions before.

The figure below represents the voltage across the capacitor in the offset mode as a function of time.

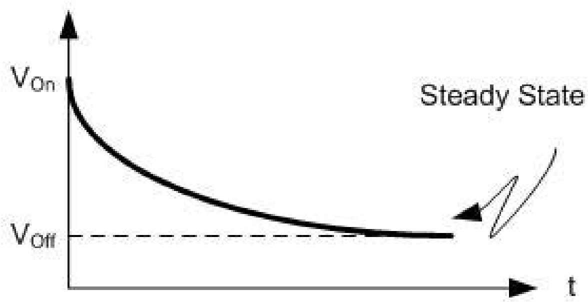

Fig. 8.7: Voltage Across C in the Offset Mode.

The previous discussion expresses and explains exactly the switching behavior of the designed RC circuit which simulates ”from circuit analysis point of view” the interval training protocol we designed before.

National Instruments Multisim has been used to simulate the proposed interval training protocol. Figure 8.8 below shows simulation results for the proposed interval training protocol for both HR and VO_2 responses.

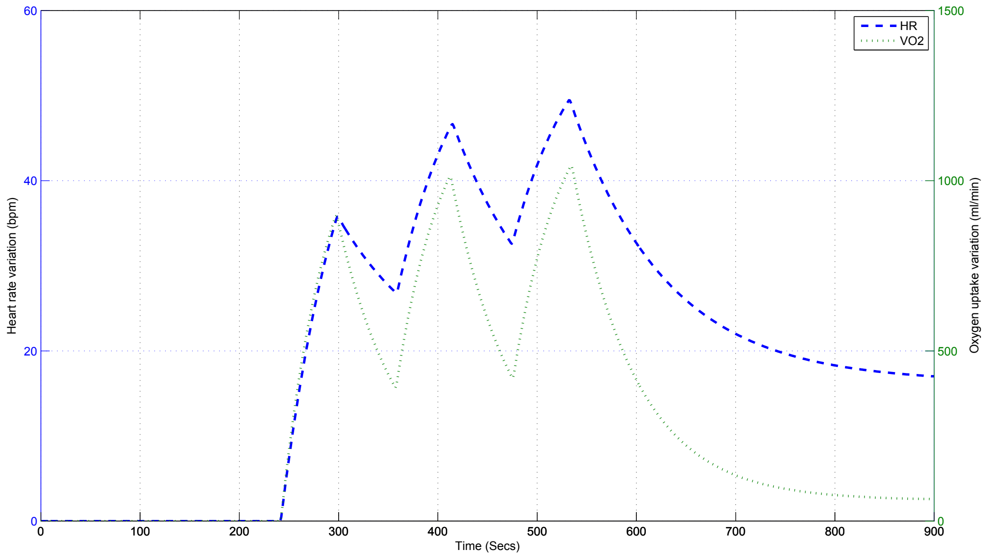

Fig. 8.8: Heart Rate and Oxygen Uptake Responses Simulation.

8.3 RC simulation and experimental results.

In this section we will try to present experimental results in order to compare and match them with the simulation results. Two new subjects were asked to run on the treadmill under the new interval training protocol. The experiments conditions as well as the tools were the same as we used before.

Subjects' characteristics are presented in Table 8.2.

Table 8.2: New Subjects Physical Characteristics.

Subjects	Age(yr)	Height(cm)	Weight(kg)
1	30	185	84
2	29	170	69

Experimental results for new subjects 1 and 2 are shown in Figures 8.9 and 8.10 respectively. From the figures below we can say that the experimental results match the simulation results. However in the case of the VO_2, the experimental results were skewed due to the presence of extensive noise. Therefore, recent studies find experimental HR data more efficient to use, they are clearer and more accurate.

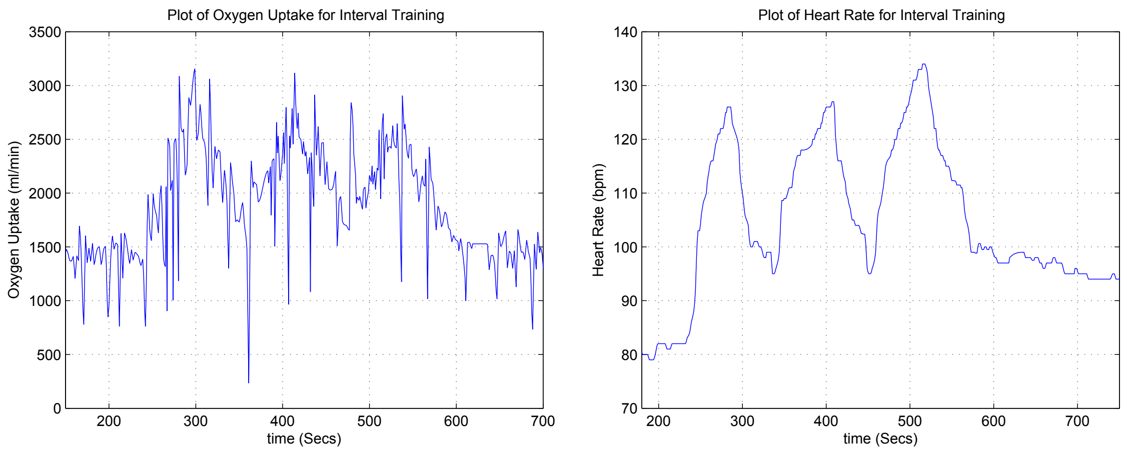

Fig. 8.9: HR and VO_2 Experimental Results for New Subject 1.

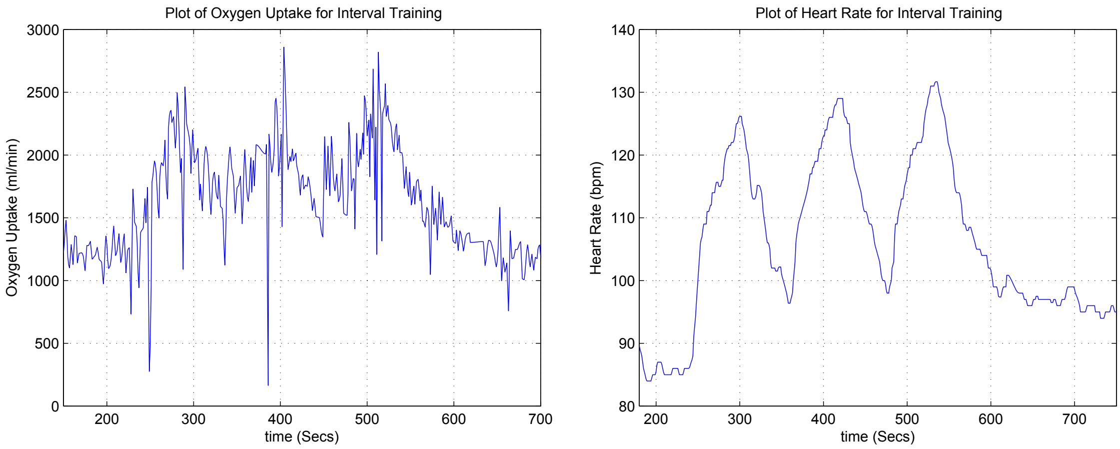

Fig. 8.10: HR and VO_2 Experimental Results for New Subject 2.

8.4 Conclusion.

A first order RC circuit is the simplest type of RC circuit. It has been chosen because of its good approximation of the mathematical model. Time constant of the RC circuit may be found by noting the time at which the response has dropped to 36.8% of its initial value. Large values of C and R provide large time constants and slow dissipation of the stored energy as a consequence. RC circuit can be expressed as a transfer function which has the same characteristics of a first order process.

Both HR and VO_2 responses to exercise have been identified to be modeled as a first order transfer function. Hence, RC circuit is the best match of their responses from the circuit analysis point of view. Average values of onset and offset time constants and steady states gains were used as the parameter values of the transfer function in the simulation. A simple RC circuit was built to simulate and ensure the continuity of onset and offset states and outputs during the switching period. Two new subjects were asked to run under the proposed interval training protocol. Experimental results match the simulation results. However, in the case of VO_2, the experimental results were skewed due to the presence of extensive noise.

Chapter 9

Controller Design and Simulation Study

9.1 Individualized adaptation for the proposed interval training protocol.

The proposed interval training protocol is based on the established average model for eight healthy young male subjects (Group A). However, for an individual exerciser who is young and healthy, the proposed protocol might need to be adjusted due the differences of the intra- and inter-subjects.

In this chapter, we present a hybrid system model (a dynamic system that exhibits both continuous and discrete dynamic behaviors) to describe the adaptation process and propose a multi-loop PI (Proportional and Integral) control approach for the tuning of interval training protocol.

9.2 Multi-loop PI controller.

PID controller is a control loop feedback controller widely used in industrial control systems. The PID abbreviation refers to the individual terms that make up the controller itself. These are P for proportional term, I for integral term and D for the derivative term in the controller.

In general, simple as well as complex industrial control systems may in a way or another comprise a control network whose main control module is a PID controller. P, I and D weighted sum can be used to adjust the process via the control element, and by tuning these three parameters, the controller can provide control action designed for specific process requirements.

The figure below shows symbolic, time domain and Laplace transform version of the PID controller respectively [106].

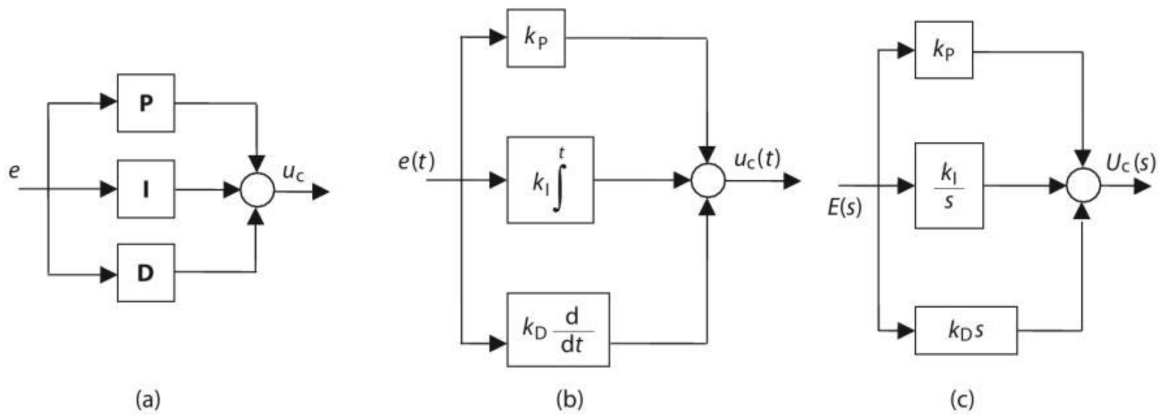

Fig. 9.1: Three Different Representations of the PID Controller.

Figure 9.2 below shows the controller inputs and outputs, the figure will be used to discuss in details the three terms of the PID controller.

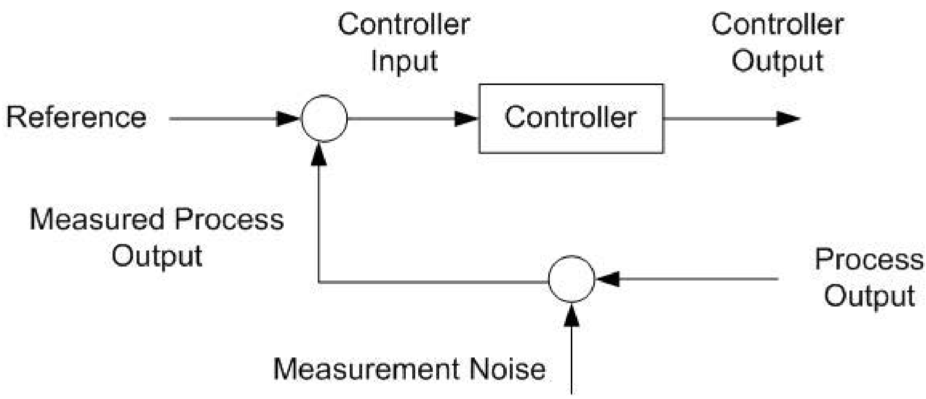

Fig. 9.2: Inputs and Outputs of a Feedback Loop PID Controller.

1. Proportional (P) Action:

   The proportional term depends on the present error; it produces an output value or signal that is proportional to the current error value or signal, it can be represented in time domain as:

$$u(t) = K_{\mathrm{p}}.e(t) \tag{9.1}$$

   where K_p is the proportional gain and e(t) is the process error signal and can be noted as:

$$e(t) = Reference - Measured \tag{9.2}$$

   On the one hand, if the proportional gain K_p is too high, the system can become unstable. On the other hand, if the proportional gain is too low, the control action may become too small when responding to system disturbances.

2. Integral (I) Action:

   Integral control is denoted by the I term in the PID controller, and is the sum of the instantaneous error over time. It is required when the controller needs a correct for any steady state offset from a constant reference signal value, it compensates the shortcoming of proportional control by eliminating offset without the use of a large controller gain.

   Integral control is proportional to both the magnitude and duration of the error, it gives the accumulated offset error which is then multiplied by the integral gain K_i and added to the controller output as follows:

$$u(t) = K_{\mathrm{i}}.\int_0^t e(\tau)\,.d\tau \tag{9.3}$$

   where K_i is the integral gain.

The integral term accelerates the movement of the process towards the desired setpoint. However, it can cause an overshoot in the present value due to its dependency on the accumulated errors from the previous one.

3. Derivative (D) Action:

   The purpose of the derivative control is to improve the closed-loop stability. It is calculated by determining the slope of the error over time, in other words, it uses the rate of change of an error signal as an input to introduce an element of prediction into the control action.

   The derivative term structure is given by:

$$u(t) = K_{\mathrm{d}}.\frac{de}{dt} \tag{9.4}$$

   where K_d is the derivative gain.

   The derivative control is mainly used to minimize the magnitude of the overshoot produced by the integral term. However, it may slow the transient response of the controller due to possible measurement noise amplification. Hence, more care is needed when using derivative control [107].

The proportional, integral, and derivative actions are summed to generate the output of the PID controller, the final structure of the PID controller is:

$$u(t) = K_{\mathrm{p}}.e(t) + K_{\mathrm{i}}.\int_0^t e(\tau)\,.d\tau \ + K_{\mathrm{d}}.\frac{de}{dt} \tag{9.5}$$

Where u(t) is the controller output, e is the error, t is the present time and τ is the variable of integration.

It has been mentioned before that HR and VO_2 responses to exercise can be modeled as a first order transfer function for both onset and offset exercises. And the general form of the transfer function can be noted as follows:

$$G(s) = \frac{K}{1 + \tau s} \tag{9.6}$$

Where K, τ are the steady state gain and the time constant respectively.

Based on the previous equation, we can conclude that we need two terms only from the PID controller to control the responses of both HR and VO_2, the proportional and the integral terms. Hence, a PI controller is adequate for our processes, and our PI controller notation will be given as:

$$u(t) = K_{\mathrm{p}}.e(t) + K_{\mathrm{i}}.\int_0^t e(\tau)\,.d\tau \tag{9.7}$$

To obtain the optimum values or behavior for the desired control responses, we need to tune some or in some cases all of our controller parameters. PI controller tuning is a difficult problem, even though we have only two parameters to control, because tuning process must satisfy different requirements which may conflict with one another within the system.

It is very important to understand the mechanisms of how each term can affect the output of the controller. Our first manual tuning method was based on the table below to obtain the desired set points from our controller.

Table 9.1: The Effects of Increasing K_p and K_i on the Controller Output.

Response	**Rise Time**	**Overshoot**	**Settling Time**	**Steady State Error**
K_p	Decrease	Increase	Negligible	Decrease
K_i	Decrease	Increase	Increase	Eliminate

A second approach or method that has been used in tuning our PI controller outputs is called Ziegler and Nicholas first method, first because they proposed more than one method, however, the first one is simple and applicable to use. Their method was based on conducting a number of experiments for determining values of K_p, K_i as well as K_d based on the transient step response of a plant.

Furthermore, the method applies to plants with neither integrator nor dominant complex-conjugate poles, whose unit step response resemble a reaction curve called the S-shaped curve with no overshoot. The figure below shows the S-shaped reaction curve.

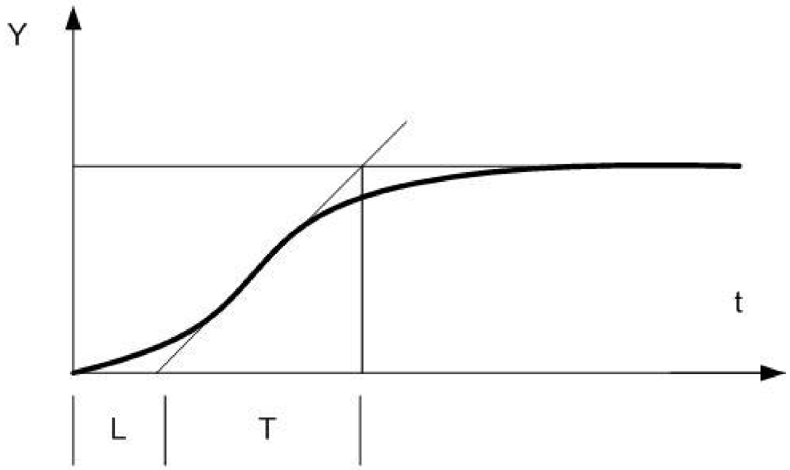

Fig. 9.3: Characterization of a Step Response in the ZieglerNichols Step Response Method.

The previous curve can be characterized by two constants, delay time L and time constant T, which are determined by the intersections between the tangent and the coordinate axes. The controller parameters are then obtained from the table below.

Table 9.2: PID Controller Parameters Obtained for the ZieglerNichols Step Response Method.

Controller	K_p	K_i	K_d
PI	$0.9\ \frac{T}{L}$	$0.27\ \frac{T}{L^2}$	0

Tables 9.1 and 9.2 have been compiled from [108].

The above illustrates the basics of a single input-single output (SISO) PI control scheme because it has only one controlled variable and one manipulated variable. However, our system consists of more than one input as well as more than one output. Therefore, a multiloop multi input-multi output (MIMO) needs to be explained and addressed as it is the basic control scheme for our design.

Due to the variation of the process interactions between input and output variables, MIMO processes are more difficult to deal with compared to the SISO processes [109]. In multiloop MIMO controller, the processes are treated as a collection of multi-single loops, and therefore, the controller is designed and implemented on each loop by taking loop interactions into account, the advantage of this scheme is that each loop can be treated as it was an independent loop.

The figure below shows a two input-two output formulation of MIMO process.

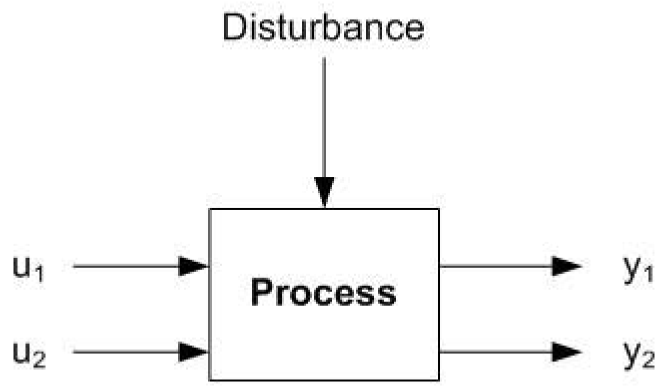

Fig. 9.4: MIMO (2x2) Process.

Where, u_1 and u_2 are the inputs, and y_1 and y_2 are the process outputs.

A multiloop controller will be used to control our 2x2 process, because each manipulated variable depends on only a single controlled variable such as a set of feedback controllers. The figure below shows the typical representation of the 2x2 controller. Where, R_1 and R_2 are the reference inputs, and y_1 and y_2 are the controller outputs.

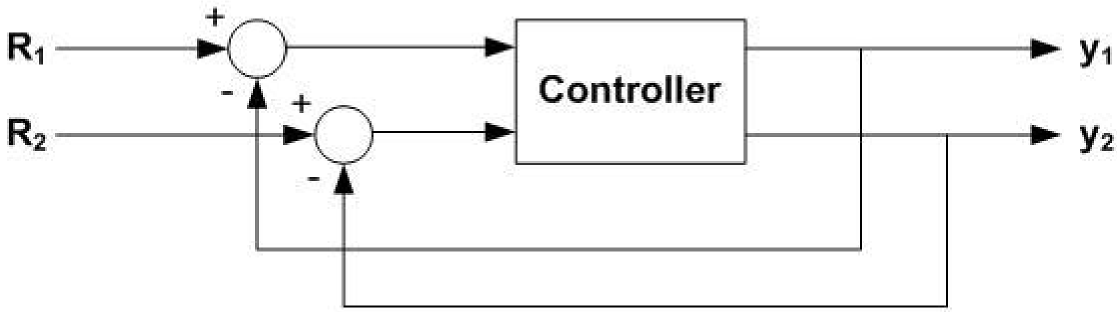

Fig. 9.5: MIMO (2x2) Controller Structure.

Based on figure 9.4, four transfer functions are required to represent the process interactions of the two controlled variables and the two manipulated variables.

$$\frac{Y_1(s)}{U_1(s)} = G_{\text{p11}}(s) \tag{9.8}$$

$$\frac{Y_1(s)}{U_2(s)} = G_{\text{p12}}(s) \tag{9.9}$$

$$\frac{Y_2(s)}{U_1(s)} = G_{\text{p21}}(s) \tag{9.10}$$

$$\frac{Y_2(s)}{U_2(s)} = G_{\text{p22}}(s) \tag{9.11}$$

The input-output relations for the process can be written as:

$$Y_1(s) = G_{\text{p11}}(s)U_1(s) + G_{\text{p12}}(s)U_2(s) \tag{9.12}$$

$$Y_2(s) = G_{\text{p21}}(s)U_1(s) + G_{\text{p22}}(s)U_2(s) \tag{9.13}$$

Equation 9.12 and 9.13 represent the structure of our PI controller. Due to the interactions between two or more control loops, the controller tuning becomes more difficult. However, the two controllers would not be tuned independently.

9.3 Hybrid system model.

Next section of this chapter will present a hybrid system model to describe the adaptation process of our proposed training protocol. However, it is essential to give an overview of the dynamic system that exhibits both continuous and discrete dynamic behavior in order to explain the necessity of using such a model in our design.

Hybrid system model is usually used when we need to combine the values of the continuous variables and a discrete control mode [110], its flexibility in modelling dynamic systems wins when it comes to encompassing large class of systems within its structure.

The hybrid system model will be mainly used in our design to represent the switching behavior of our process, the system has the ability to guide as well as synchronize the switching mechanism within the switched system which consists of a family of continuous or/and discrete time subsystems.

Hybrid system model has attracted an increasing attention in recent years, the extensive investigations that have been made in the past decade lead to some solutions over the following interesting problems [111]:

1. Ensure the stability of the switched system by finding a switching rule.
2. Seek stability results under arbitrarily switching sequences by assuming that the switching sequence is unknown.
3. Achieve closed-loop stability and performances of the switched systems under known and unknown switching sequences by designing new controllers.
4. Estimate a signal that cannot be directly measured by utilizing design observers for switched systems.
5. Find low-order switched systems to approximate the high-order switched ones.

Despite the flexibility and the benefits of using the hybrid system model, the analysis and design of such a system are more difficult than that of purely discrete or purely continuous systems, because the discrete dynamics may affect the continuous evolution and vice versa.

Form the general description of the hybrid system point of view; we can represent our model as a sequence of discrete actions, in each action, the system evolves continuously according to some dynamical actions until a transition instantaneously occurs.

Based on the previous description, we can assume that in our HR model, the action could be in the onset or offset mode, when the exerciser is on the onset mode, the HR increases continuously according to some formula. When the exerciser is participating in the offset mode, the HR decreases, the controller keeps the HR within some limit by adjusting the time of both onset and offset modes.

From mathematical point of view, the formal definition of the hybrid system model is given by [112]:

$$H = (Loc, Var, Lab, Edg, Act, Inv) \tag{9.14}$$

Where:

Loc is a finite set of vertices.

Var is a finite set of real-valued variables.

Lab is a finite set of synchronization labels.

Edg is a finite set of transitions or edges.

Act is a set of activities and Inv is a set of invariants at a location.

The state in the mathematical model can be changed in two ways, discrete or instantaneous transition and time delay.

9.4 The adaptation framework.

The final goal of the adaptation of the proposed interval training protocol is tuning the duty cycle (Δ t_1) as shown in Figure 9.6, and the period (Δ t_1 + Δ t_2) to achieve desired training effects.

The adaptation process is a set of successive interval training experiments for a particular user. This process can be described by using a hybrid system model.

Specifically, each single experiment can be considered as a discrete event and the dynamics of cardio-respiratory responses to exercise can be depicted by a continuous linear model. It will be shown under modest assumptions we can simplify this special hybrid system as a simple discrete time system.

The intermission between the interval training experiments can be hours or days. However, in order to simplify the process, we first assume that the intermission is invariant (similar as the sampling time of a discrete time system) given that the subject has similar physiological conditions before each training. For each training, the cardio respiratory responses (HR/VO_2) are actually the outputs of continuous systems.

Next, we can simplify the analysis by picking up some key characteristics from the continuous processes which are associated with exercise effects, such as mean value and standard deviation (STD). The proposed training protocol (see Figure 7.1) contains three-period square wave.

In this study we pick up the lowest point and the highest point of the third period of HR response $y(t_4)$ and $y(t_5)$ respectively as the reflections of exercise effects (see Figure 9.6).

Under the above assumptions, we can now simply treat every single interval training experiment as a simple static system, which has two inputs (the duty cycle Δ t_1 and the period (Δ t_1 + Δ t_2)) and two outputs (y(t_4) and y(t_5)). Then, the overall adaptation process can be simply treated as a two input-two output (2x2) discrete time system.

In order to determine the model of the two input-two output static system, we investigate HR response for the proposed interval training protocol. Figure 9.6 shows the protocol and its response.

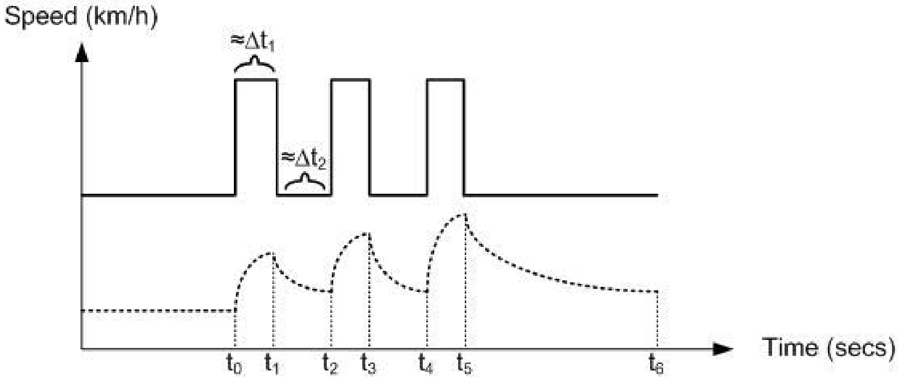

Fig. 9.6: HR Response During Interval Training Protocol.

Based on the previous model, the two inputs (the duty cycle Δ t_1 and the period (Δ t_1 + Δ t_2)) and the outputs y(t_1), y(t_2), y(t_3), y(t_4) and y(t_5) can be obtained as follows:

$$y_{\mathrm{HR}}(t_1) = K_1.(1 - \ e^{\frac{-\Delta t_1}{\tau_1}}) \tag{9.15}$$

$$y_{\mathrm{HR}}(t_2) = y_{\mathrm{HR}}(t_1) - K_2.(1 - \ e^{\frac{-\Delta t_1}{\tau_1}}).(1 + \ e^{\frac{-\Delta t_2}{\tau_2}}) \tag{9.16}$$

$$y_{\mathrm{HR}}(t_3) = y_{\mathrm{HR}}(t_1) + y_{\mathrm{HR}}(t_2).\ e^{\frac{-\Delta t_1}{\tau_1}} \tag{9.17}$$

$$y_{\mathrm{HR}}(t_4) = y_{\mathrm{HR}}(t_3).(1 - (K_2/K_1)(1 - \ e^{\frac{-\Delta t_2}{\tau_2}})) \tag{9.18}$$

$$y_{\mathrm{HR}}(t_5) = y_{\mathrm{HR}}(t_1) + y_{\mathrm{HR}}(t_4).\ e^{\frac{-\Delta t_1}{\tau_1}} \tag{9.19}$$

Where K_1, K_2, τ_1 and τ_2 are the onset and offset gains and time constants respectively.

9.5 Controller design and simulation study.

As the adaptation can be depicted as a discrete time system, we can design a discrete time multi-loop controller (Proportional and Integral controller) to adjust the two inputs (the duty cycle Δ t_1 and the period (Δ t_1 + Δ t_2)) to regulate the two outputs ($y(t_4)$ and $y(t_5)$) to reach the desired reference values. Figure 9.7 is the block diagram of the proposed control system. Two discrete PI controllers C_1 and C_2 have been built and connected to the HR model to control the desired output values $y(t_4)$ and $y(t_5)$ separately. The controller parameters (the coefficients of P and I action) of these two simple multi PI controllers are tuned by trial and error. We simulated the control performance in Matlab Simulink.

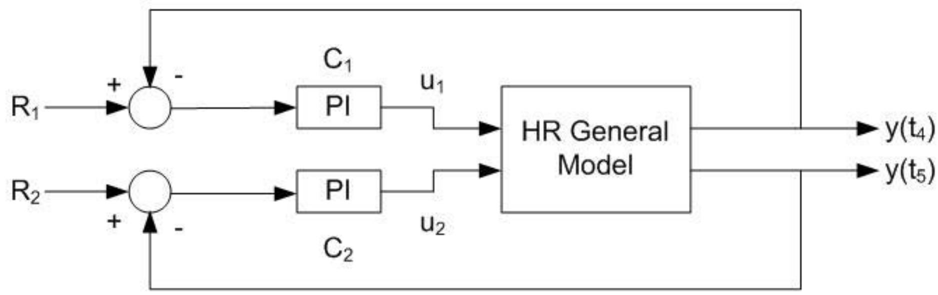

Fig. 9.7: Controller Structure.

Figure 9.8 below shows the detailed controller structure during simulation.

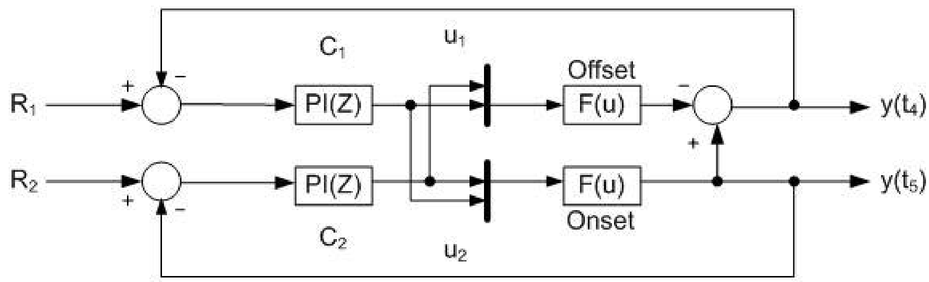

Fig. 9.8: Detailed controller structure.

Up to now, we can see even though our aim is to regulate a continuous process; we proposed a simple discrete time control technique to fulfill the goal.

During interval training of an individual subject, at the first iteration the exerciser is asked to run under the predefined training protocol. HR response at t_4 and t_5 (as shown in figure 9.6) will then be measured and feedbacked to the multi-loop control system to update controller outputs' inputs u_1 and u_2 (the duty cycle Δ t_1 and the period (Δ t_1 + Δ t_2)). This modification will try to adjust the measured process values ($y(t_4)$ and $y(t_5)$) to the desired setpoints for next training exercise. This recursive process will be repeated until we finally reach the desired set points. The self-adaptation feature gives the exerciser the opportunity to reach his desired setpoints after a number of iterations. Figure 9.9 and 9.10 below show the simulated controller outputs, $y(t_4)$ and $y(t_5)$.

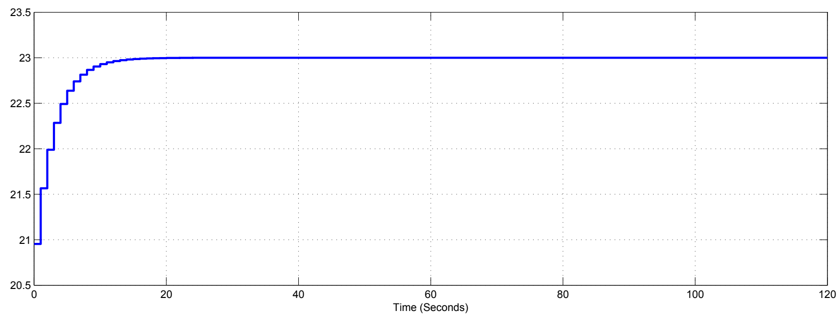

Fig. 9.9: $y(t_4)$ Output Signal.

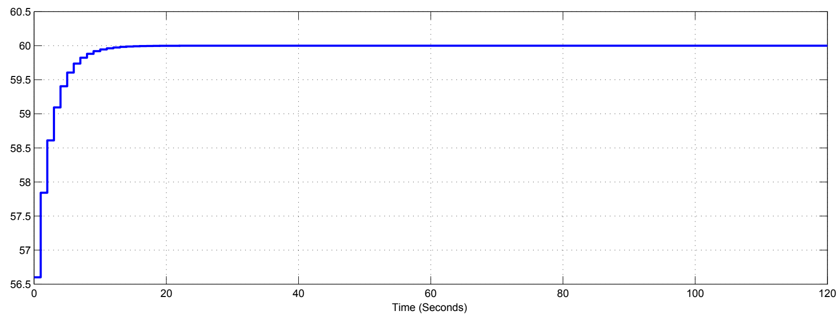

Fig. 9.10: $y(t_5)$ Output Signal.

From Figures 9.9 and 9.10, we conclude that after at least 12 iterations (12 training exercises) the system will reach to the desired setpoints.

In other words, t_4 and t_5 have to be observed 12 times and re-entered to controller to get finally the desired outputs.

Figure 9.11 below shows the HR response after12 iterations.

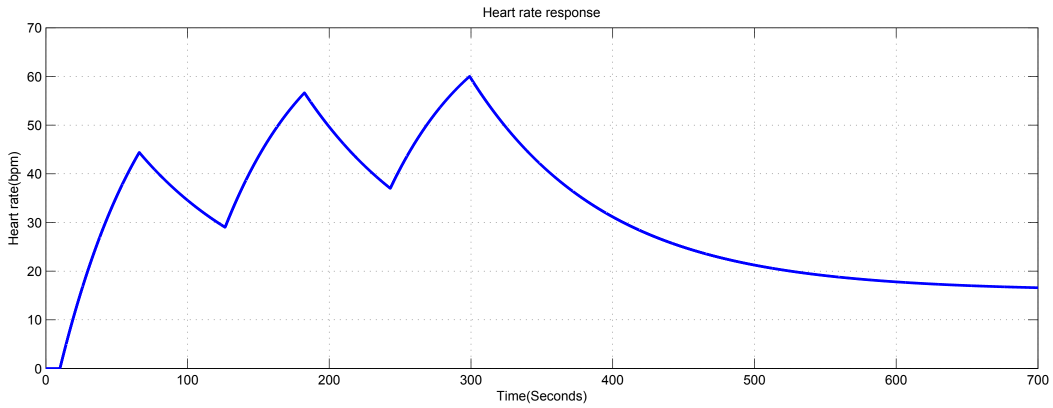

Fig. 9.11: Continuous Controller Output.

The third waveform in Figure 9.11 shows that the output signal finally reached the desired reference values R_1 and R_2 at t_4 and t_5 respectively.

It should be emphasized that the proposed multi-loop PI control algorithm only performs one time between two training experiments. Therefore, it is very easy to be implemented in low cost portable devices which have limited computation power.

9.6 Conclusion.

In this chapter, a hybrid system model was presented to describe the adaptation process, and propose a multi-loop PI control approach for tuning of interval training protocol. PI controller is a control loop feedback controller widely used in industrial control systems. P refers to proportional and I refers to integral term, these two terms make up the controller structure. By tuning I and P, the controller can provide control action designed for specific process requirements.

Proportional action depends on the present error; it produces an output value that is proportional to the current value. The system becomes unstable if the proportional gain is too high. Nevertheless, the control action may become too small when responding to system disturbances if the proportional gain is too low. The integral action represents the sum of the instantaneous error over time. It is essential when the controller needs a correct for any steady state offset from a constant reference signal. As a consequence, it is proportional to both the magnitude and duration of the error.

The integral term accelerates the movement of the process towards the desired setpoints. PI controller tuning is a difficult task, even though we have only two parameters to control, because tuning process must satisfy different requirements which may conflict with one another within one system. Manual tuning was used in this study in addition to Ziegler and Nicholas first method which is based on conducting a number of experiments for determining values of proportional and integral gains based on the transient step response of a plant.

Interval training protocol control scheme was presented as 2-input 2-output process, therefore, a multiloop controller was used to control our 2x2 process. Due to the interactions between two or more control loops, the controller tuning operation becomes more difficult. However, the two controllers have not been tuned independently.

Hybrid system model was used because we needed to combine the values of the continuous variables and a discrete control mode. However, the analysis and design of such a system are more difficult than that of purely discrete or purely continuous system, because the discrete dynamics may affect the continuous evolution and vice versa.

HR model was represented using the hybrid model as a sequence of discrete actions and in each action the system evolves continuously according to some dynamical actions until a transition instantaneously occurs.

The adaptation of the proposed interval training protocol was described using a hybrid system model, the final goal of this model was to tune the duty cycle as well as the period to achieve desired training effects. The lowest point and the highest point of the third period of HR model were picked as the reflections of exercise effects. Based on the previous assumptions, the inputs of our system were the duty cycle and the period, and the outputs were $y(t_4)$ and $y(t_5)$.

Matlab Simulink was used to simulate the control performance. The recursive process of our controller was repeated until we reached the desired setpoints. This self adaptation feature of our PI controller gave the exerciser the opportunity to reach his desired setpoints after a number of iterations.

The simulation results of our controller showed that after at least 12 iterations the system reached to the desired setpoints.

Chapter 10

Experimental Verification for the Proposed Adaptation Approach

10.1 Experiment location and setup.

In this chapter we will provide a practical way to examine the functionality of our designed controller. Stair climbing combined with our proposed interval training protocol has been chosen to demonstrate the effectiveness of our designed controller and its ability to control the exerciser's HR response within some margins which guarantee cardio vascular system improvement.

The PI controller itself has been implemented on Texas Instrument eZ430 programmable watch. Also $K4b^2$ has been used to collect and monitor both HR as well as VO_2 data.

UTS building one' emergency exit has been used in this experiment, the exercisers participate in climbing the stairs starting from level 14 towards level 26 or until the protocol setup time is finished. Each level consists of two sets of steps; each one contains 11 steps which gives us 22 steps in total for each level in the building.

All experiments were conducted at the same hour of the day between 9.30 a.m. and 10.30 a.m.. The temperature was measured to be around 25° Celsius, and the humidity was set at approximately 50%. The emergency exit has acceptable efficient air ventilation and all location attributes did assure that all equipment were operating under normal environmental temperatures and conditions.

We tried here to implement the proposed interval training protocol that has been created earlier but using different exercising technique which is stair ascending or climbing. Therefore, the setup of the interval training protocol remains the same except changing the type of the onset exercise from running on the treadmill to ascending stair in free environment.

Subjects in this experiment will be requested to ascend a staircase of steps without any pause; the exercisers will attempt to achieve the training protocol without holding the banisters or the handrail. The experiments were carried out at free speed, and the exercisers were given the instruction to walk up at their normal pace. However, the speed was monitored and a control beep was generated by the watch itself to indicate each exerciser to stay within 4-5 km/h walking speed.

Instead of walking on low speed as in the interval training protocol, the subject was asked to walk aside on the same step he has reached when the onset period finishes, and we assumed that continuous walking on the same step is the perfect match of the offset period in the original interval training protocol. The participants were instructed to use their left legs for the first step, to only place one foot on each step (foot-over-foot ascent) and to continue walking in straight line. The figure below shows the attributes of the staircase used in the present study.

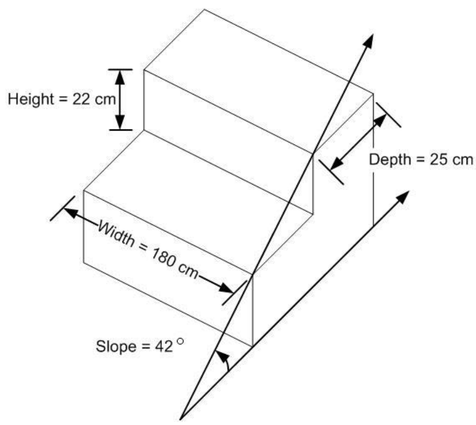

Fig. 10.1: Staircase Measurements.

10.2 Pre and post experiment preparation and subjects characteristics.

Following arrival to the experiment location, heart rate belt and gas analyzer unit have been fixed to the subject's body. Also, the subject was asked to wear the eZ430 watch on his right hand. After that, the subject was asked to sit and rest for five minutes prior to any exercise; we wanted to have some seated time before subject commenced the experiment.

After the five minutes period, the subject was asked to stand up next to the first set of stairs and wait for a two minute period whilst waiting to commence the training (walk-climb-walk) protocol. As mentioned before, going from seated to standing would induce an increase in HR/VO_2, so we waited for the subject to stand for two minutes before commencing walking to allow for bodily responses to settle down.

The figure below shows the walk-climb-walk interval training protocol.

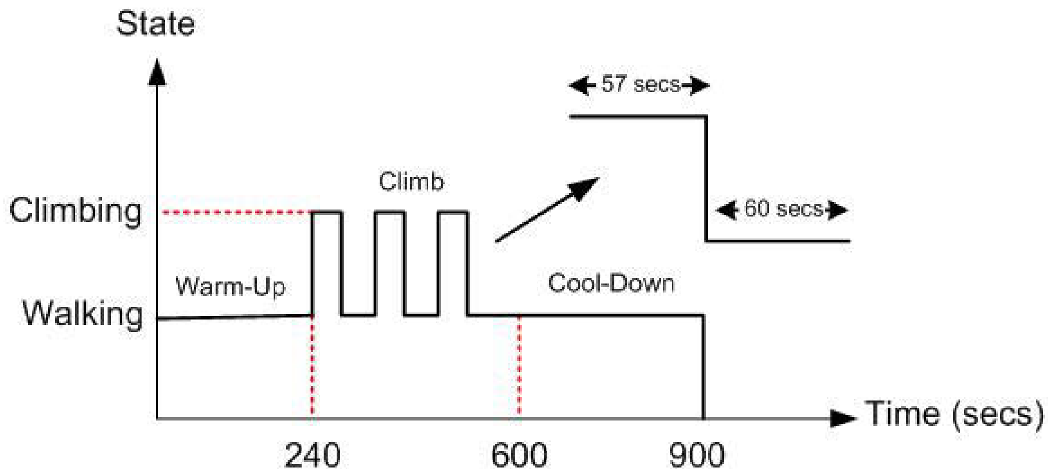

Fig. 10.2: Walk-Climb-Walk Interval Training Protocol.

Following two minutes of standing next to the first set of steps, the subject commenced walking on the flat platform.

Following the specified period of walking, the subject then started to climb the staircase. Following the climbing period, the subject went back to walking on the same step he has already reached when he finished the climbing period. Following the final walk in the protocol, the subject was escorted to a chair and he rested for five minutes.

During experiments, a real-time HR monitor was observed to guarantee the safety of the subject and the test was terminated when signs of poor perfusion, failure of HR to increase with increased intensity, or noticeable change in heart rhythm were detected.

Three subjects have participated in this part of the study, the participants were free from any known cardiac or metabolic disorders, hypertension, and were not under any medication. An informed consent was obtained from each participant before each experiment.

The physical characteristics of the participants have been recorded and presented in the table below.

Table 10.1: Physical Characteristics of the Subjects Participated in Climbing Exercise.

Subjects	**Age(yr)**	**Height(cm)**	**Weight(kg)**
1	31	172	75
2	32	184	90
3	26	170	55

Next, we will show down the calculation and explanation for the whole process for Subject 1.

Only final results and graphs for Subjects 2 and 3 will be shown after that.

Based on Subject 1's age, we can calculate his maximum heart rate which is equal to:

$$HR_{\max} = 205.8 - 0.685 \times (SubjectAge) \tag{10.1}$$

$$HR_{\max} = 205.8 - 0.685 \times (31) = 184.6 \approx 185bpm \tag{10.2}$$

Participating at 80% of the subject's maximum heart rate which is 148 bpm will guarantee improving the cardio vascular system performance as discussed before.

Based on this value and regardless if the exerciser has finished the climbing or the onset period of the protocol, an extra condition has been updated on the watch to indicate the exerciser whether he has reached his 80% of his maximum heart rate or not.

10.3 Controller implementation on eZ430 programmable watch.

The following control structure has been implemented on the programmable watch.

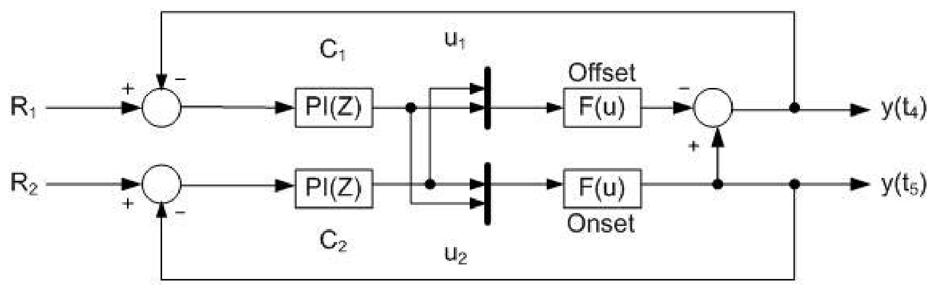

Fig. 10.3: Controller Structure Implementation.

Integrated sensor that has been already embedded in the watch such as the 3-Axis Accelerometer was used to indicate the exerciser about his speed and to keep it within 4-5 km/h. The sensor has many benefits such as low power consuming, small size, high performance and the most important one is the high shock durability. It is used specifically for activity monitoring as well as speed and distance measurements. It can be seen from the controller structure that some values need to be inserted manually into the watch before commencing the training protocol. Before starting the first iteration, the exerciser using the basic features of the watch has to enter the following inputs:

1. Age: the watch will then calculate the maximum heart rate and accordingly calculate the cardiovascular improvement working zone which is at 80% of the exerciser's maximum heart rate.

2. Duty cycle (Δ t_1): this parameter is used to set up the onset period of the training within the intervals segment.

3. Period (Δ t_1 + Δ t_2): this time frame represents the onset/offset period within the intervals segment.

Both R_1 and R_2 in the controller can be calculated using the manually inserted age, R_2 will target the offset level in the training protocol and will be set at 60% of the maximum heart rate. At this stage the training protocol time frame is fixed and implemented as in figure 10.2.

The table below shows the value the exercisers age and their corresponding 60-80% of maximum heart rate values.

Table 10.2: Exercisers Age and Their Corresponding 60-80% of Maximum Heart Rate Values.

Subjects	**Age(yr)**	**80% HR_{Max}(bpm)**	**60% HR_{Max}(bpm)**
1	31	148	111
2	32	147	110
3	26	150	113

Now let us move to the practical part and see in details how the previous description can be done by the exerciser. Three iterations have been done and here is the procedure as well as the result for the first iteration. Keep in mind that based on the simulation results in chapter 9, the exerciser needs 12 iterations to reach to his desired setpoints. However, we will see that the exerciser has almost reached to his desired setpoints after only three iterations.

Subject 1: **Iteration 1**:

The exerciser inserts his age manually into the watch which is 31. Based on this value, the watch will set R_1 at 148 bpm and R_2 at 111 bpm.

As default, the onset time for the first iteration will be 60 secs and the offset time will be 60 secs as well. The duty cycle is 50 and the period is 120 secs. The table below shows the watch and controller parameters before the first iteration:

Table 10.3: Watch and Controller Parameters Values.

Iteration	**Onset Time(secs)**	**Offset Time(secs)**	**Period (secs)**	**Duty Cycle**	**y(t_4)**	**y(t_5)**
Ref.	60	60	120	50	111	148

The exerciser then will start commencing the interval training protocol, the figure below shows the HR response after the first iteration:

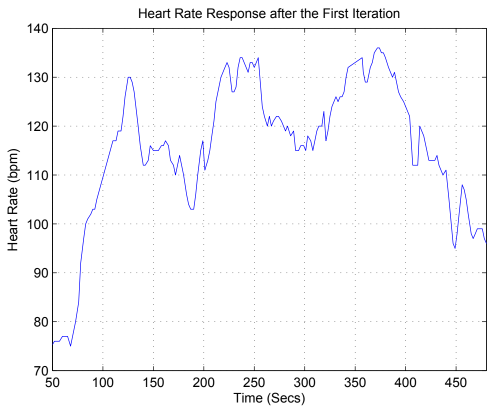

Fig. 10.4: Subject 1's HR Response After the First Iteration.

The table below shows the watch and the controller parameters after the first iteration:

Table 10.4: Watch and Controller Parameters Values After the First Iteration.

Iteration	**Onset Time(secs)**	**Offset Time(secs)**	**Period (secs)**	**Duty Cycle**	**y(t_4)**	**y(t_5)**
Ref.	60	60	120	50	111	148
1.	53	55.75	108.75	48.74	115	136

Subject 1: **Iteration 2**:

After the first iteration, the watch will measure the value of t_4 and t_5 and feedback them to the multi-loop control system to update the controller outputs' inputs (the duty cycle and the period). This modification will try to adjust the measured process values $y(t_4)$ and $y(t_5)$ to desired setpoints for the next training session or iteration.

Figure 10.5 below shows the HR response after the second iteration:

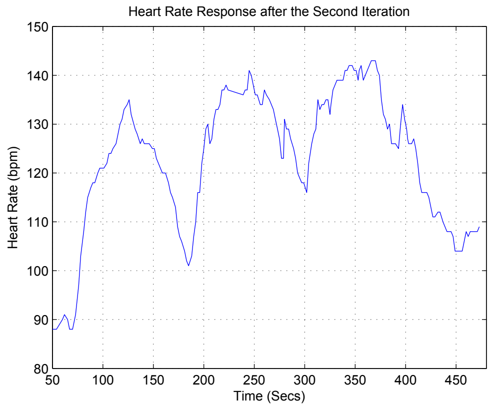

Fig. 10.5: Subject 1's HR Response After the Second Iteration.

Table 10.5 below shows the watch and the controller parameters after the second iteration:

Table 10.5: Watch and Controller Parameters Values After the Second Iteration.

Iteration	**Onset Time(secs)**	**Offset Time(secs)**	**Period (secs)**	**Duty Cycle**	**$y(t_4)$**	**$y(t_5)$**
Ref.	60	60	120	50	111	148
1.	53	55.75	108.75	48.74	115	136
2.	54.1	56.18	110.28	49.06	116	143

Subject 1: **Iteration 3**:

As in iteration number 2, the watch will measure the new value of t_4 and t_5 and feedback them to the multi-loop control system to update the controller outputs' inputs trying to adjust the measured process values $y(t_4)$ and $y(t_5)$ to desired setpoints for the next training session or iteration.

The figure below shows the HR response after the third iteration.

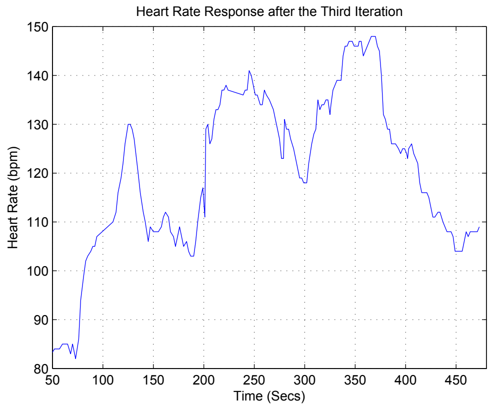

Fig. 10.6: Subject 1's HR Response After the Third Iteration.

Table 10.6 shows the watch and the controller parameters after the third iteration.

Table 10.6: Watch and Controller Parameters Values After the Third Iteration.

Iteration	**Onset Time(secs)**	**Offset Time(secs)**	**Period (secs)**	**Duty Cycle**	**y(t_4)**	**y(t_5)**
Ref.	60	60	120	50	111	148
1.	53	55.75	108.75	48.74	115	136
2.	54.1	56.18	110.28	49.06	116	143
3.	54.55	56.38	110.93	49.18	118	148

We can conclude from the previous table that the exerciser has almost reached to the desired setpoints after only 3 iterations. We kept in mind that after certain number of training sessions, the training capacity of the exerciser will improve, and this might affect the result of his HR response. We will try in the future to improve the performance of our controller to reach the desired setpoints with a minimum number of iterations.

Subject 2: **Iteration 1**:

The table below shows the watch and controller parameters before the first iteration:

Table 10.7: Watch and Controller Parameters Values.

Iteration	**Onset Time(secs)**	**Offset Time(secs)**	**Period (secs)**	**Duty Cycle**	**y(t_4)**	**y(t_5)**
Ref.	60	60	120	50	110	147

The figure below shows also the HR response after the first iteration:

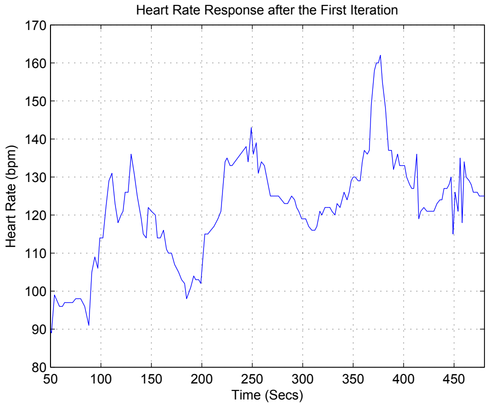

Fig. 10.7: Subject 2's HR Response After the First Iteration.

The table below shows the watch and the controller parameters after the first iteration:

Table 10.8: Watch and Controller Parameters Values After the First Iteration.

Iteration	**Onset Time(secs)**	**Offset Time(secs)**	**Period (secs)**	**Duty Cycle**	**$y(t_4)$**	**$y(t_5)$**
Ref.	60	60	120	50	110	147
1.	52.25	55.52	107.77	48.48	118	162

Subject 2: **Iteration 2**:

Figure 10.8 below shows the HR response after the second iteration:

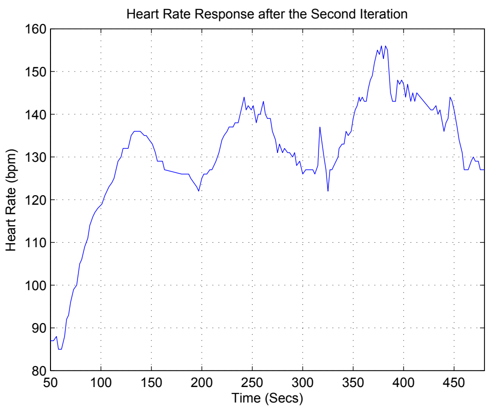

Fig. 10.8: Subject 2's HR Response After the Second Iteration.

Table 10.9 below shows the watch and the controller parameters after the second iteration:

Table 10.9: Watch and Controller Parameters Values After the Second Iteration.

Iteration	**Onset Time(secs)**	**Offset Time(secs)**	**Period (secs)**	**Duty Cycle**	**$y(t_4)$**	**$y(t_5)$**
Ref.	60	60	120	50	110	147
1.	52.25	55.52	107.77	48.48	118	162
2.	53.58	56.18	109.76	48.82	125	155

Subject 2: Iteration 3:

The figure below shows the HR response after the third iteration.

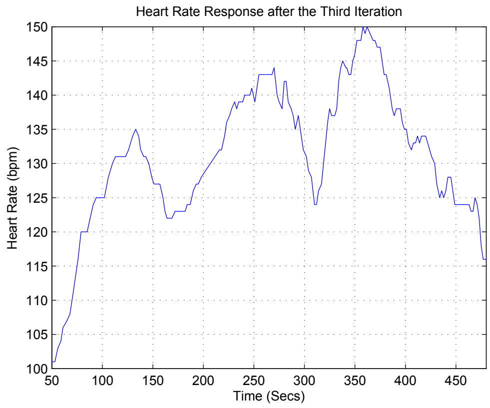

Fig. 10.9: Subject 2's HR Response After the Third Iteration.

Table 10.10 shows the watch and the controller parameters after the third iteration.

Table 10.10: Watch and Controller Parameters Values After the Third Iteration.

Iteration	**Onset Time(secs)**	**Offset Time(secs)**	**Period (secs)**	**Duty Cycle**	**$y(t_4)$**	**$y(t_5)$**
Ref.	60	60	120	50	110	147
1.	52.25	55.52	107.77	48.48	118	162
2.	53.58	56.18	109.76	48.82	125	155
3.	54.44	56.33	110.77	49.15	124	149

Subject 3: **Iteration 1**:

The table below shows the watch and controller parameters before the first iteration:

Table 10.11: Watch and Controller Parameters Values.

Iteration	**Onset Time(secs)**	**Offset Time(secs)**	**Period (secs)**	**Duty Cycle**	**y(t_4)**	**y(t_5)**
Ref.	60	60	120	50	113	150

The figure below shows the HR response after the first iteration:

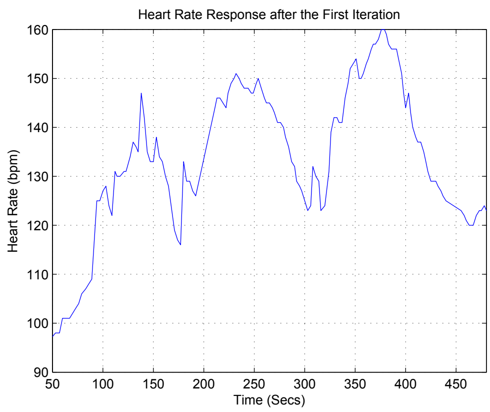

Fig. 10.10: Subject 3's HR Response After the First Iteration.

The table below shows the watch and the controller parameters after the first iteration:

Table 10.12: Watch and Controller Parameters Values After the First Iteration.

Iteration	**Onset Time(secs)**	**Offset Time(secs)**	**Period (secs)**	**Duty Cycle**	**y(t_4)**	**y(t_5)**
Ref.	60	60	120	50	113	150
1.	54.48	56.18	110.66	49.23	123	160

Subject 3: **Iteration 2**:

Figure 10.11 below shows the HR response after the second iteration:

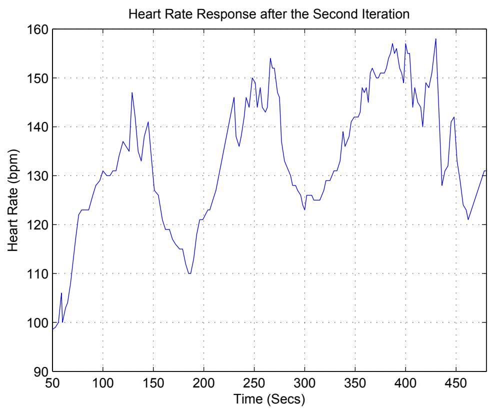

Fig. 10.11: Subject 3's HR Response After the Second Iteration.

Table 10.13 below shows the watch and the controller parameters after the second iteration:

Table 10.13: Watch and Controller Parameters Values After the Second Iteration.

Iteration	**Onset Time(secs)**	**Offset Time(secs)**	**Period (secs)**	**Duty Cycle**	**$y(t_4)$**	**$y(t_5)$**
Ref.	60	60	120	50	113	150
1.	54.48	56.18	110.66	49.23	123	160
2.	55.52	56.59	112.11	49.52	122	156

Subject 3: Iteration 3:

The figure below shows the HR response after the third iteration. Also, Table 10.14 shows the watch and the controller parameters after the third iteration.

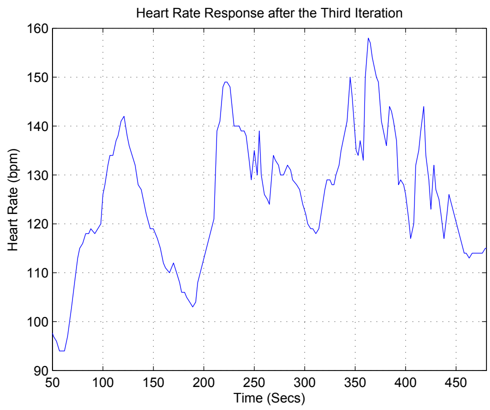

Fig. 10.12: Subject 3's HR Response After the Third Iteration.

Table 10.14: Watch and Controller Parameters Values After the Third Iteration.

Iteration	Onset Time(secs)	Offset Time(secs)	Period (secs)	Duty Cycle	$y(t_4)$	$y(t_5)$
Ref.	60	60	120	50	113	150
1.	54.48	56.18	110.66	49.23	123	160
2.	55.52	56.59	112.11	49.52	122	156
3.	56.25	56.78	113.03	49.77	118	157

10.4 Conclusion.

A new training protocol was presented in this chapter; the structure of the proposed interval training protocol was the same. However, the type of the training was changed from running on a treadmill to climbing staircase. We needed to show that interval training protocol can be implemented in different environment. Therefore, we implemented the interval protocol as well as our designed controller on eZ430 programmable watch.

The new experiment preparation operations were the same as the previous one but in different location. Three participants have commenced the new training setup.

Firstly, and before starting the first training session, each exerciser using some basic features entered his age, the duty cycle and period into the watch. The watch was guiding the exerciser into the interval training protocol structure by generating some beeps to indicate and instruct him prior each training action.

For the second iteration, the watch itself adjusted the values of the duty cycle as well as the period; the participant now will run under new conditions based on the output of the designed controller. Experimental results showed that the exercisers almost reached their desired setpoints after only three iterations. Further investigation is required and more subjects need to be recruited for the validation of this study.

Chapter 11
Conclusion and Future Work

11.1 Conclusion.

Cardiovascular fitness is an indication of health and physiological status and is mostly determined by physical activity participation and genetic contributors. It reflects the capacity of the respiratory system to carry out prolonged exercise, it also describes the ability of the heart, lungs a well as organs to deliver and consume oxygen during sustained physical activity. Oxygen consumption VO_2 and heart rate HR are embedded indicators within the cardiovascular system; these cardio respiratory endurances have been recognized as one of the fundamental components of cardiovascular and physical fitness.

Both HR and VO_2 can give a fair reflection of the intensity of work or exercise which is being performed, it is important to mention that HR and VO_2 are linearly related over a wide range of submaximal intensities, which means that both VO_2 and HR increase linearly with increasing exercise intensity up to near maximal exercise. However, the relationship between HR and VO_2 becomes non-linear during light and very highly intense activity. The first part of this study has combined the attributes and the dynamic characteristics of HR and VO_2 responses of onset and offset exercises in order to build up an effective interval training protocol which improves the cardiovascular system for two different age groups.

VO_2 and HR are important when building an effective training protocol, because observing these two factors can help predict the amount of energy spent during training protocols which is mainly used to determine goals such as fat burning or cardiovascular system improvement. Although the estimation of energy can be based on the relationship between HR and VO_2, the accuracy of predicting both energy and VO_2 has limitations because the relationship is curvilinear at very low and very high exercise intensities.

Firstly, two designed square-wave exercise protocols were applied to investigate the dynamic characteristics of HR and VO_2 responses of both the onset and offset exercises for two different age groups, A and B. For the values of HR and VO_2 to remain located in the linear part, a moderate speed of 9 km/h was examined and set to be the highest level in the training protocol for group A.

For the same previous reason, a moderate speed of 8 km/h was also examined and set to be the highest level in the training protocol for group B, each participant, at varying times, reached a reading of 80% of his HR_{max} at these speeds in both groups, A and B. Warm up and cool down periods have been also implemented within the training protocol to avoid any kind of stiffness or fatiguing effect may occur before, during and after the running time.

The $K4b^2$ portable device was used to measure breath-by-breath VO_2 and beat-by-beat HR. $K4b^2$ is a versatile system and was used because it has previously been reported to be valid, accurate and reliable. It can be used in the field or in the lab without any kind of limitation. The serial station mode has been used in this study. Under this operating mode, the portable unit was simply connected to the PC through a serial port, and all functions could be controlled via this serial link.

To obtain accurate measurements, three types of analyzer calibration have to be performed before data measurement and collection process. Room air calibration, reference gas calibration and delay calibration. These calibrations are essential to update the baseline and the gain of the analyzer in order to match the readings with the predicted reference gas and atmospheric values.

All experiments of the first part of this study have been performed at Center for Health Technologies (CHT), University of Technology, Sydney (UTS). Experiments were conducted in controlled laboratory environment and at the same hour of the day in order to eliminate the specific dynamic action of food for all practical purposes. The room in which experiments were performed was large enough to accommodate the necessary equipment and allow access to the participant in case of an emergency.

Previous studies have shown that many internal and environmental factors may have drastic effects on the readings during the experiment, even when all of the laboratory conditions have been set to be the same for all participants. Some environmental and undetectable factors may still affect the results. Therefore, to avoid any variance that may happen to the recorded data, the proposed training protocols were repeated twice and the data was interpolated, averaged as well as filtered.

According to the experimental results, it was concluded that the time constants and steady state gains of the onset exercise for both HR and VO_2 are distinctively different with those of the offset exercise. As a first observation, it has been clearly identified that all subjects have similar HR and VO_2 profiles. For each individual subject, steady state gain of offset is smaller than steady state gain of onset for both HR and VO_2 and that is due to the struggle that the body undergoes in recovery in the small time duration. Moreover, the difference between the onset and offset gain of VO_2 is noticeably higher than that in the case of the HR and this is due to different measurement scales for each parameter.

Matlab system identification toolbox was used to establish the first-order process model for each step response data. Based on the modelling results, it can be seen that the time constant of offset is larger than that of onset for both HR and VO_2. This was the case for all subjects in both groups, A and B. However, subject number 8 in group B showed another outcome, his offset time constant for VO_2 was smaller than his onset VO_2 time constant. Emotional effects as well as physiological status may still have affected the results of all participants. Nevertheless, there is no clear reason behind this singular result for this specific participant.

It has also been noticed that the time constant of VO_2 is smaller than time constant of HR for both onset and offset responses in group A, this important observation shows that the mechanism of oxygen consumption in human body in early ages as in group A, is responding faster than the one in HR. The experimental results show that this is not the case in group B, on the one hand the VO_2 offset time constant is smaller than the HR offset time constant as in group A. However, on the other hand, VO_2 onset time constant is larger than HR onset time constant for most of the participants in group B.

Secondly, average values of onset and offset time constants as well as steady state gains for VO_2 and HR profiles were presented and used to build an interval training protocol. To build a training protocol, targets have to be set first; our aim in this study was to build an interval training protocol to improve the cardiorespiratory fitness. Determining an actual HR_{max} was the key to constructing a well-designed training program. All running intervals should be completed at a maximum of 70% to 80% of HR_{max}.

Inbar maximum heart rate equation was utilized to build the interval training protocols. Average age for each group was implemented in the equation to create an average model values for each group. The interval training protocol of group A consists of three running intervals within the running segment while the proposed interval training protocol of group B contains only two running intervals. This number of intervals in each protocol was determined by the time where the exerciser exceeds an 80% of his maximum heart rate and it differs based on the age variation between the two groups.

Thirdly, a switching RC circuit model was presented to simulate HR and VO_2 responses for the proposed interval training protocol. However, there is no existing tool to directly simulate the switching behavior that ensures the continuity of both states and outputs during switching period. We constructed an RC circuit to simulate the proposed interval training protocol.

Two subjects at this stage of the study were asked to run under the new interval training protocol conditions. These experiments led us to clearly compare the experimental results with the simulation ones. It was concluded that experimental results match the simulation results. However, in the case of the VO_2, the experimental results were skewed due to the presence of extensive noise.

The second part of this study focused on creating an individualized adaptation for the proposed interval training in order to be controlled and adjusted later on using a multiloop controller. The proposed interval training protocol was based on the established average model for certain number of participants. Yet for an individual exerciser who is young and healthy, the proposed protocol might need to be adjusted due to the differences of the intra- and inter-subjects.

Because the adaptation process is a set of successive interval training experiments for a particular user, a hybrid system model was presented to describe the adaptation process and propose a multi-loop PI controller for the tuning of interval training protocol. Under some valid assumptions, every single interval training experiment was treated as a simple two-input-two-output discrete time system, where the inputs represented the duty cycle and the period and the outputs represented the lowest and highest points of the third period of HR response. Therefore, a discrete time multiloop controller was designed to adjust the two inputs to regulate the two outputs to reach the desired reference vales. The recursive process as well as the self adaptation feature of the controller gave the exerciser the opportunity to reach his desired setpoints after a number of iterations.

Based on the simulation results, it was concluded that after at least 12 iterations, the system will reach to the desired setpoints. In other words, the time of the lowest and highest point in the HR model have to be observed 12 times and re-entered to the designed controller to get the desired outputs. It should be emphasized that the proposed multi-loop PI control algorithm only performs one time between two training experiments. Therefore, it is very easy to be implemented in low cost portable devices which have limited computation power.

The final stage of this study was to verify the proposed adaptation scheme. Stair climbing combined with the proposed interval training protocol were chosen and implemented on eZ430 Texas Instrument watch to demonstrate the effectiveness of the designed controller. Experimental results showed that the exerciser reached his desired setpoints after three iterations only. Though, more subjects need to be recruited for the validation of the proposed models, interval training protocol and the feedback control based adaptation scheme.

11.2 Future work.

The training protocols setup requires further development to improve its performance, reliability and ability to handle wide age range diversity. It is intended that the training protocol will be redesigned to fulfill different age requirements. As discovered from the experimental studies, the speed limit will be an important issue, so more experiments will help us reach the target of creating one training protocol setup with one high speed running limit which suits different age group.

The designed interval training protocol itself requires additional adjustment to handle more physical targets such as fat burning, developing endurance and aerobic capacity and developing the lactic acid system. More experiments on male and female subjects will be conducted to firstly validate the results that we have reached in this study, and secondly be the grounds of the new interval training setup. The new design will need to take into consideration the number of speed intervals within the training protocol, the frequency as well as the ease of use of such a training regime to achieve different physical targets.

Furthermore, the multi-loop controller requires some improvement, we will aim for a new controller design which can adjust more than two inputs to regulate the values of each single interval within the interval training protocol not only to regulate the lowest and the highest point of the last period of HR response. The new design has to give the exerciser the freedom to choose which response he or she needs to regulate HR or VO_2. The new design also needs to take into account the intermission between the interval training sessions and the difference in the physiological conditions for each exerciser before and after each training session.

Further common environments will be investigated, such as free speed running, swimming and jumping. These types of environments can have a wide range of effects on the individual or exerciser. Therefore, the ability for the designed controller and the interval training to control and cope respectively with these training schemes under free-conditions environments would be beneficial. The controller design will be improved to quickly and effectively reach the desired setpoints. All efforts will move forward towards minimizing the number of iterations for each exerciser.

Bibliography

[1] *K4b^2 User manual.* x, 32, 33, 42

[2] Sallis JF, McKenzie TL, "Physical education's role in public health," *Res Q Exerc Sport*, vol. 62, no. 2, pp. 124–37, 1991. 1

[3] Bishop D., "Warm up i: potential mechanisms and the effects of passive warm up on exercise performance," *Sports Med*, vol. 33, no. 6, pp. 439–54, 2003. 1

[4] Bishop D., "Warm up ii: performance changes following active warm up and how to structure the warm up," *Sports Med*, vol. 33, no. 7, pp. 483–98, 2003. 1

[5] Grodjinovsky A, Magel JR, "Effect of warming-up on running performance," *Res Q*, vol. 41, no. 1, pp. 116–9, 1970. 1

[6] Bergh U, Ekblom B, "Influence of muscle temperature on maximal muscle strength and power output in human skeletal muscles," *Acta Physiol Scand*, vol. 107, no. 1, pp. 33–7, 1979. 1

[7] Goodwin JE, "A comparison of massage and sub-maximal exercise as warm-up protocols combined with a stretch for vertical jump performance," *J Sports Sci*, vol. 20, no. 1, pp. 48–9, 2002. 1

[8] Gray S, Nimmo M, "Effects of active, passive or no warmup on metabolism and performance during high-intensity exercise," *J Sports Sci*, vol. 19, pp. 693–700, 2001. 1

[9] Pyke FS, “The effect of preliminary activity on maximal motor performance,” *Res Q*, vol. 39, no. 4, pp. 1069–76, 1968. 1

[10] Stewart IB, Sleivert GG, “The effect of warm-up intensity on range of motion and anaerobic performance,” *J Orthop Sports Phys Ther*, vol. 27, no. 2, pp. 154–61, 1998. 1

[11] Matthew Stewart, Roger Adams, Albert Alonso, Blake Van Koesveld, Scott Campbell, “Warm-up or stretch as preparation for sprint performance?,” *Journal of Science and Medicine in Sport*, vol. 10, pp. 403–410, 2007. 1

[12] Shellock FG, Prentice WE, “Warming-up and stretching for improved physical performance and prevention of sports-related injuries,” *Sports Med*, vol. 2, pp. 267–78, 1985. 1

[13] High DM, Howley ET, Franks BD, “The effects of static stretching and warm-up on prevention of delayed-onset muscle soreness,” *Res Q Exerc Sport*, vol. 60, no. 4, pp. 357–61, 1989. 1

[14] Rodenburg JB, Steenbeek D, Schiereck P, et al., “Warm-up, stretching and massage diminish harmful effects of eccentric exercise,” *Int J Sports Med*, vol. 15, pp. 414–9, 1994. 1

[15] Evans RK, Knight KL, Draper DO, et al., “Effects of warm up before eccentric exercise on indirect markers of muscle damage,” *Med Sci Sports Exerc*, vol. 34, no. 12, pp. 1892–9, 2002. 1

[16] Wright V, Johns RJ, “Quantitative and qualitative analysis of joint stiffness in normal subjects and in patients with connective tissue disease,” *Ann Rheum Dis*, vol. 20, pp. 36–46, 1961. 1

[17] Pope RP, Herbert RD, Kirwan JD, "Effects of flexibility and stretching on injury risk in army recruits," *Aust Physiother*, vol. 44, pp. 167–72, 1998. 1

[18] Pope RP, Herbert RD, Kirwan JD, Graham BJ, "A randomized trial of pre-exercise stretching of prevention of lower-limb injury," *Med Sci Sports Exerc*, vol. 31, no. 2, pp. 271–7, 2000. 1

[19] American College of Sports Medicine, "Acsm's guidelines for exercise testing and prescription," *Baltimore: Lippincott Williams and Wilkins*, vol. 7, 2006. 2

[20] Balderrama C, Ibarra G, De La Riva J, Lopez S, "Evaluation of three methodologies to estimate the vo_{2max} in people of different ages," *Applied Ergonomics*, vol. 42, pp. 162–68, 2010. 2

[21] Tommy Boone, "Introduction to exercise physiology," *Jones and Bartlett Publishers*, 2013. 2

[22] Micheal A. Clark, Scott C. Lucett, "Nasm essentials of personal fitness training," *National Academy of Sports Medicine*, vol. 3, 2007. 2

[23] Grant, B., and O'Brien Cousins, S., "Ageing and physical activity: the promise of qualitative research," *Journal of Ageing and Physical Activity*, vol. 9, pp. 237–244, 2001. 2

[24] Arida, R.M., de Jesus Vieira, A., Cavalheiro, E.A, "Effect of physical exercise on kindling development," *Epilepsy Res*, vol. 30, no. 2, pp. 127–132, 1998. 2

[25] Gomes da Silva, S., Dona, F., da Silva Fernandes, M.J., Scorza, F.A., Cavalheiro, E.A., Arida, R.M, "Physical exercise during the adolescent period of life increases hippocampal parvalbumin expression.," *Brain Dev*, vol. 32, no. 2, pp. 137–142, 2010. 2

[26] Billat, L. Veronique, "Interval training for performance: A scientific and empirical practice," *Sports Medicine*, vol. 31, no. 1, pp. 13–19, 2001. 3, 26

[27] Astrand, Per-Olof and Kaare Rohdahl, *Work Physiology*. New York: McGraw-Hill Book Company, 1970. 3

[28] Ioannis G. Nasis, Ioannis Vogiatzis, Grigoris Stratakos, Dimitris Athanasopoulos, Antonia Koutsoukou, Andreas Daskalakis, Stavroula Spetsioti, Aphrodite Evangelodimou, Charis Roussos, Spyros Zakynthinos, "Effects of interval-load versus constant-load training on the BODE index in COPD patients," *Respiratory Medicine*, vol. 103, no. 9, pp. 1392–1398, 2009. 3

[29] Ragnheiour Harpa Arnardottir, Gunnar Boman, Kjell Larsson, Hans Hedenstrom, Margareta Emtner, "Interval training compared with continuous training in patients with COPD," *Respiratory Medicine*, vol. 101, no. 6, pp. 1196–1204, 2007. 3

[30] B. Villemur, A. Marquer, E. Gailledrat, C. Benetreau, B. Bucci, V. Evra, V. Rabeau, M.P. De Angelis, J.-Y. Bouchet, P. Carpentier, D. Perennou., "New rehabilitation program for intermittent claudication: Interval training with active recovery. pilot study.," *Annals of Physical and Rehabilitation Medicine*, vol. 54, no. 5, pp. 275–281, 2011. 3

[31] Parisa Amiri-Farsani, Davar Rezaeimanesh, Eidy Alijani, "The effect of eight-week sprint and endurance interval training on some lung volumes and capacities in female nonathletic students at islamic azad university of abadan.," *Social and Behavioral Sciences*, vol. 15, pp. 2101–2104, 2011. 3

[32] Eastwood, P. R., Hillman, D. R., finucane, K. E, "Inspirary muscle performance in endurance athletes and sedentary subjects," vol. 6, no. 2, pp. 95–104, 2001. 3

[33] Enright, S. J., Unnithan, V. B., Davies, D. H., "Effect of high-aspiratory muscle training on lung volumes,diaphragm thickness,and exercise capacity in subjects who are healthy," vol. 86, no. 3, pp. 345–54, 2006. 3

[34] Cottin, F., Medigue, C., Leprater, P. M., Papelier, Y., Koralsztein, J. P., Billatv, "Heart rate variability during exercise performed below and above ventilatory threshold," *France Laboratory of exercise Physiology and Genetics*, vol. 36, no. 4, pp. 594–600, 2004. 3

[35] Deruell, F., Brosbois J.M., Muccip., Bartf., Lensel, G., Fabrec, "Ventilatory threshold characterizations during incremental rowing and cycling exercises in older subjects," vol. 29, no. 5, pp. 564–78, 2004. 3

[36] Celine Freyssin, Chantal Verkindt, Fabrice Prieur, Philippe Benaich, Sebastien Maunier, Philippe Blanc, "Cardiac rehabilitation in chronic heart failure: Effect of an 8-week, high-intensity interval training versus continuous training," *Archives of Physical Medicine and Rehabilitation*, vol. 93, no. 8, pp. 1359–1364, 2012. 3

[37] . Athanasios Tasoulis, Ourania Papazachou, Stavros Dimopoulos, Vasiliki Gerovasili, Eleftherios Karatzanos, Theodoros Kyprianou, Stavros Drakos, Maria Anastasiou-Nana, Charis Roussos, Serafim Nanas, "Effects of interval exercise training on respiratory drive in patients with chronic heart failure," *Respiratory Medicine*, vol. 104, no. 10, pp. 1557–1565, 2010. 3

[38] M. Siahkouhian, D. Khodadadi, K. Shahmoradi, "Effects of high-intensity interval training on aerobic and anaerobic indices: Comparison of physically active and inactive men," *Science and Sports*, 2013. 4

[39] A. Faruk Ugras, "Effect of high intensity interval training on elite athletes' antioxidant status," *Science and Sports*, 2012. 4

[40] Martins, R. A et al., "Effects of aerobic and strength-based training on metabolic health indicators in older adults," *Lipids Health Dis*, vol. 22, no. 9, p. 76, 2010. 4

[41] Girard A, Pappas GJ, "Approximation metrics for discrete and continuous systems," *IEEE Trans Autom Control*, vol. 52, no. 5, pp. 782–798, 2007. 10

[42] R. Alur, T. A. Henzinger, G. Lafferriere, and G. J. Pappas, "Discrete abstractions of hybrid systems," *Proc. IEEE*, vol. 88, no. 7, pp. 971–984, 2000. 10

[43] Bouchard C, Daw EW, Rice T, Perusse L, Gagnon J, Province MA, Leon AS, Rao DC, Skinner JS, Wilmore JH., "Familial resemblance for VO_{2max} in the sedentary state: the HERITAGE family study," *Med. Sci. Sports Exercise*, vol. 30. 11

[44] Ekblom-Bak, Elin, "The importnace of non-exercise physical activity for cardiovascular health and longevity," *Br J Sports Med*, vol. 48, no. 3, pp. 233–8, 2014. 11

[45] Donatelle, Rebecca J., "Health, the basics," *San Francisco: Pearson Education, Inc.*, vol. 6. 11

[46] Charles H. Hillman, Edward P. Weiss, James M. Hagberg, Bradley D. Hatfield, "The relationship of age and cardiovascular fitness to cognitive and motor processes," *Psychophysiology*, vol. 39, no. 3, pp. 303–312, 2002. 11

[47] Darren K. McGuire, Benjamin D. Levine, Jon W. Williamson, Peter G. Snell, C. Gunnar Blomqvist, Bengt Saltin, Jere H. Mitchell, "A 30-year follow-up of the dallas bed rest and training study: I. effect of age on the cardiovascular response to exercise," *Circulation*, vol. 18. 11

[48] C J Caspersen, K E Powell, and G M Christenson, "Physical activity, exercise, and physical fitness: definitions and distinctions for health-related research," *Public Health Rep*, vol. 100, no. 2, pp. 126–131, 1985. 12

[49] Carl J. Caspersen, Kenneth E. Powell, Gregory M. Christenson, "Physical activity, exercise, and physical fitness: definitions and distinctions for health-related research," *Public health reports [0033-3549] Caspersen, C J*, vol. 100, no. 2, p. 126, 1985. 12

[50] Henry L. Taylor, David R. Jacobs Jr., Beth Schucker, Joan Knudsen, Arthur S. Leon, Guy Debacker, "A questionnaire for the assessment of leisure time physical activities," *J Chronic Dis*, vol. 31. 12

[51] Y. Claire Wang, Amber Hsiao, C. Tracy Orleans, Steven L. Gortmaker, "The caloric calculator: Average caloric impact of childhood obesity interventions," *American Journal of Preventive Medicine*, vol. 4, no. 2, pp. e3–e13, 2013. 12

[52] Henry J. Montoye, "Physical activity and health: an epidemiologic study of an entire community," *Prentice-Hall, Inc., Englewood Cliffs, NJ,*. 12

[53] Folsom AR, Caspersen CJ, Taylor HL, Jacobs DR Jr, Luepker RV, Gomez-Marin O, Gillum RF, Blackburn H., "Leisure time physical activity and its relationship to coronary risk factors in a population-based sample. the minnesota heart survey," *Am J Epidemiol.*, vol. 121, no. 4, pp. 570–9, 1985. 12

[54] Henry L. Taylor, "Physical activity: is it still a risk factor?," *Prev Med*, vol. 12, no. 1, pp. 20–24, 1983. 13

[55] President's Council on Physical Fitness and Sports, "Physical fitness research digest," *Washington, DC,*, vol. 1. 13

[56] R. Acharya U, A. Kumar, P.S. Bhat, C.M. Lim, S.S. lyengar, N. Kannathal, S.M. Krishnan, "Classification of cardiac abnormalities using heart rate signals," *Med Boil Eng Comput*, vol. 42, no. 3, pp. 288–93, 2004. 14

[57] Achten J., Jeukendrup AE., "Heart rate monitoring applications and limitations," *Sports Med*, vol. 33, no. 7, pp. 517–38, 2003. 14, 41, 48

[58] Carlo Castagna, Romualdo Belardinelli, Franco M. Impellizzeri, Grant A. Abt, Aaron J. Coutts, Stefano D'Ottavio, "Cardiovascular responses during recreational 5-a-side indoor-soccer," *Journal of Science and Medicine in Sport*, vol. 10, no. 2, pp. 89–95, 2007. 14

[59] Lippincott Williams and Wilkins, "Acsm's guidlines for exercise: testing and prescription," *American College of Sports Medicine*, vol. 6, 2000. 16

[60] Heyward, V. H., "Advanced fitness assessment and exercise prescription," *Champaign, IL: Human Kinetics*, vol. 4, 2002. 16

[61] Jackson, A. S., Ross, R. M., "Understanding exercise for health and fitness," *Houston: CSI Software*, vol. 2, 1992. 16

[62] Robert A. Robergs, Roberto Landwehr, "The surprising history of the HR_{max}=220-age equation," *JEPonline*, vol. 5, no. 2, pp. 1–10, 2002. 16

[63] Inbar O, Oren A, Scheinowitz M, Rotstein A, Dlin R, Casaburi R, "Normal cardiopulmonary responses during incremental exercise in 20-70-yr-old men," *Med Sci Sport Exercise*, vol. 26, no. 5, pp. 538–546, 1994. 16

[64] Holland, L. J., Bhambhani, Y. N., Ferrara, M. S., Steadward, R. D., "Reliability of the maximal aerobic power and ventilatory threshold in adults with cerebral palsy," *Archive of physical and medical rehabilitation*, vol. 75, pp. 687–69, 1994. 17

[65] Thomas W.L. Holmes, David J. Williams, "Cardiac output measurement," *Anaesthesia and Intensive Care Medicine*, vol. 11, no. 2, pp. 58–61, 2010. 17

[66] McArdle W, Katch F, Katch V, "Exercise physiology: energy, nutrition and human performance," *Baltimore (MD): Williams and Wilkins*, vol. 4, 1996. 19

[67] Ulf Ekelund, Eric Poortvliet, Agneta Yngve, Anita H., Andreas Nilsson, Michael S., "Heart rate as an indicator of the intensity of physical activity in human adolescents," *Eur J Appl Physiol*, vol. 85, pp. 244–249, 2001. 19

[68] Duffeld R, Edge J, Bishop D, "Effects of high-intensity interval training on the VO_2 response during severe exercise.," *Journal of Science and Medicine in Sport*, vol. 9, pp. 249–55, 2006. 21

[69] Helgerud J, Hoydal K, Wang E, Karlsen T, Berg P, Bjerkaas M, Simonsen T, Helgesen C, Hjorth N, Bach R, Hoff J, "Aerobic high-intensity intervals improve VO_2 more than moderate training.," *Medicine and Science in Sports and Exercise. Official Journal of the American College of Sports Medicine*, pp. 665–71, 2007. 21

[70] Rushall, Brent S., Pyke, Frank S., *Physical education and training; Physical fitness*. Macmillan Co. of Australia (South Melbourne), 1990. 23

[71] Pate RR, Pratt M, Blair SN, Haskell WL, Macera CA, Bouchard C, Buchner D, Ettinger W, Heath GW, King AC, et al., "Physical activity and public health. a recommendation from the centers for disease control and prevention and the american college of sports medicine," *American College of Sports Medicine, JAMA*, vol. 273, pp. 402–7, 1995. 24

[72] Gibala MJ, "High-intensity interval training: a time-efficient strategy for health promotion?," *Curr Sports Med Rep*, vol. 6, pp. 211–3, 2007. 24

[73] Hawley JA, Gibala MJ, "Exercise intensity and insulin sensitivity: how low can you go?," *Diabetologia*, vol. 52, pp. 1709–13, 2009. 24

[74] Burgomaster KA, Howarth KR, Phillips SM, Rakobowchuk M, Macdonald MJ, McGee SL, et al., "Similar metabolic adaptations during exercise after low volume sprint interval and traditional endurance training in humans," *J Physiol*, vol. 586, pp. 151–60, 2008. 24

[75] Burgomaster KA, Hughes SC, Heigenhauser GJ, Bradwell SN, Gibala MJ, "Six sessions of sprint interval training increases muscle oxidative potential and cycle endurance capacity in humans," *J Appl Physiol*, vol. 98, pp. 1985–90, 2005. 24

[76] Martin J. Gibala, Jonathan P. Little, Martin van Essen, Geoffrey P. Wilkin, Kirsten A. Burgomaster, Adeel Safdar, Sandeep Raha and Mark A. Tarnopolsky, "Short-term sprint interval versus traditional endurance training: Similar initial adaptations in human skeletal muscle and exercise performance," *Journal of Physiology*, vol. 575, no. 3, pp. 901–911, 2006. 24

[77] Talanian JL, Galloway SD, Heigenhauser GJ, Bonen A, Spriet LL, "Two weeks of high-intensity aerobic interval training increases the capacity for fat oxidation during exercise in women," *Journal of Applied Physiology*, vol. 101, pp. 1439–47, 2007. 24

[78] Rakobowchuk M, Tanguay S, Burgomaster KA, Howarth KR, Gibala MJ, MacDonald MJ, "Sprint interval and traditional endurance training induce similar improvements in peripheral arterial stiffness and flow-mediated dilation in health humans," *American Journal of Physiology- Regulatory, Integrative, and Comparative Physiology*, vol. 295, pp. 236–42, 2008. 24

[79] Tjonna AE, Stolen TO, Bye A, Volden M, Slordahl SA, Odegard R, Skogvoll E, Wisloff U, "Aerobic interval training reduces cardiovascular risk factors more than a multitreatment approach in overweight adolescents," *Clinical Science*, vol. 116, no. 4, pp. 317–26, 2009. 24

[80] Talanian JL, Holloway GP, Snook LA, Heigenhauser GJ, Bonen A, Spriet LL, "Exercise training increases sarcolemmal and mitochondrial fatty acid transport proteins in human skeletal muscle," *American Journal of Physiology, Endocrinology, and Metabolism*, vol. 299, no. 2, pp. E180–88, 2010. 24

[81] Burgomaster KA, Heigenhauser GJ, Gibala MJ, "Effect of short-term sprint interval training on human skeletal muscle carbohydrate metabolism during exercise and time-trial performance," *J Appl Physiol*, vol. 100, pp. 2041–7, 2006. 24

[82] MacDougall JD, Hicks AL, MacDonald JR, McKelvie RS, Green HJ, Smith KM, "Muscle performance and enzymatic adaptations to sprint interval training," *J Appl Physiol*, vol. 84, pp. 2138–42, 1998. 24

[83] Burgomaster KA, Cermak NM, Phillips SM, Benton CR, Bonen A, Gibala MJ, "Divergent response of metabolite transport proteins in human skeletal muscle after sprint interval training and detraining," *Am J Physiol Regul Integr Comp Physiol*, vol. 292, pp. R1970–R1976, 2007. 24

[84] Rakobowchuk M, Tanguay S, Burgomaster KA, Howarth KR, Gibala MJ, MacDonald MJ, "Sprint interval and traditional endurance training induce similar improvements in peripheral arterial stiffness and flowmediated dilation in healthy humans," *Am J Physiol Regul Integr Comp Physiol*, vol. 295, pp. R236–242, 2008. 24

[85] Babraj JA, Vollard NBJ, Keast C, Guppy FM, Cottrell G, Timmons JA, "Extremely short duration high intensity training substantially improves insulin action in young sedentary males," *BMC Endocr Disord*, vol. 9, pp. doi:10.1186/1472–6823–9–3, 2009. 24

[86] *Full Vision Inc MdI TMX425 Treadmill Specification Data Sheet.* 28

[87] Duffield R, Dawson B, Pinnington HC, Wong P., "Accuracy and reliability of a cosmed K4b^2 portable gas analysis system," *Journal of Science and Medicine in Sport*, vol. 7, no. 1, pp. 11–22, 2004. 28

[88] Pinnington HC, Wong P, Tay J, Green D, Dawson B., "The level of accuracy and agreement in measures of F_EO2, F_ECO_2, and V_E, between the cosmed K4b^2 portable, respiratory gas analysis system and a metabolic cart," *Journal of Science and Medicine in Sport*, vol. 4, no. 3, pp. 324–35, 2001. 28

[89] *eZ430-Chronos Development Tool User Guide*. 35

[90] Astrand PO, Saltin B., "Oxygen uptake during the first minutes of heavy muscular exercise," *J Appl Physiol*, vol. 16, no. 6, pp. 971–6, 1961. 41

[91] Gonzalez-Alonso J, Mora-Rodriguez R, Coyle EF, "Stroke volume during exercise: interaction of environment and hydration," *Am J Physiol Heart Circ Physiol*, vol. 278, pp. H321–30, 2000. 41

[92] Gonzalez-Alonso J, Teller C, Andersen SL, Jensen FB, Hyldig T, Nielsen B, "Influence of body temperature in the development of fatigue during prolonged exercise in the heat," *J Appl Physiol*, vol. 86, no. 3, pp. 1032–9, 1999. 41

[93] McArdle WD, Magel JR, Lesmes GR, Pechar GS, "Metabolic and cardiovascular adjustment to work in air and water at 18, 25 and 33 degrees c," *J Appl Physiol*, vol. 40, no. 1, pp. 85–90, 1976. 41

[94] Craig AB, Dvorak M, "Thermal regulation of man exercising during water immersion," *J Appl Physiol*, vol. 25, no. 1, pp. 28–35, 1968. 41

[95] W. D. McArdle, J. R. Magel, R. J. Spina, T. J. Gergley, and M. M. Toner, "Thermal adjustment to cold-water exposure in exercising men and women," *J Appl Physiol*, vol. 56, no. 6, pp. 1572–7, 1984. 41

[96] Bradfield R B, "A technique for determination of usual daily energy expenditure in the field," *The American Journal of Clinical Nutrition*, vol. 24, pp. 1148–54, 1971. 42

[97] Mc.Crory M A, Mole P A, Nommsen-Rivers L A, Dewey K G, "Between-day and within-day variability in the relation between heart rate and oxygen consumption: effect on the estimation of energy expenditure by heart-rate monitoring," *The American Journal of Clinical Nutrition*, vol. 66, pp. 18–25, 1997. 42

[98] Balderrama C, Ibarra G, De La Riva J, Lopez S, "Evaluation of three methodologies to estimate the VO_{2max} in people of different ages," *Applied Ergonomics*, vol. 42, pp. 162–168, 2010. 48

[99] Su SW, Wang L, Celler BG, Savkin AV, Guo Y, "Identification and control for heart rate regulation during treadmill exercise," *IEEE Trans Biomed Eng*, vol. 54, no. 7, pp. 1238–46, 2007. 50

[100] Su SW, Huang S, Wang L, Celler BG, Savkin AV, Guo Y, Cheng T, "Nonparametric hammerstein model based model predictive control for heart rate regulation," *Proceedings of 29th EMBC*, pp. 2984–2987, 2007. 50

[101] Martin Braun, *Differential Equations and Their Applications: An Introduction to Applied Mathematics*. Springer, 1992. 50

[102] Wolfgang Altmann, *Practical Process Control for Engineers and Technicians*. Newnes, 2005. 51

[103] *R2012b Documentation*. 55

[104] Steven W Su, Weidong Chen, Dongdong Liu, Yi Fang, Weijun Kuang, Xiaoxiang Yu, Tian Guo, Branko G Celler, and Hung T Nguyen, "Dynamic modeling of heart

rate response under different exercise intensity," *The Open Medical Informatics Journal*, vol. 4, pp. 81–85, 2010. 62

[105] William H. Hayt, Jr., Jack E. Kemmerly, *Engineering Circuit Analysis*, vol. 5. McGRAW-HILL, INC., 1993. 69

[106] Michael A. Johnson, J. Crowe, Mohammad Hassan Moradi, *PID Control: New Identification and Design Methods*. Springer, 2005. 80

[107] Astrom, K. J. and Hagglund, T., "Pid controllers: theory, design, and tuning," *ISA, NC*, vol. 2, 1995. 82

[108] Karl John Astrom, *Control Systems Design*. 2002. 84

[109] M. A. Johnson and M. H. Moradi, Ed., "Pid control: new identification and design methods," *Springer-Verlag, London*, pp. 389–427, 2005. 85

[110] Goebel R., Sanfelice R., Teel A., "Hybrid dynamical systems," *IEEE Control Systems Magazine*, vol. 29, no. 2, p. 2893, 2009. 87

[111] Huijun Gao, James Lam, Changhong Wang, "Model simplification for switched hybrid systems," *Systems and Control Letters*, vol. 55, no. 12, pp. 1015–1021, 2006. 87

[112] Maria D. Di Benedetto, Alberto L. Sangiovanni-Vincentelli, *Hybrid Systems: Computation and Control*, vol. 4. Springer, 2001. 88