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Analysis of acceleration and deceleration during cyclic exercise

Jeena Vadi

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ABSTRACT

ANALYSIS OF ACCELERATION AND DECELERATION DURING CYCLIC EXERCISE

**by
Jeena Vadi**

The Cyclic Exercise Protocol is a novel protocol that is designed to create a series of cyclic waves of exercise and recovery. This exercise protocol involves short bursts of exercise lasting for 60 seconds or less followed by a period of complete cardio recovery. This study involves the analysis of the acceleration and the deceleration regions of the cyclic exercise sessions. The objective of this study was to develop an algorithm to quantitatively analyze the acceleration and the deceleration regions of cyclic exercise sessions. The acceleration and the deceleration regions of cycles were split into three segments and each segment was fit with mathematical curves and the variation of data from the fit was calculated. The cycles data was analyzed using *Mathematica* version 4.1. The subjects for this study were healthy volunteers.

The parameters extracted included the time constants and slopes from the mathematical fits and the mean square errors. The mean square error values obtained were less than 14.8 ($\pm 3.5\%$ error in the variation of the heart rate), showing that the algorithm is creating a proper mathematical fit to the different regions of acceleration and deceleration.

**ANALYSIS OF ACCELERATION AND DECELERATION
DURING CYCLIC EXERCISE**

**by
Jeena Vadi**

**A Thesis
Submitted to the Faculty of
New Jersey Institute of Technology
In Partial Fulfillment of the Requirements for the Degree of
Master of Science in Biomedical Engineering**

Department of Biomedical Engineering

May 2005

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APPROVAL PAGE

**ANALYSIS OF ACCELERATION AND DECELERATION
DURING CYCLIC EXERCISE**

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*To my family
with love and appreciation for the sharing
and caring that makes life worthwhile*

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CHAPTER 1

INTRODUCTION

1.1 Scope of Research

The scope of this research involves the analysis of acceleration and deceleration regions of cyclic exercise sessions. The cyclic exercise protocol is designed to train the exertion phase and recovery phase of exercise in a cycle and it is aimed at improving the overall health of a person. The underlying principle of this exercise protocol is that rest, recovery and the body's natural rhythm are important to fitness and conditioning. The human body has inherent rhythms that occur with different periods and at different times as cycles. The cyclic exercise protocol that is designed to train exercise and recovery as a cycle helps to improve the inherent rhythms of the body, which play a key role in a person's health. In a cycle session the acceleration region represents the exercise phase and the deceleration region represents the recovery phase.

The main objective of this research was to develop an algorithm to quantitatively analyze the acceleration and deceleration regions of cyclic exercise sessions and to see if it provides any significant information regarding the health of subjects. The subjects for this study were healthy volunteers. After an initial baseline session the subjects started doing the cycles session, which yielded cyclic waves of cardiovascular exercise and recovery data. For quantitative analysis the acceleration and the deceleration regions were divided into three sections. The three different regions in each case, which followed different curves, were fit with mathematical curves and the variation of data from the fit was calculated. The exercise data was analyzed using Mathematica version 4.1.

1.2 Goals for the Study

1. To develop an algorithm to analyze the acceleration and deceleration region of cycles exercise sessions data.
2. To fit appropriate curves to the data and to extract the parameters of interest and observe the trend of various parameters while the subjects go through their cycles session.

1.3 Physiology and Background

This research analyses the acceleration and deceleration region of cyclic exercise sessions, which is aimed at improving the overall health of subjects by increasing the heart rate variability and the amplitude of circadian rhythms. To better understand the heart rate variability and its interpretations, knowledge of the cardiovascular system and the autonomic nervous system is fundamental. The section presents the physiology of the heart as well as the cyclic exercise protocol.

1.3.1 Cardiovascular System

The cardiovascular system or the circulatory system is the transport system of the body [1]. It is made up of the heart, as well as a closed system of vessels and blood. The heart is a muscular pumping device which pumps blood throughout the circulatory system. Embryologically, the heart starts beating before the formation of the brain and this beating is self initiated from within the heart itself [2]. Blood contained in the circulatory system is pumped by the heart around a closed circuit of vessels as it repeatedly passes through the various “circulations” of the body. The vital role of the cardiovascular

system in maintaining homeostasis is dependent upon the continuous and controlled movement of blood to reach every cell in the body. Regulation of blood pressure and flow must change in response to cellular activity. Consequently, numerous control mechanisms help to regulate and integrate the diverse functions and component parts of the cardiovascular system to supply blood to specific body areas according to need.

1.3.1.1 Anatomy of the Human Heart. The main organ of the cardiovascular system is the heart. It is responsible for the circulation of the blood according to the need of the body. Figure 1.1 shows the heart and its chambers. The heart is located in the thoracic cavity approximately midline between the sternum (breast bone) anteriorly and the vertebrae posteriorly. The heart has a broad base at the top and tapers to a pointed tip known as the apex at the bottom. It is situated at an angle under the sternum so that its base lies predominantly to the right and the apex to the left of the sternum. The size of the heart is no larger than one's own fist. It is a hollow organ composed of cardiac muscular tissue. Its beating action maintains the flow of blood through the entire human body. From the heart numerous blood vessels branch out and spread to every corner of the body. These vessels form the vasculature of the cardiovascular system. There are three main types of blood vessels, namely, arteries which carries oxygenated blood from the heart to the various systems of the body, the veins which carry deoxygenated blood from the various parts of the body back to the heart, and capillaries which join the arteries and veins and are the site for gaseous and chemical exchange between the various cells and the blood.

1.3.1.2 Heart as a Dual Pump. Even though anatomically the heart is a single organ, the right and left sides of the heart functions as two separate pumps. The heart is divided into right and left halves and has four chambers; an upper and a lower chamber within each half. The upper chambers, the atria, receive blood returning to the heart and transfer it to the lower chambers, the ventricles, which pump blood from the heart. The vessels that return blood from the tissues to the atria are veins and those that carry blood away from the ventricles to the tissues are the arteries. The two halves of the heart are separated by the septum, a continuous partition that prevents the mixture of blood from the two sides of the heart. This separation is important because the right half of the heart is receiving and pumping oxygen poor blood while the left side of the heart receives and pumps oxygen rich blood.

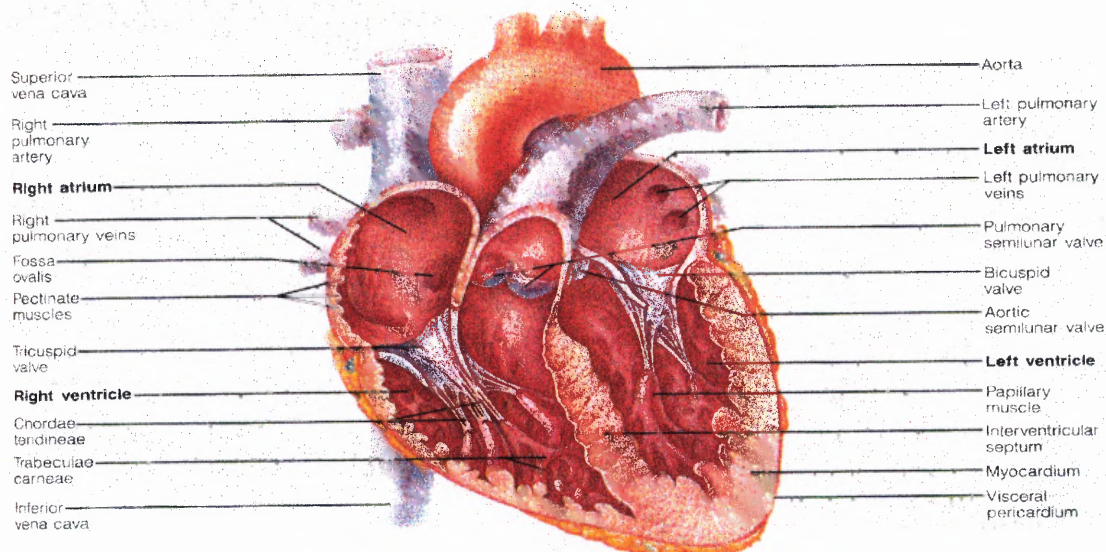


Figure 1.1 The heart. (From E. N. Marieb, *Human Anatomy and Physiology*, 3rd ed. New York: The Benjamin/Cummings Publishing Company, Inc., 1995)

The blood travels continuously through the circulatory system to and from the heart through two separate vascular (blood vessel) loops, both originating and terminating at the heart. The pulmonary circulation consists of a closed loop of vessels carrying blood

between the heart and lungs, whereas the systemic circulation consists of a closed loop of vessels carrying blood between heart and other organ systems.

Blood returning from the systemic circulation enters the right atrium via large veins known as vena cava. In the lungs, the blood loses the extra carbon dioxide and picks up the oxygenated blood and returns to the left atrium. The blood from the left atrium flows into the left ventricle and eventually into the aorta that supplies the oxygenated blood to all parts of the body. This is called the systemic circulation. Figure 1.2 shows the systemic and pulmonary circulation.

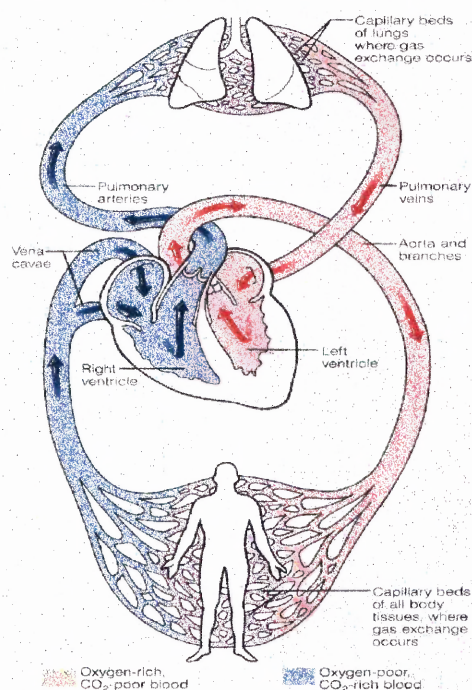


Figure 1.2 Systemic and pulmonary circulations. (From E. N. Marieb, *Human Anatomy and Physiology*, 3rd ed. New York: The Benjamin/Cummings Publishing Company, Inc., 1995)

1.3.1.3 The Electrocardiogram. The heart contracts, or beats, rhythmically as a result of an action potential that it generates by itself, a property known as autorhythmicity. The electrocardiogram (ECG) is a record of the overall spread of electrical activity through

the heart. The ECG is used primarily as a tool for evaluating the electrical events within the heart. The action potentials of cardiac muscles can be viewed as batteries that cause charge to move throughout the body fluids. These moving charges, or currents, represent the sum of the action potentials occurring simultaneously in many individual cells and can be detected by recording electrodes at the surface of the skin. Figure 1.3 illustrates a typical normal ECG recorded between the right and left wrists for one heartbeat.

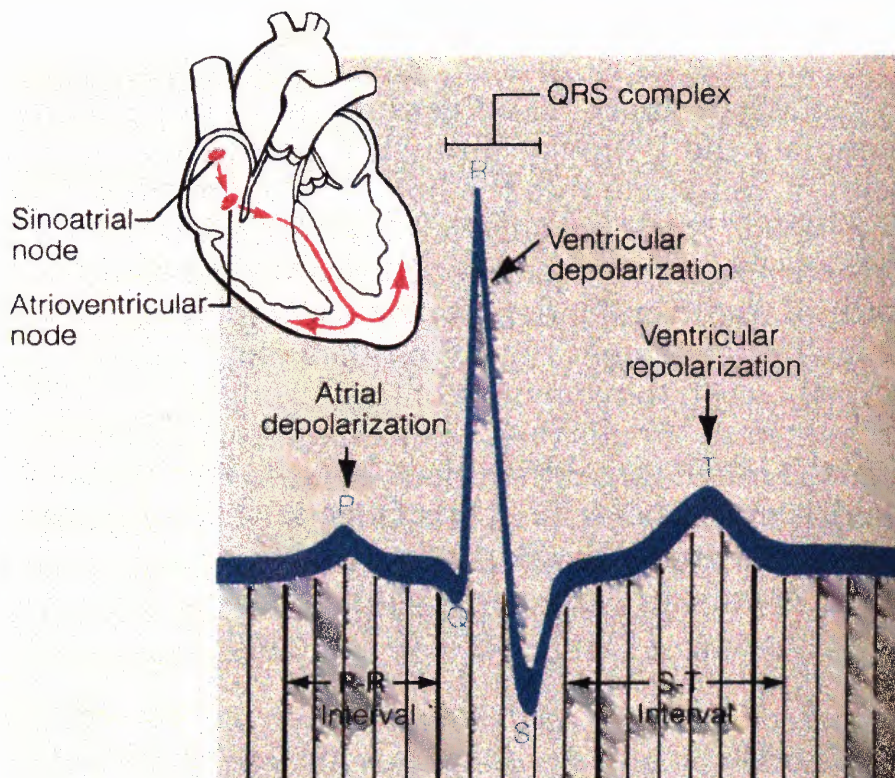


Figure 1.3 The electrocardiogram. (From E. N. Marieb, *Human Anatomy and Physiology*, 3rd ed., 1995)

The first deflection, the P wave, corresponds to the current flow during atrial depolarization (contraction). The second deflection, the QRS complex, is a result of ventricular depolarization. The third and final deflection is the T wave. The T wave is a result of ventricular repolarization (relaxation). It should be noted that atrial

repolarization is usually not evident in the ECG because it occurs at the same time as the QRS complex. The distance between two consecutive QRS complexes on an ECG record is calibrated to the beat-to-beat heart rate.

Because electrical activity triggers mechanical activity, abnormal electrical patterns are usually accompanied by abnormal contractile activity of the heart. Thus the evaluation of ECG can be useful in diagnosing abnormal heart rates, arrhythmias, and damage of the heart muscle.

1.3.2 Exercise – Neural Review

The heart is innervated by both divisions of the autonomic nervous system, which can modify the rate and strength of contraction, even though nervous stimulation is not required to initiate contraction. The parasympathetic nerve to the heart, the vagus nerve, primarily supplies the atria, especially the SA (sinoatrial) and AV (atrioventricular) nodes. Parasympathetic innervation of the ventricles is sparse. The cardiac sympathetic nerves also supply the atria, including the SA and AV nodes, and richly innervate the ventricles as well.

1.3.2.1 Sympathetic Regulation of Heart Rate. The sympathetic nervous system controls heart action in emergency or exercise situations, where there is a need for greater blood flow and speeds up the heart rate through its effect on the pacemaker tissue [1]. The sympathetic nervous system innervates the AV node, the SA node and the atria and the ventricles of the heart and its regulation of heart rate is brought about by the combination of neural and hormonal pathways. Sympathetic efferent impulses travel from the brain via pre-ganglionic and postganglionic neurons to their target organs. At

their terminus these postganglionic fibers release norepinephrine or at the adrenal gland epinephrine. These catecholamines exert both a chronotropic (increased heart rate) and inotropic effect (increased contractility) on the heart.

1.3.2.2 Parasympathetic Regulation of Heart Rate. The parasympathetic nervous system's influence on the SA node is to decrease the heart rate [1]. Parasympathetic nerve impulses reach the heart via the right and left vagus nerves, innervating the SA and AV nodes but only the atrial myocardium. Vagal efferent impulses trigger the release of a neurotransmitter, acetylcholine (ACh) at their synapses. (ACh) combines with myocardial muscarinic receptors which are the membrane-bound proteins that contains a recognition site for acetylcholine (ACh) and the combination of Ach with the receptor initiates a physiologic change of slowing the heart rate, which results in increased efflux of K^+ ions and a reduced influx of Ca^{++} ions, the net result of which is to hyperpolarize the cell thus slowing the rate of depolarization and hence the heart rate [18]. Figure 1.4 shows the sympathetic and the parasympathetic nervous system.

During exercise, an increase of sympathetic activity and a decrease of vagal discharge lead to an increase of heart rate, stroke volume, and myocardial contractility to satisfy energy demand of working muscles [23]. Exercise cardioacceleration results from release of parasympathetic inhibition at low exercise intensities and from both parasympathetic inhibition and sympathetic activation at moderate intensities [24].

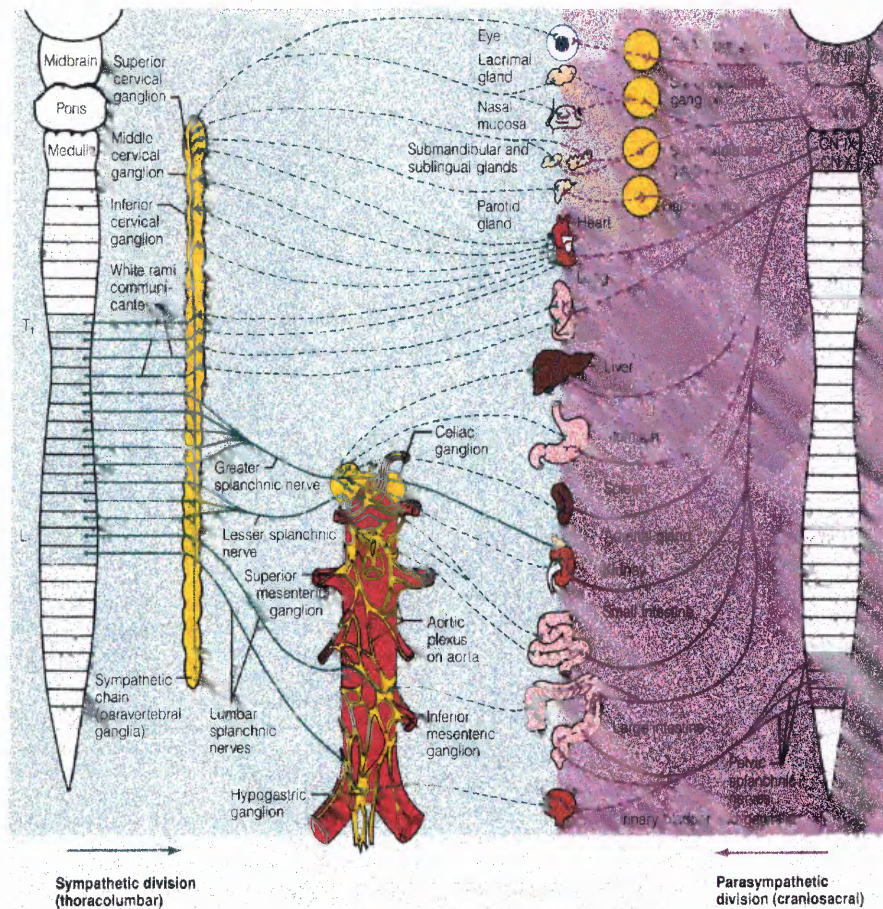


Figure 1.4 Sympathetic and parasympathetic nervous system. (From E. N. Marieb, *Human Anatomy and Physiology*, 3rd ed. New York: The Benjamin/Cummings Publishing Company, Inc., 1995)

1.3.2.3 Heart Rate and Heart Rate Variability. The oscillation in the interval between consecutive heartbeats as well as the oscillations between consecutive instantaneous heart rates is heart rate variability [13]. The beating of the heart and its regulation is controlled by the autonomic nervous system.

Physiology of Changes in Heart Rate

Change in heart rate is sensitive to changes in body temperature, plasma electrolyte concentrations and hormone concentrations [5]. However, the most important influence

of beat-to-beat variations of heart rate comes from the autonomic nervous system. More specifically, sympathetic activity increases heart rate, whereas activity in the parasympathetic (vagus) nerves causes the heart rate to decrease. Due to considerably more parasympathetic activity to the heart than sympathetic activity in the resting state, the normal resting heart rate is below the inherent rate of 100 beats/minute.

The autonomic nervous system innervates the heart in a number of places. The sympathetic nervous system terminates at the SA node, the conduction system, atrial and ventricular myocardium, and coronary vessels. The parasympathetic fibers terminate in the SA and AV nodes, atrial and ventricular musculature, and coronary vessels. Interplay between the two systems will cause the heart to speed up or slow down, depending on which system is more active [6].

Perhaps the most important site of innervation of the autonomic nervous system on the heart occurs at the SA node. The SA node possesses an inherent discharge rate, often referred to as the pacemaker potential. The pacemaker potential is a slow depolarization of the cells of the SA node. The innervation of the sympathetic and parasympathetic nervous system on the SA node changes the characteristics of depolarization within the SA node cells, thus changing heart rate.

Heart Rate Variability as a Measure of Autonomic Function

Changes in heart rate usually involve the reciprocal action of the two divisions of the autonomic nervous system. An increased heart rate is the result of reduced parasympathetic tone and a concomitant increase in sympathetic activity. A decrease in heart rate is usually the result of increased parasympathetic tone and a simultaneous

decrease in sympathetic tone. Therefore, changes in heart rate reflect the action of the sympathetic and parasympathetic nervous systems on the heart. However, under certain conditions, it is possible for heart rate to change by activity of only one division of the autonomic nervous system, independent of the other division, rather than reciprocal changes in both [7].

Initially, the effect of the autonomic nervous system on the heart was estimated by utilizing the traditional technique of average heart rate [7]. As a reference, the average heart rate was measured under normal resting conditions. Then the average heart rate was measured under the administration of drugs. The drugs used were atropine, which blocks the effects of the parasympathetic nervous system, and propranolol, which masks the effects of the sympathetic nervous system. A qualitative assessment could then be made of the autonomic nervous system by comparing the reference heart rate to the heart rate while under the administration of the drugs. This method looks at the average over time of heart rate. However, when the ECG is looked at on a beat-to-beat basis, rather than over a period of time, fluctuations in the heart rate are observed [7]. Recent research indicates that fluctuations in heart rate are a healthy sign. In fact, one hypothesis is that the larger variations in the heart rate correlate to a healthier autonomic nervous system. Goldsmith et al. studied and compared 24-h HRV in aerobically trained and untrained healthy young men and observed that parasympathetic activity is substantially greater in trained than in untrained men [3].

By contrast a number of physiologic and disease states produce alterations in autonomic function, which reduce the variability in heart rate [8]. The increase in heart rate that accompanies exercise is due in part to a reduction in vagal tone. Recovery of

heart rate immediately after the exercise is a function of vagal reactivation [22]. A delayed decrease in heart rate during first minute after graded exercise was found to be a predictor of overall mortality, independent of workload, the presence/absence of myocardial perfusion, changes in heart rate during exercise, in this study [22].

1.3.3 Exercise Physiology

The cyclic exercise protocol is designed to train exercise and recovery together as a cycle. This research analyses the acceleration and the deceleration of the cycles of the cyclic exercise sessions. One of the major concepts in exercise physiology is that physical activity from the perspective of conferring health benefits may be the end goal of exercise, rather than physical activity for the purposes of achieving maximal levels of physical fitness for competition. Modest exercise such as walking, outdoor work, and stair climbing can contribute to achievable levels of physical fitness for the general population as well as "athletes" and confers the benefits of increased longevity. It is hypothesized that since cyclic exercise is the exercise that confers maximum benefits to the body with minimum exertion [5], moderate exercise may be much more palatable to a patient than the idea of vigorous or strenuous exercise and may result in increased compliance with a recommended program.

Exercise generally takes two basic physiologic forms—dynamic exercise and static, or isometric exercise—although most athletic activities are a variable combination of them such as distance running [15].

Dynamic Exercise constitutes an alteration in the length of skeletal muscle with comparatively little change in muscle tension [15].

Static Exercise is essentially the reverse - that is, a marked alteration in skeletal muscle tension with little or no change in muscle length [15].

1.3.3.1 Cardiac Output and Control. The heart alternately contracts to empty and relaxes to fill with blood. The cardiac cycle consists of alternate periods of systole (contraction and emptying) and diastole (relaxation and filling). Cardiac output is the volume of blood pumped by each ventricle per minute. The two determinants of cardiac output are the heart rate (beats per min) and stroke volume (volume of blood pumped per beat or stroke). The average resting heart rate is 70 beats per minute, and the average resting stroke volume is 70 ml/beat producing an average cardiac output of 5 lit/min [1].

$$\text{Cardiac Output(CO)} = \text{Heart rate} * \text{Stroke volume}$$

$$\text{CO} = 70 \text{ beats/min} * 70 \text{ ml/beat} \approx 5 \text{ liters/min.}$$

Each minute the right ventricle normally pumps 5 liters of blood through the lungs, and the left ventricle pumps 5 liters of blood through the systemic circulation. This is the resting cardiac output. During exercise the cardiac output can increase to 20 to 25 liters/min and outputs as high as 40 liters per minute have been recorded in trained athletes during heavy exercise. The difference between cardiac output at rest and the maximum volume of blood the heart is capable of pumping per minute is called the cardiac reserve [1]. The reserve is a major determinant of exercise capacity in a population of normal subjects and patients with heart disease.

Systole is the active contraction phase of the cardiac cycle, the phase during which the heart performs its principal function, the ejection of blood into the pulmonary and systemic circulations. The delivery of blood to these circulations, measured as stroke

volume, is an important indicator and demonstration of cardiac function [4]. The stroke volume is defined as the difference between the end diastolic volume and the end systolic volume. The stroke volume is determined by three factors namely, preload, afterload and contractility.

1.3.3.2 Preload. Preload is the workload (stretch, filling) on the ventricle before contraction begins [1]. This is measured by end diastolic volume, and diastolic pressure and right atrial pressure and is regulated by the venous return to the heart. Physiologically, preload can be defined as the initial stretching of the cardiac myocytes (cells that line the walls of the heart) prior to contraction and is related to the sarcomere (smallest unit of the muscle fiber) length.

1.3.3.3 Afterload. Afterload refers to the wall tension against which the ventricle must contract during systole [4]. It is the workload imposed on the heart after the contraction has begun. In simple terms, the afterload is closely related to the aortic pressure. A simple measure of afterload is mean arterial pressure.

1.3.3.4 Inotropy – Contractility. Contractility is the innate ability of the fibers of the heart muscle to shorten, which translates into a shrinking of the cardiac chambers during each heartbeat [4]. Changes in stroke volume can be accomplished by changes in ventricular inotropy (contractility). Changes in ionotropy are unique to cardiac muscle. A simple measure of cardiac contractility is ejection fraction (EF) is the fraction of blood ejected by the ventricle relative to its end- diastolic volume. $EF = (SV/$

EDV) · 100 where SV = stroke volume, EDV = end-diastolic volume). Cardiac contractility increases with sympathetic stimulation [16]. Changes in contractility alter the rate of force and pressure development by the ventricle and therefore changes the rate of ejection.

Sympathetic stimulation increases the cardiac output by influencing the heart rate and the stroke volume. Sympathetic stimulation increases stroke volume not only by strengthening cardiac contractility but also by enhancing venous return. Sympathetic activity to the heart increases during exercise, when the working skeletal muscles need increased delivery of oxygen-laden blood to support their high rate of ATP consumption [1]. During the initial stages of exercise, increased cardiac output is due to an increase in both heart rate and stroke volume. When the level of exercise exceeds 40% to 60% of the individual's capacity, stroke volume has either plateaued or begun to increase at a much slower rate. Thus, further increases in cardiac output are largely the result of increases in heart rate [1].

1.3.3.5 Behavior of the Heart During Exercise. Autonomic nervous system activity contributes to the regulation of cardiac output during rest, exercise, and cardiovascular disease [17].

The heart rate increases during exercise [1].

- The increase in heart rate is proportional to the workload.
- The increase in heart rate is produced by an increase in sympathetic discharge, a decrease in parasympathetic (vagus nerve) discharge and an increase in circulating catecholamines (epinephrine and nor epinephrine).

Stroke volume increases during exercise [1].

- The increase in stroke volume is caused by an increase in ventricular contractility.
- The end diastolic volume (preload) does not change very much during exercise.

Cardiac output increases during exercise [1].

- Stroke volume may increase two fold.
- Heart rate may increase three fold.
- Cardiac output may increase six fold (from 5 liters/min to 30 liters/min)

Effect of exercise training on the cardiovascular system

At rest

- Reduced heart rate
- Increased stroke volume
- Increased end-diastolic volume
- Increased blood volume

At maximal workload

- Increased maximum stroke volume
- Increased maximum cardiac output
- Decreased maximum heart rate
- Increased maximum oxygen extraction
- Increase maximum oxygen consumption

Effects of Exercise on the Vascular System

Total peripheral resistance decreases during exercise.

- The arterioles perfusing exercising muscles are dilated by the metabolic byproducts that accumulate during exercise.
- The flow of blood through the exercising muscles and the number of capillaries through which the blood flows are increased.
- The resistance of the arterioles perfusing the skin decreases
- Cutaneous blood flowing increases
- The increased cutaneous blood flow contributes to the dissipation of the heat produced by the exercising muscles.
- The resistance of arterioles perfusing non-exercising muscles and other tissue beds, such as the kidney and gastrointestinal track, increase.
- Coronary vascular resistance decreases
- Coronary blood flow increases
- Delivery of oxygen to the myocardium increases to meet the demand.

1.3.4 Cyclic Exercise Protocol

The data for this study is collected from the cyclic exercise program, which is performed based on a specific protocol. The cyclic exercise protocol is based on Dr. Dardik's theory.

1.3.4.1 Dr. Dardik's Theory. The theory is radically simple. *"Everything is waves"* - From the earliest time, everything in nature has displayed rhythmic cycles such as light waves, sound waves, radio waves, and gravitational waves. And every second of our

lives, our own heart valves open and close, for survival itself is based on maintaining these rhythms [9].

There is a simple blueprint for human health: the collective, appropriate organization of the body's waves or rhythms, from the biochemistry to the heart, according to Dr. Irving Dardik's theory. Conversely, there is only one disease: the "flattening" of the body's waves. Because the human body's waves are fractal (self-similar repeating patterns at different scales), Dardik believes that shaping comparatively larger waves in the body - such as the critically important heart wave (the combination of the heart's systolic and diastolic beats and the increase and decrease of the heart rate during exertion and recovery) - can organize the smaller waves, down to the cellular level. And because waves repeat themselves with "memory," he states, it is possible to help organize the body's rhythms with relatively brief training sessions that accelerate heart waves, and by synchronizing with the powerful circadian and other natural patterns, adding variability and preventing flattening [9].

Traditional exercise regimens are based on maintaining a prolonged increase in heart rate followed by a single recovery period. The efficacy of a cyclic exercise protocol designed to generate a series of cyclic waves of cardio acceleration lasting for less than a minute followed by recovery to a steady state was tested. An observational study conducted by Goldsmith et al, studied the effects of this type of cyclic regimen, consisting of four to seven cycles per session, in a group of healthy women [5]. Cardio respiratory fitness, autonomic function, and quality of life were assessed before and after eight weeks of exercise, performed three days per week and it was found that a short

course of the cyclic exercise protocol in healthy adult women is associated with evidence of enhanced cardiorespiratory fitness, autonomic function and quality of life.

The implementation of a “cyclic” exercise protocol is designed to train not only the activation phase, but also the relaxation phase of exercise in a wave like or pulsatile fashion. The physiological importance of “training recovery” is derived from the concept that recovery itself is a dynamic process, mediated primarily by the parasympathetic nervous system [5]. Therefore training recovery as well as activation may result in greater neuroautonomic plasticity, which may in turn enhance healthy function.

1.3.4.2 Baseline Determination. A baseline determination was done prior to the actual cycles sessions. From the baseline cycles session the target heart rate is calculated for the individual subject for the succeeding cycles sessions. Target heart rates for each succeeding cycle were calculated as percentages of the peak heart rate determined from the baseline session [5].

1.3.4.3 Cycles Session. Traditional exercise regimens are based on increasing the heart rate to a target range determined by age and fitness and maintaining that level of activity for a sustained period. The cycles exercise protocol employs an interval-type protocol, where there are alternating periods of exertion and recovery.

The cycles protocol is designed to train not only exercise but also recovery together as a cycle. This generates cyclic waves of exercise and recovery. A single cycle consists of a short burst of exercise followed by a period of cardiovascular recovery. The "Cycles" are performed in sets of three to seven cycles, three times per week. Each cycles

session takes between 30 - 45 minutes involving 3-7 minutes of exertion per cycles session and the total amount of exertion is no more than 40 minutes per month. During a cycle, subjects are required to exercise at a predetermined exertion level and reach a defined heart rate goal determined by the baseline session.

It has been hypothesized that the cycles program with short bursts of exercise and recovery as a wave helps in training the larger 24-hour rhythm of the body thereby improving the overall health of an individual [5].

CHAPTER 2

METHODOLOGY

2.1 Introduction

The cycle exercise protocol used in this study was based on a program developed by Dr. Irving Dardik. The subjects for this study included two healthy individuals. The data acquired from the subjects during the study was heart rate. This section presents the implementation of the exercise protocol including subject selection, protocol implementation and data acquisition.

2.2 Subject Selection

The subjects were two healthy volunteers. Upon arrival, subjects were briefed on the cycle baseline exercise test protocol and were familiarized with the equipment used.

2.3 Study Design

A baseline testing was done before the actual cycles exercise session. Based on the cycles baseline session, the target heart rates – heart rate to be achieved by each subject undergoing the cycles, was determined. The subject then performed the cycles exercise with an increased target at every successive cycle.

2.4 Protocol Description

One significant way to enhance the natural rhythms of the body is to create them ourselves. Much of our natural activity is rhythmic, from laughter to running. Because the

human body's waves are fractal (self-similar repeating patterns at different scales), shaping the comparatively larger waves in the body - such as the critically important heart wave (the combination of the heart's systolic and diastolic beats and the increase and decrease of the heart rate during exertion and recovery) - can organize the smaller waves, down to the cellular level [9].

Since waves repeat themselves it is possible to help organize the body's rhythms with relatively brief training sessions that accelerate heart waves, and by synchronizing with the powerful circadian and other natural patterns, adding variability and preventing flattening [6]. Heart rate (HR) recovery after exercise has long been used as a marker for physical fitness, possibly related to the high vagal tone associated with fitness and good health [12]. The cycles exercise program is designed to generate a series of cyclic waves of cardiovascular exercise and recovery. Burke et al. demonstrated that a seven-week interval training performed at 85-95% of VO_2 (Oxygen consumption) resulted in a 5% increase in VO_2 peak in active young women [14]. The cycles exercise program is embedded within a holistic lifestyle program called LifeWaves®, designed to adjust the circadian rhythm (i.e., the body's natural 24-hour "clock,"), which organizes all biological processes, including metabolic rises and dips, blood pressure peaks and valleys, hormonal releases, etc.[19].

Cycles were performed in sets of three to seven cycles, three times per week, for 3 weeks. Each cycle session took between 30-45 minutes involving 3-7 minutes of exertion per cycle session. Each cycle in a session consisted of a short burst of exercise (for less than 1 minute) followed by a period of complete recovery. This increased the parasympathetic nervous system activity and hence may accelerate the increase in

parasympathetic nervous system activity during recovery. The cycles were performed in sets of three to seven and at specific times of the day. The study was designed such that the cycles performed in the afternoon sessions required more exertion than the morning session because the work performance typically increases in the afternoon [20,21]. This is critically important because the body chemistry is different at different times of the day, month and year. The exertion levels, the numbers of cycles per session and target heart rates vary throughout the month. The subjects were given target heart rates and are required to achieve those goals. These target heart rates were determined by the baseline cycles session. Table 2.1 show the target heart rate for subject S1 for session 9.

Table 2.1 Target heart rates and exertion level for subject S1 for session 9

Target Heart Rates in beats/min	Exertion Scale
131	(2)
142	(3)
156	(4)
165	(5)
No goal	(5)

Exertion Scale:

- 1) *Easy Pace*
- 2) *Accelerate to Moderate Pace*
- 3) *Accelerate to Moderately Vigorous Pace*
- 4) *Accelerate to Vigorous Pace (Maximum Effort)*
- 5) *Maximum effort from the start of the cycle to the finish (Spike)*

No Goal: Do a spike (maximum effort from the start of the cycle to the finish), but stop if your heart rate stops rising, if your heart rate drops, if you become tired, or if you have gone for a full minute.

The equipment used for data collection was a heart rate measurement device- the Polar S810 HR Monitor and a chest strap included with it. The data acquired by the monitor was ECG (Electrocardiogram). The monitor then converted the ECG into either five-second averaged heart rate (HR) or Interbeat intervals (IBI). The five second averaged heart rate files, have their data averaged every 5 seconds and the Interbeat interval files records the distance between an R-R wave in an ECG signal in milliseconds. The data files used in this study are the Interbeat interval files.

2.5 Baseline Determination

A baseline determination was done prior to the actual cycles session. This cycles testing session was done for a baseline establishment, which in turn was used for determination of target heart rate for succeeding cycles in actual cycle session. Subjects were requested to refrain from caffeine and meals for three hours prior to cycles testing. The subjects were briefed on the exercise protocol. Baseline determination session consisted of 5 cycles. During the first cycle of the baseline-testing phase, the subjects were required to exercise at an easy pace until the heart rate stabilized. The heart rate is said to have stabilized when it is varying at most +/- three beats over 15 seconds, which occurs less than one minute of exertion. The subjects were looking at the monitor to check for their heart rate stability. The subjects then stopped exercise, sat down and began initiating the recovery phase of the cycle. The heart rate data was collected using a Polar S810 HR

monitor watch and chest strap (Polar Electro Inc., Woodbury NY) and then downloaded to a computer. The cycles session was monitored by a trainer.

The subject performed the 2nd, 3rd, and 4th cycle (including exertion and recovery) in a similar manner, but increased the level of exertion for exercise with each successive cycle. The final cycle of the baseline test was used to determine the peak heart rate for the subsequent cycles sessions. The final cycle was vigorous and it consisted of a brief exertion continued until the heart rate plateaued or the subject completed one minute of exertion. Then the subject began the final recovery period.

2.6 Cycles Session

Once the cycles baseline testing had been completed, the subject started the cycles regimen consisting of three to seven cycles per day, and three days per week for 3 weeks. The subjects moved through the same type of exercise-recovery cycles described in the cycles testing section. Target heart rates for each cycle were calculated as percentages of the peak heart rate determined from the baseline session. Table 2.2 shows the target heart rate determination for cycles sessions. The target heart rate for each cycle began at the low end of the range and progressively increased in a step-wise incremental fashion to the high end of the range.

Table 2.2 Target heart rate determinations

Week	Time of Day	Target Heart Rate Ranges (percentage of peak heart rate from baseline session)
1	6 a. m.- 9 a.m.	60%-92%
2	9 a. m – noon	70%-97%
3	3 p. m – 6 p. m	75%-100%

The subjects underwent the cycles session three times a week. Each week had three sessions. The target heart rate goals were matched to the appropriate files according to the sessions and the date. Once the actual cycles sessions had been completed in 3 weeks, the 4th week was the resting period for the subjects. Figure 2.1 shows the graph of the cycles performed by subject S2 in one session.

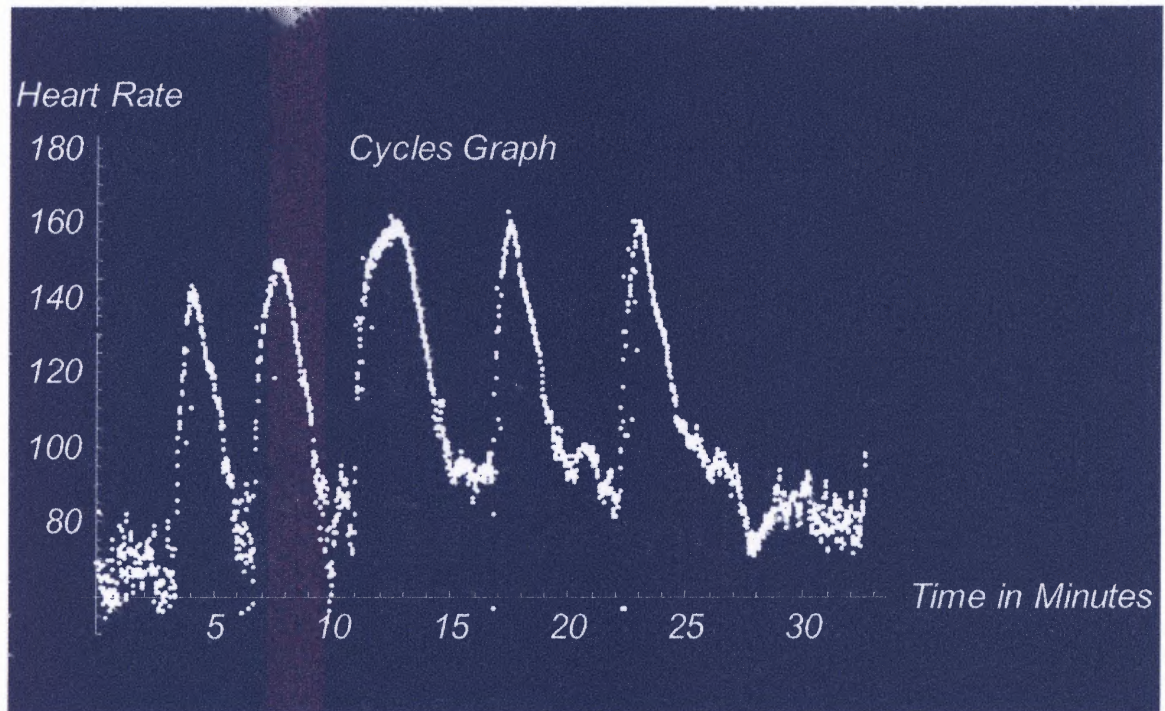


Figure 2.1 Graph of cycles performed by subject S2.

Table 2.3 shows a typical cycles schedule for a subject for 11 consecutive sessions.

Table 2.3 Typical cycles schedule for a subject for 11 consecutive sessions

Early Morning Session 6-9 AM								
Session 1 (Tuesday)		Session 2 (Thursday)		Session 3 (Saturday)		Session 4 (Monday)		
Target Heart Rates in Beats/Min	Exertion Scale	Target Heart Rates in Beats/Min	Exertion Scale	Target Heart Rates in Beats/min	Exertion Scale	Target Heart Rates in Beats/Min	Exertion Scale	
112	(1)	116	(1)	122	(2)	124	(2)	
122	(2)	134	(2)	136	(3)	138	(3)	
141	(3)	151	(4)	152	(4)	146	(4)	
149	(4)	139	(5)	141	(5)	143	(5)	
138	(5)	141	(5)	144	(5)	146	(5)	
				147	(5)	148	(5)	
						151	(5)	
Morning Session 9-12 AM								
Session 5 (Wednesday)		Session 6 (Friday)		Session 7 (Sunday)				
Target Heart Rates in Beats/Min	Exertion Scale	Target Heart Rates in Beats/Min	Exertion Scale	Target Heart Rates in Beats/min	Exertion Scale			
122	(2)	124	(3)	126	(4)			
130	(3)	136	(4)	144	(5)			
144	(4)	150	(5)	160	(5)			
150	(5)	157	(5)					
154	(5)							
Afternoon Session 3-6 PM								
Session 8 (Tuesday)		Session 9 (Thursday)		Session 10 (Saturday)			Session 11 (Tuesday)	
Target Heart Rates in Beats/Min	Exertion Scale	Target Heart Rates in Beats/Min	Exertion Scale	Target Heart Rates in Beats/min	Exertion Scale		Target Heart Rates in Beats/Min	Exertion Scale
129	(2)	131	(2)	134	(2)		138	(3)
141	(3)	142	(3)	146	(3)	Two Day Recovery	150	(4)
154	(4)	156	(4)	154	(5)		158	(4)
160	(5)	165	(5)	160	(5)		161	(5)
165	(5)	No goal	(5)	No goal	(5)		No goal	(5)
				150	(5)		151	(5)
						153	(5)	

Exertion Scale:

1. *Easy Pace*
2. *Accelerate to Moderate Pace*
3. *Accelerate to Moderately Vigorous Pace*
4. *Accelerate to Vigorous Pace (Maximum Effort)*
5. *Maximum effort from the start of the cycle to the finish (Spike)*

No Goal: Do a spike (maximum effort from the start of the cycle to the finish), but stop if your heart rate stops rising, if your heart rate drops, if you become tired, or if you have gone for a full minute.

2.7 *Mathematica* for Cycles Analysis

All computer applications associated with this study were designed using *Mathematica* 4.1 software developed by Wolfram Research. *Mathematica* integrates a numeric symbolic computational engine, graphic system, programming languages, documentation system, and an advanced connectivity to other applications. The kernel is the computational engine of *Mathematica*. The medium of the front end (the interface between the user and the kernel) is the *Mathematica* notebook. *Mathematica* notebooks enable the user to communicate with the kernel and it combine all the calculations, code, results, and graphics into one interactive technical document. The program for analysis of cycles exercise was written as *Mathematica* notebook.

CHAPTER 3

DATA ACQUISITION AND ANALYSIS

3.1 Introduction

This research analyzes the acceleration and the deceleration regions of cyclic exercise sessions. An algorithm was developed for this analysis. The data acquired for this study included the interbeat by intervals during cycles exercise.

The application used for cycles analysis was *Mathematica*. This section describes the use of *Mathematica* for this study and the algorithms by which the acceleration and deceleration regions of cycles were analyzed. This section also explains the different parameters extracted from the acceleration and the deceleration regions including the exponents, slopes and mean square errors.

3.2 Cycles Data Acquisition

The heart rate exercise data acquired for the study, involved the recording of R-R intervals or, the interbeat interval in milliseconds. The equipment used during data collection was a simple to use heart rate measurement device - the Polar S810 HR Monitor and a chest strap included with it. For registration of R-R intervals using the Polar® system an elastic belt (Polar T31™ transmitter, Polar Electro, Kempele) is fixed to the chest of the volunteer at the level of the lower third of the sternum. The belt contains a case with heart rate electrodes, electronic processing unit and electromagnetic field transmitter. The heart rate signals are continuously transmitted to the receiver unit via an electromagnetic field. The required distance between transmitter and receiver for

successful signal registration is 10-90cm. The receiver is connected to a computer through a serial port. The data acquired by the heart rate monitor is the electrocardiogram (ECG). The monitor then converts the ECG into interbeat intervals (IBI). The interbeat interval is the distance between successive R-R waves in an ECG signal in milliseconds. The digitally coded R-R interval length is continuously submitted to the software Polar[®] Precision Performance[®] software that in turn displays a heart tachogram on the monitor [10]. The subject then performs the cycles exercise with an increased target at every successive cycle.

3.3 Cycles Analysis:

After the completion of the baseline test the subjects started with the actual cycles session. Target heart rates were calculated as percentages of peak heart rate determined from the baseline session. The heart rates progressively increased in an incremental fashion until the target heart rate was achieved. During the cycles that required high heart rates, the subjects exercised vigorously to assist in reaching such high heart rates within the allotted 60 seconds [5].

The heart rate data collected during exercise was in the form of interbeat intervals in milliseconds. The data is then converted into beats/min using the formula:

$$\text{Heart rate in beats/minute} = 60,000 \text{ milliseconds/min} / \text{interbeat intervals in milliseconds/beat}$$

and the acceleration and deceleration parameters were analyzed using a Mathematica program (Version 4.1). The Mathematica code is shown in the appendix. Figure 3.1 shows the graph of a typical cycles session.

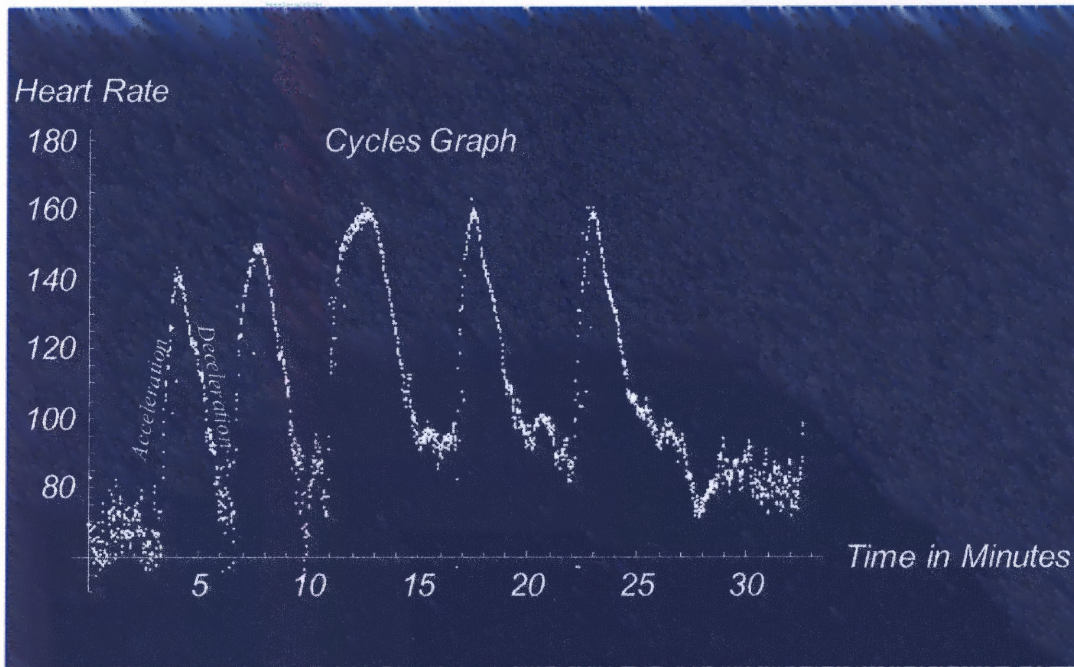


Figure 3.1 Graph of cycles showing the acceleration and deceleration regions.

The heart rate calculated from the interbeat interval data acquired from the Polar S810 HR Monitor contained some artifacts, which could lead to erroneous results when analyzed [11]. By eliminating the spikes in the heart rate (defined as sudden burst in heart rate value), which removed much of the artifacts, the data was ready for further processing.

Each cycle in a complete cycle session was analyzed as two different regions, an acceleration region and a deceleration region. The acceleration region denotes the acceleration phase of exercise and the deceleration region denotes the recovery period. The acceleration and deceleration regions are marked for the first cycle in figure 3.1. In order to define the acceleration and the deceleration regions, the peak value (the highest heart rate achieved by a subject during the execution of the cycle), the acceleration valley and the deceleration valley had to be determined for each cycle.

Peak value: The peak value represents the highest heart rate achieved by a subject during the execution of the cycle. This is a two dimensional parameter and consists of the position in the time series and the value of the peak heart rate of the cycles.

Algorithm for peak value determination:

1. The cycles data was smoothed to eliminate spikes (sudden burst in heart rate) and dropouts (sudden lowering in heart rate).
2. The mean value was subtracted from the cycles data.
3. Maximum heart rate value (mx) and minimum heart rate value (mn) were calculated from the entire data points.
4. Heart rate values more than 40% of mx are considered as peaks and heart rate values less than 40% of mn are considered as valleys.
5. Tested whether the peak is in between two valleys.

Table 3.1 displays the peak value parameter of the subject S1 during a specific cycle session. The peak value parameter consists of the position of the peak in the data file (peak index) and the highest value of heart rate achieved by the subject S1.

Table 3.1 Cycle numbers, peak position and peak values of subject S1

Cycle Number	Peak index	Peak value achieved (heart rate in beats/min)
1	292	139
2	537	147
3	799	159
4	1120	162
5	1154	163

Valley: This is also a two dimensional parameter, which indicates the minimum value (heart rate) of the cycles and its position in the time series. Two kinds of valleys are calculated for the acceleration and the deceleration parameter extraction. They are acceleration valleys and deceleration valleys. The acceleration valley is the minimum stabilized heart rate value (varying less than \pm three beats over 15 seconds) in an acceleration phase and the deceleration valley is the minimum stabilized heart rate value (varying less than \pm three beats over 15 seconds) in the recovery phase. The acceleration valley was determined by back-calculating 200 data points from the peak value through the acceleration phase and checking where the heart rate became stabilized. The data point where the heart rate became stabilized was chosen as the acceleration valley. 200 data points was selected because, by observation, the acceleration valley was found within these 200 data points. The deceleration valley was determined by forward-calculating 350 data points from the peak value through the deceleration phase and checking where the heart rate became stabilized. The data point where the heart rate became stabilized was chosen as the deceleration valley. For deceleration valley calculation 350 data points were selected because, by observation, the deceleration valley was found within these 350 data points. The two valleys, the acceleration valley and the deceleration valley, occurred at different points.

The protocol for calculating the acceleration valley and the deceleration valley was based on the heart rate becoming stabilized, which was defined as heart rate varying less than \pm three beats over 15 seconds. But to simplify the calculation and to avoid programming difficulties, the algorithm used 15 data points sections (overlapping over

one data point), out of 200 data points for the acceleration valley and 350 data points for the deceleration valley, to test for heart rate stability.

Acceleration Valley:

The acceleration valley is the minimum stabilized heart rate value in an acceleration phase. The acceleration valley was determined by back-calculating 200 data points from the peak value through the acceleration phase and checking whether the heart rate became stabilized. The algorithm for determination of the acceleration valley point is described below.

The Algorithm for acceleration valley calculation:

1. Back calculate 200 data points from the peak values. By observation, the acceleration valley was found to be within these 200 points.
2. Partition the values as sets of 15 points. These 15 values were overlapping over one data point.
3. In each 15 data point set, the 15th value (max), 1st value (min) and 8th value (middle) of heart rate were identified.
4. The differences, middle-max and middle-min values were calculated.
5. If both the differences were less than three, the data point (the 1st data point from the 15 values set) was picked as the acceleration valley. One more criterion for acceleration valley determination was that the minimum value for heart rate should be less than 100.

The *Mathematica* program segment that calculated the acceleration valley follows.

(**** Acceleration valley calculation****)

```

throwvalue1=Table[0,{Length[peakvalu]};
fvalcalc[j_]:=
(val1=Take[origcycle1,{peakvalu[[j,2]],peakvalu[[j,2]]-200,-1}];
val2=Table[0,{Length[val1]};
Do[val2[[i]]=val1[[i,2]],{i,1,Length[val1]};
val15=Partition[val2,15,1];
meanval=Table[0,{Length[val15]};
Do[meanval[[i]]=val15[[i,8]],{i,1,Length[val15]};
maxval=Table[0,{Length[val15]};
Do[maxval[[i]]=val15[[i,1]],{i,1,Length[val15]};
minval=Table[0,{Length[val15]};
Do[minval[[i]]=val15[[i,15]],{i,1,Length[val15]};
valdiff1=Table[0,{Length[val15]};
Do[valdiff1[[i]]=Abs[(meanval[[i]]-maxval[[i]])],{i,1,Length[val15]};
valdiff2=Table[0,{Length[val15]};
Do[valdiff2[[i]]=Abs[(meanval[[i]]-minval[[i]])],{i,1,Length[val15]};
Do[throwvalue1[[j]]=Catch[Do[i;If[(valdiff1[[i]]<3)&&(valdiff2[[i]]
<3)&&(minval[[i]]<100),Throw[i]],{i,1,Length[val15]}]]];
Do[fvalcalc[j],{j,1,Length[peakvalu]};
peak=peakvalu[[All,2]];
valleyindex=Table[0,{Length[peakvalu]};
Do[valleyindex[[i]]=peak[[i]]-throwvalue1[[i]]+1,{i,1,Length[peakvalu]};
acclnvalley=Table[0,{i,Length[peakvalu]},{j,2}];
Do[acclnvalley[[i,2]]=valleyindex[[i]],{i,1,Length[peakvalu]};
Do[acclnvalley[[i,1]]=origcycle1[[valleyindex[[i]],2]],{i,1,Length[peakvalu]};
Print["Peakvalues = ", peakvalu];
Print["Acceleration Valleys = ", acclnvalley];

```

Table 3.2 shows the cycle numbers, the position (index) and values of acceleration valleys for subject S1 for a specific cycle session.

Table 3.2 Cycle numbers, acceleration valley position and its values of subject S1

Cycle Number	Acceleration valley index	Acceleration valley - Minimum value in beats/min
1	185	65
2	391	76
3	662	77
4	1008	94
5	1343	83

Deceleration Valley:

The deceleration valley is the minimum stabilized heart rate value (varying less than \pm three beats over 15 seconds) in the recovery phase. The deceleration valley was determined by forward-calculating 350 data points from the peak value through the deceleration phase and checking whether the heart rate became stabilized. The algorithm for determination of the deceleration valley point is described below.

Algorithm for deceleration valley calculation:

1. Forward calculate 350 data points after each peak value.
2. Partition the values as sets of 15 data points.
3. In each 15 data point set, the 1st value (max1), the 15th value (min1), the 8th value (middle), the 4th value (max2) and the 12th value (min2) of heart rate were identified. (the 4th and 12th values were calculated for more accurate deceleration valley calculation as the heart values during deceleration were found to be less fluctuating than heart rate values during acceleration)
4. The differences, middle-max1, middle-min1, middle-max2, and middle-min2 values were calculated.
5. If all the differences were less than three, the point was picked as the valley. One more criterion for deceleration valley heart rate determination was that it should be less than 100.

The *Mathematica* program segment that calculates the deceleration valley is written below.

```
(**** Deceleration valley calculation*****)
```

```
throwvalue2=Table[0,{Length[peakvalu]}];
fvalcalc2[j_]:=
```

```

(val1a=Take[origcycle1,{peakvalu[[j,2]],peakvalu[[j,2]]+350}];
val2a=Table[0,{Length[val1a]}];
Do[val2a[[i]]=val1a[[i,2]],{i,1,Length[val1a]}];
val15a=Partition[val2a,15,1];
meanvala=Table[0,{Length[val15a]}];
Do[meanvala[[i]]=val15a[[i,8]],{i,1,Length[val15a]}];
maxvala=Table[0,{Length[val15a]}];
Do[maxvala[[i]]=val15a[[i,1]],{i,1,Length[val15a]}];
nextmaxa=Table[0,{Length[val15a]}];
Do[nextmaxa[[i]]=val15a[[i,4]],{i,1,Length[val15a]}];
minvala=Table[0,{Length[val15a]}];
Do[minvala[[i]]=val15a[[i,15]],{i,1,Length[val15a]}];
nextmina=Table[0,{Length[val15a]}];
Do[nextmina[[i]]=val15a[[i,12]],{i,1,Length[val15a]}];
valdiff1a=Table[0,{Length[val15a]}];
Do[valdiff1a[[i]]=Abs[(meanvala[[i]]-maxvala[[i]])],{i,1,Length[val15a]}];
valdiff2a=Table[0,{Length[val15a]}];
Do[valdiff2a[[i]]=Abs[(meanvala[[i]]-minvala[[i]])],{i,1,Length[val15a]}];
valdiff3a=Table[0,{Length[val15a]}];
Do[valdiff3a[[i]]=Abs[(meanvala[[i]]-nextmaxa[[i]])],{i,1,Length[val15a]}];
valdiff4a=Table[0,{Length[val15a]}];
Do[valdiff4a[[i]]=Abs[(meanvala[[i]]-nextmina[[i]])],{i,1,Length[val15a]}];
Do[throwvalue2[[j]]=Catch[Do[i,If[(valdiff1a[[i]]<3)&&(valdiff2a[[i]]<3)&&(minvala[[i]]<100),Throw[i]],{i,1,Length[val15a]}]];
);
Do[fvalcalc2[j],{j,1,Length[peakvalu]}];
Print["Throwvalue = ",throwvalue2];
valleys2=Table[0,{Length[peakvalu]}];
Do[If[throwvalue2[[i]]<1,valleys2[[i]]=valleyerror,
valleys2[[i]]=throwvalue2[[i]]+peakvalu[[i,2]],{i,1,Length[peakvalu]}]
Print["Deceleration Valleys = ",valleys2];
dcclnvalley=Table[0,{i,Length[peakvalu]},{j,2}];
Do[dcclnvalley[[i,2]]=valleys2[[i]],{i,1,Length[peakvalu]}];
Do[dcclnvalley[[i,1]]=origcycle1[[valleys2[[i],2]],{i,1,Length[peakvalu]}];
Print["Deceleration Valleys = ",dcclnvalley];

```

Table 3.3 shows the cycle numbers, the position (index) and values of the deceleration valleys of subject S1 for a specific session.

Table 3.3 Cycle numbers, deceleration valley position and its values for subject S1

Cycle Number	Deceleration valley index	Deceleration valley - Minimum value in beats/min
1	332	96
2	568	89
3	892	99
4	1182	99
5	1524	100

3.3.1 Acceleration and Deceleration Regions

The acceleration region comprises the region from the acceleration valley point to the peak value point. The deceleration region comprises the region from the peak value point to the deceleration valley point. Figure 3.2 shows a sketch of the acceleration and deceleration regions with peak value, acceleration valley, and deceleration valley.

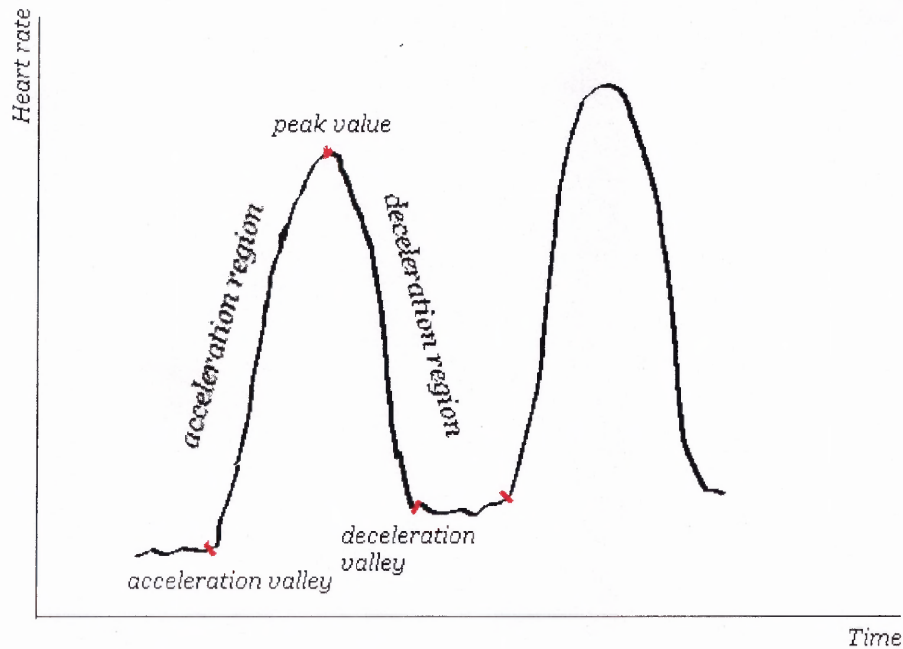


Figure 3.2 Sketch of acceleration and deceleration regions with peak value and valleys.

In this study the acceleration and deceleration regions were analyzed separately. For analysis purposes, both the acceleration region and the deceleration region were divided into three sections with equal number of points. The idea was to fit the three different regions with mathematical curves, to generate a single parameter for each fit and to find out the mean square error for the each fit for quantitative analysis. The total number of points from valley to peak value was determined and it was divided by three to get three equal segments for both acceleration and deceleration regions. If the number of points in a segment was found to be a non-integer value it was rounded upward. The first segment, the initial portion, was fitted with an exponential curve, the second segment, the middle portion, was fitted with a straight line and the third segment, the final portion, was fitted with another exponential curve. The reason behind the selection of the exponential

curve and straight line was that they both yielded a single parameter, an exponent for an exponential curve and a slope for a straight line.

There are two assumptions based on which this division of acceleration and deceleration regions into three different portions was performed and the corresponding fitting was accomplished. First, by observation, the three sections in each acceleration and deceleration region were found to follow different curves. For the acceleration region the first section was following an exponential curve ($y = C_1 e^{at}$), the second section was following a straight line ($y = bt + d$) and the third section was following another exponential curve ($y = 1 - C_2 e^{-gt}$). For the deceleration region the first section was following an exponential curve ($y = 1 - C_3 e^{ht}$), the second section was following a straight line ($y = mt + n$), and the third section was following another exponential curve ($y = C_4 e^{-kt}$). This assumption was found to be true when the mean square error values obtained for individual curve fitting yielded values close to zero. Second was a physiological observation. During the first section of the acceleration region the heart rate was found to be accelerating, during the second section, this acceleration was found to be zero and during the final section this acceleration was found to be decreasing. Similarly during the first section of the deceleration region the heart rate was found to be decelerating, during the second section the deceleration was found to be zero and during the final section the deceleration was found to be decreasing.

3.3.2 Acceleration Parameters

The acceleration region comprises the region from the acceleration valley point to the peak value point. For analysis purposes, based on the above-mentioned assumptions the

acceleration region was divided into three sections. Figure 3.3 shows the sketch of the three portions of an acceleration phase.

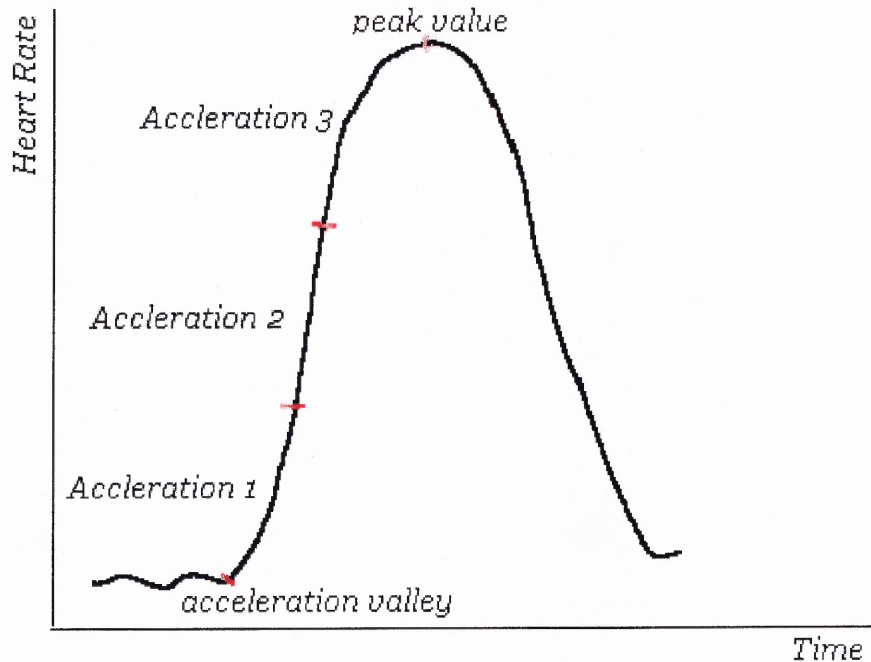


Fig 3.3 Sketch of three acceleration regions.

Acceleration 1:

The first section of the acceleration region, the initial rising phase (acceleration 1), was fitted with an exponential curve ($y = C_1 e^{at}$) using the *Mathematica* function 'Fit' and the exponent of the exponential curve was extracted. The function 'Fit' finds a least-squares fit to the list of data. The important parameters extracted from the acceleration 1 region were the exponent (a) and the mean square error. From the exponent value the time constant ($1/a$) was calculated. In order to curve fit the acceleration 1 region, the logarithmic values of the exponential ($C_1 e^{at}$) were taken to make it linear. While doing the curve fitting there were some outliers, which caused the mean square error to be a

larger value than expected, even though the curve was found to be fitting properly. These outliers were removed using the following algorithm.

1. The data was fitted with appropriate curves (exponential curve for acceleration 1 and acceleration 3 regions and straight line for acceleration 2 region).
2. The errors between the original data point values and the curve fit values were calculated.
3. The standard deviation of the errors was calculated.
4. The data points occurring outside the standard deviation of the errors were removed.

The major reason for the outliers was the movement artifacts caused during exercise. The data points outside 68% of the mean of errors between the data points and the curve fit values were recognized as artifacts. Hence one standard deviation of errors was used for outlier removal. After removing the outliers, the curve was 'refitted' with a new exponential. From this new curve fit the exponent and the mean square errors were calculated. The *Mathematica* program segment that did the exponential curve fitting at the first part of the acceleration region, outlier removal and curve 'refitting' is written below.

(**** Finding the parameters- exponents and mean square errors- for the first section of acceleration (accln1). It is fitting with an exponential ****)

```
coeff1=Table[0,{Length[peakvalu]};
mser1=Table[0,{Length[peakvalu]};
faccln1[j_]:=
(accln1=Take[origcycle1,{acclnvalley[[j,2]],acclnvalley[[j,2]]+acclnperthird[[j]]});
SD6=Table[0,{Length[accln1]};
Do[SD6[[n]]=accln1[[n,2]],{n,1,Length[accln1]};
XYs=Transpose[{accln1[[All,1]],Log[accln1[[All,2]]]};
g1[X_]=Fit[XYs,{1,X},X];
c1=CoefficientList[g1[X],{X}];
```

```

g11[X_]=Exp[c1[[1]]]*Exp[c1[[2]]*X];
errors1=Table[0,{Length[acln1]};
Do[errors1[[i]]=g11[i+acln1[[1,1]]-1]-acln1[[i,2]},{i,1,Length[acln1]};
SD5=errors1;
Do[SD4 = 1/Length[SD5))*(Sum[SD5[[n]], {n, 1, Length[SD5]}]);
(**mean of errors**)
SD3=Table[0,{Length[SD5]};
Do[SD3[[n]] = (SD5[[n]] - SD4)^2, {n, 1, Length[SD5]};
Do[SD2 = (1/Length[SD5))*(Sum[SD3[[n]], {n, 1, Length[SD5]}]);
Do[SD1=Sqrt[SD2];
(**standard deviation of errors**)
SD={};
Do[If[(SD5[[n]]<(SD4+SD1) )&&(SD5[[n]]>(SD4-SD1)),SD=Append[SD,n]},{n,1,
Length[SD5]};
acln11=Table[0,{Length[SD]};
Do[acln11[[p]]=SD6[[SD[[p]]]},{p,1,Length[SD]};
acln1=Table[0,{Length[acln11]},{n,2};
Do[acln1[[i,1]]=SD[[i]},{i,1,Length[acln11]};
Do[acln1[[i,2]]=acln11[[i]},{i,1,Length[acln11]};
XYs1=Transpose[{acln1[[All,1]],Log[acln1[[All,2]]]};
g1a[X_]=Fit[XYs1,{1,X},X];
c1a=CoefficientList[g1a[X],{X};
g11a[X_]=Exp[c1a[[1]]]*Exp[c1a[[2]]*X];
errors1a=Table[0,{Length[acln1]};
Do[errors1a[[i]]=g11a[SD[[i]]]-acln1[[i,2]},{i,1,Length[acln1]};
mse1=Table[0,{Length[acln1]};
Do[mse1[[i]] = (errors1a[[i]])^2, {i, 1, Length[acln1]};
Do[mser1[[j]] = (1/Length[acln1))*(Sum[mse1[[i]], {i, 1, Length[acln1]}]);
Do[coeff1[[j]]=c1a[[2]]
);
(*facln1[1];
Show[ListPlot[acln1,PlotStyle->{PointSize[0.02],Hue[0.6]}],
Plot[g11[X],{X,First[acln1[[1]]],First[Last[acln1]}],
PlotStyle->{Hue[0]}],AxesLabel->{"Index","Heart Rate"}];
Show[ListPlot[acln1,PlotStyle->{PointSize[0.02],Hue[0.6]}],
Plot[g11a[X],{X,First[acln1[[1]]],First[Last[acln1]}],
PlotStyle{Hue[0]}],AxesLabel->{"Index","Heart Rate"}];*)
Do[facln1[j],{j,1,Length[peakvalu]};
Print["Coefficients1 [Exponent]= ",coeff1]
Print["Mean square error = ", mser1];

```

The parameters extracted from the first acceleration region (acceleration 1) were the exponent and mean square error.

Exponent: This is the exponent of the exponential fit. The time constant was calculated by inverting the exponent value.

Mean Square Error (MSE): This is the mean of the square of the differences of the original data points and the curve fit values. Mean square error shows the variation of the original data from the exponential curve. The lower the mean square error value, the better the fit to the curve.

Figure 3.4 shows an exponential fit to the first section of the acceleration region (acceleration 1) for subject S2 for 1st cycle in a specific cycles session.

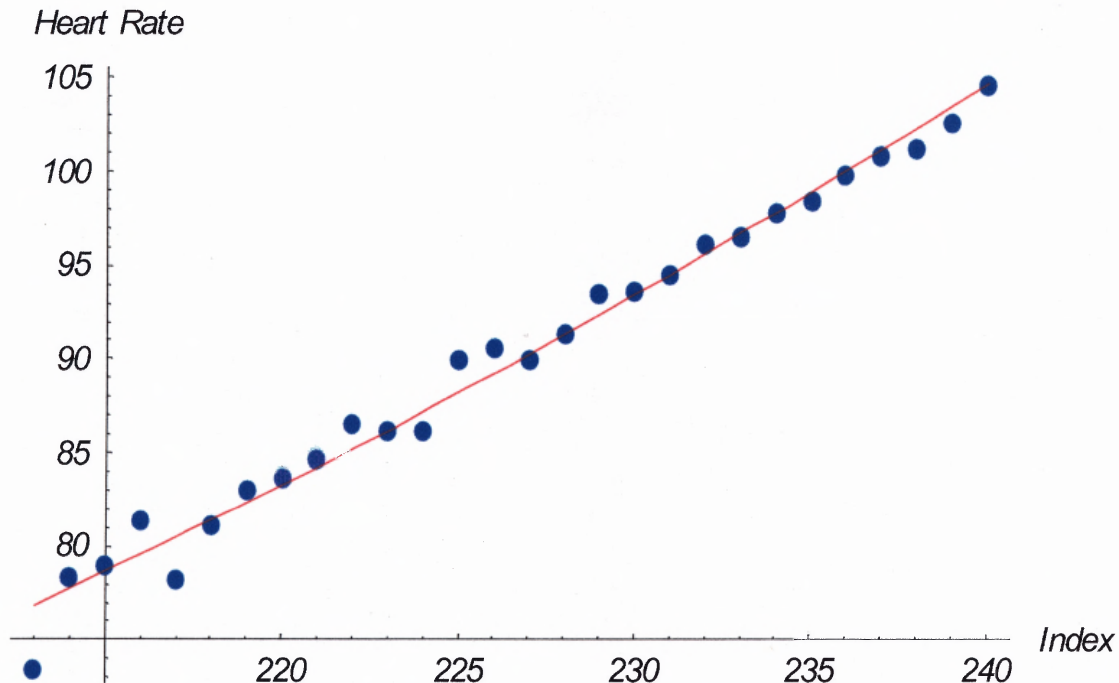


Figure 3.4 An exponential fit to acceleration 1 for 1st cycle in a specific cycles session for subject S2.

Table 3.4 shows the time constant and mean square error for the first section of acceleration of subject S1 for a specific cycle session.

Table 3.4 Time constant and mean square error for acceleration 1 of subject S1

Cycle Number	Time constant	Mean Square Error
1	89.928	0.16
2	148.809	0.64
3	9.293	6.40
4	129.870	1.34
5	145.773	0.52

Outlier Removal:

Figure 3.5 shows a typical situation where some of the outliers were removed and refitted with a new curve. Figure 3.5(a) shows the curve fitting of the acceleration 1 region with 5 data points as outliers (4 points below the curve and 1 point above the curve). The standard deviation of the errors between the curve fit values and the original data point values were calculated. The data points outside this standard deviation of the error were considered as outliers and they were removed. The resultant curve was 'refitted' with a new exponential. Figure 3.5 (b) shows the curve fitting of acceleration 1 region after outlier removal.

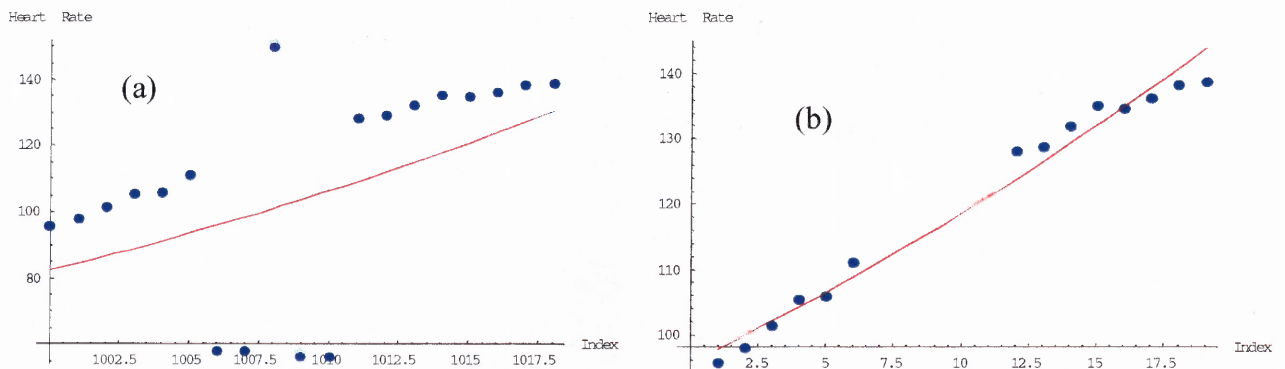


Figure 3.5 A typical outlier removal for acceleration 1 region. (a) Acceleration 1 region with some outliers (b) Acceleration 1 region after outlier removal.

Acceleration 2:

The second section of the acceleration region, the zero accelerating region (acceleration 2), was fitted with a straight line ($y = bt + d$) using the *Mathematica* function 'Fit' and the slope of the straight line was extracted. The function 'Fit' finds a least-squares fit to the list of data. The important parameters extracted from the second acceleration region were the slope (b) and the mean square error. While doing the curve fitting there were some outliers because of which the mean square error was found to be a larger value than expected, even though the data was found to be fitting the straight line properly. These outliers were removed using the following algorithm.

1. The data was fitted with a straight line for the acceleration 2 region.
2. The errors between the original data point values and the curve fit values were calculated.
3. The standard deviation of the errors was calculated.
4. The data points occurring outside the standard deviation of the errors were removed.

After removing the outliers, the curve was 'refitted' with a new exponential curve. From this new curve fit the slope and the mean square error were calculated. The *Mathematica* program segment that did the straight line fitting at the second section of the acceleration region, outlier removal and curve 'refitting' is written below.

(****Finding the parameters -slopes and mean square errors- for the middle section (accln2) of acceleration region. It is fitting with a straight line****)

```
coeff2 = Table[0, {Length[peakvalu]};
mser2 = Table[0, {Length[peakvalu]};
faccln2[j_]:=
(accln2 = Take[origcycle1, {(acclnvalley[[j,2]]+
acclnperthird[[j]]),(acclnvalley[[j,2]]+(2*acclnperthird[[j]])});
```

```

ASD6 = Table[0, {Length[acln2]};
Do[ASD6[[n]] = acln2[[n,2]], {n,1,Length[acln2]};
g2[X_] = Fit[acln2, {1,X},X];
c2 = CoefficientList[g2[X],{X}];
errors2=Table[0, {Length[acln2]};
Do[errors2[[i]]=g2[i+acln2[[1,1]]-1]-acln2[[i,2]], {i,1,Length[acln2]};
ASD5=errors2;
Do[ASD4 = (1/Length[ASD5])*(Sum[ASD5[[n]], {n, 1, Length[ASD5]}]);
(**mean of errors**)
ASD3=Table[0, {Length[ASD5]};
Do[ASD3[[n]] = (ASD5[[n]] - ASD4)^2, {n, 1, Length[ASD5]};
Do[ASD2 = (1/Length[ASD5])*(Sum[ASD3[[n]], {n, 1, Length[ASD5]}]);
Do[ASD1=Sqrt[ASD2]];
(*standard deviation of errors*)
ASD={};
Do[If[(ASD5[[n]]<(ASD4+ASD1) )&&(ASD5[[n]]>(ASD4-
ASD1)),ASD=Append[ASD,n]], {n,1,Length[ASD5]};
acln22=Table[0, {Length[ASD]};
Do[acln22[[p]]=ASD6[[ASD[[p]]]], {p,1,Length[ASD]};
acln2=Table[0, {Length[acln22]}, {n,2}];
Do[acln2[[i,1]]=ASD[[i]], {i,1,Length[acln22]};
Do[acln2[[i,2]]=acln22[[i]], {i,1,Length[acln22]};
g2a[X_] = Fit[acln2, {1,X},X];
c2a=CoefficientList[g2a[X],{X}];
errors2a=Table[0, {Length[acln2]};
Do[errors2a[[i]]=g2a[ASD[[i]]]-acln2[[i,2]], {i,1,Length[acln2]};
mse2=Table[0, {Length[acln2]};
Do[mse2[[i]] = (errors2[[i]])^2, {i, 1, Length[acln2]};
Do[mser2[j]] =
(1/Length[acln2])*(Sum[mse2[i]], {i, 1, Length[acln2]}]);
Do[coeff2[j]=c2a[2]]];
(*facln2[1];
Show[ListPlot[acln2,PlotStyle->{PointSize[0.2],Hue[0.6]}],
Plot[g2[X],{X,First[acln2[[1]]],First[Last[acln2]}],
PlotStyle->{Hue[0]}],AxesLabel->{"Index","Heart Rate"},
TextStyle->{FontFamily->"Helvetica",FontSize->13,
FontSlant->"Italic",FontColor->RGBColor[0,0,0]}];
Show[ListPlot[acln2,PlotStyle->{PointSize[0.02],Hue[0.6]}],
Plot[g2a[X],{X,First[acln2[[1]]],First[Last[acln2]}],
PlotStyle->{Hue[0]}],AxesLabel->{"Index","Heart Rate"}, TextStyle->
{FontFamily->"Helvetica",FontSize->13,
FontSlant->"Italic",FontColor->RGBColor[0,0,0]}];
Print["Coefficients2 [Slope]= ",coeff2];
Print["Mean square error = " , mser2];*)
Do[facln2[j], {j,1,Length[peakvalu]};
Print["Coefficients2 [Slope]= ",coeff2];

```



```
Print["Mean square error = " , mser2];
```

The parameters extracted from the second acceleration region (acceleration 2) were the slope and mean square error.

Slope: This is the slope of the straight line fit.

Mean Square Error (MSE): This shows the variation of the original data from the straight-line fit. The lower the mean square error value, the better the fit to the curve.

Figure 3.6 shows a straight line fit for the second section of the acceleration region (acceleration 2) for subject S2 for 2nd cycle in a specific cycles session.

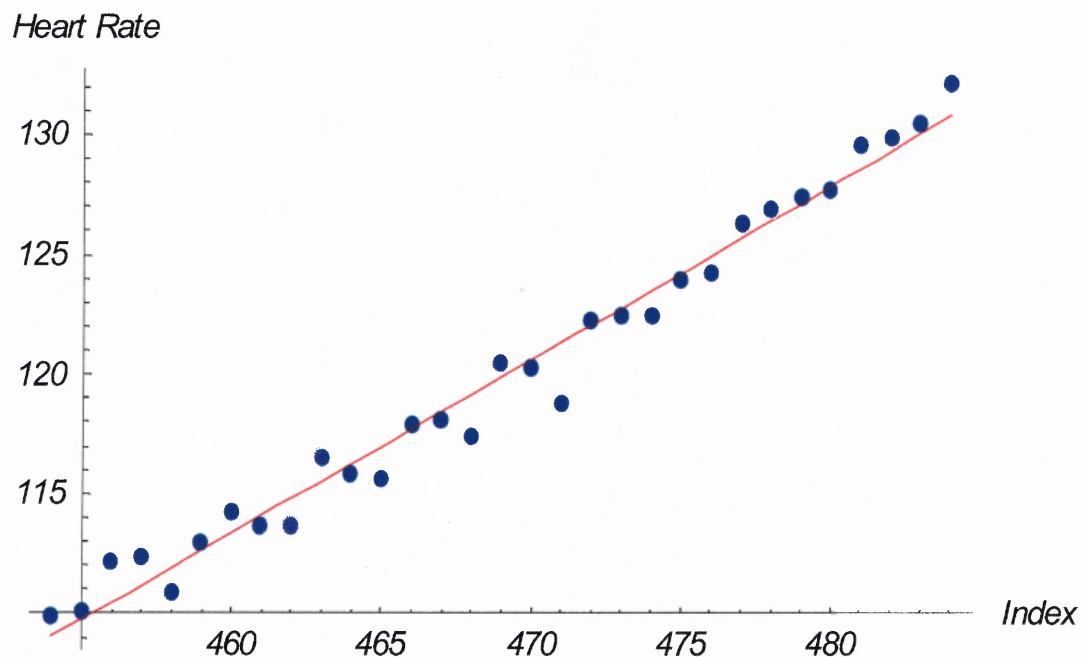


Figure 3.6 A straight line fit to acceleration 2 for 2nd cycle in a specific cycles session for subject S2.

Table 3.5 shows the slope and mean square error for the second section of acceleration of subject S1 for a specific cycle session.

Table 3.5 Slope and mean square error for acceleration 2 of subject S1

Cycle Number	Slope	Mean Square Error
1	0.363	0.37
2	0.366	0.48
3	0.594	0.66
4	0.989	0.39
5	0.806	0.13
6	0.848	0.23

Acceleration 3:

The third section of the acceleration, the decreasing acceleration phase (acceleration 3) was found to follow another exponential ($y = 1 - C_2e^{-gt}$). The algorithm did the curve fitting of the first portion of acceleration (acceleration 1) by taking the logarithmic values of the exponential (C_1e^{-at}) to make it linear. In the case of the third section of acceleration (acceleration 3), since the curve follows the exponential $y = 1 - C_2e^{-gt}$, there is a problem in taking the logarithm. This difficulty was overcome by adopting the following method to change the original curve that was following the exponential curve $y = 1 - C_2e^{-gt}$ to another curve that was following an exponential curve C_5e^{-pt} .

1. Identify the final data point value (according to the index value) of the original curve, $y = 1 - C_2e^{-gt}$
2. Each data point in that curve was subtracted from the final data point value.
3. The resulting data points produced a curve that followed an exponential curve $y' = C_5e^{-pt}$.

The curve fitting of the third section of acceleration (acceleration 3) was done by taking the logarithmic values of the exponential (C_5e^{-pt}) to make it linear. The important

parameters extracted from the third section of acceleration were the exponent (p) of the exponential fit and the mean square error. The time constant (1/p) was calculated by inverting the exponent value. As in the case of the acceleration 1 and acceleration 2 regions there were some outliers, which caused the mean square error value to be larger than expected. These outliers were removed using the following algorithm.

1. The data was fitted with an exponential curve for the acceleration 3 region.
2. The errors between the original data point values and the curve fit values were calculated.
3. The standard deviation of the errors was calculated.
4. The data points occurring outside the standard deviation of the errors were removed.

After removing the outliers, the curve was ‘refitted’ with a new exponential curve. From this new curve fit the exponent and the mean square error were calculated. The *Mathematica* program segment that did the exponential curve fitting at the third section of the acceleration region, outlier removal and curve ‘refitting’ is written below.

```
(****Finding the exponent and mean square error for the last part (accln3) of
acceleration. The shape of the curve inverted for calculation purpose. The curve is fitting
with an exponential ****)
coeff3=Table[0,{Length[peakvalu]}];
mser3=Table[0,{Length[peakvalu]}];
faccln3[j_]:=
(accln3=Take[origcycle1,{acclnvalley[[j,2]]+(2*acclnperthird[[j]]),peakvalu[[j,2]]}];
accln3rev=Table[0,{Length[accln3]}];
Do[accln3rev[[i]]=Last[Last[accln3]]-accln3[[i,2]],{i,1,Length[accln3]}];
q1={};
Do[If[accln3rev[[i]]>0,q1=Append[q1,i]],{i,1,Length[accln3rev]}];
accln3=Table[0,{Length[q1]},{n,2}];
Do[accln3[[i,1]]=q1[[i]],{i,1,Length[q1]}];
Do[accln3[[i,2]]=accln3rev[[q1[[i]]]],{i,1,Length[q1]}];
ABs=Transpose[{accln3[[All,1]],Log[accln3[[All,2]]]}];
g3[X_]=Fit[ABs,{1,X},X];
```

```

c3=CoefficientList[g3[X],{X}];
g33[X_]=Exp[c3[[1]]]*Exp[c3[[2]]*X];
errors3=Table[0,{Length[acln3]},{n,2}];
Do[errors3[[i,1]]=acln3[[i,1]},{i,1,Length[acln3]}];
Do[errors3[[i,2]]=g33[i+acln3[[1,1]]-1]-acln3[[i,2]},{i,1,Length[acln3]}];
AASD6=Table[0,{Length[acln3]}];
Do[AASD6[[p]]=acln3[[p,2]},{p,1,Length[acln3]}];
AASD5=errors3[[All,2]];
Do[AASD4=(1/Length[AASD5])*(Sum[AASD5[[n]},{n,1,Length[AASD5]}]);
AASD3=Table[0,{Length[AASD5]}];
[AASD3[[n]]=(AASD5[[n]]-AASD4)^2,{n,1,Length[AASD5]}];
Do[AASD2=(1/Length[AASD5])*(Sum[AASD3[[n]},{n,1,Length[AASD5]}]);
Do[AASD1=Sqrt[AASD2];
AASD={};
Do[If[(AASD5[[n]]<(AASD4+AASD1))&&(AASD5[[n]]>(AASD4-AASD1)),
AASD=Append[AASD,n]},{n,1,Length[AASD5]}];
acln33=Table[0,{Length[AASD]},{n,2}];
Do[acln33[[i,1]]=AASD[[i]},{i,1,Length[AASD]}];
Do[acln33[[i,2]]=acln3[[AASD[[i],2]],[i,1,Length[AASD]}];
ABs1=Transpose[{acln33[[All,1]],Log[acln33[[All,2]]]}];
g3a[X_]=Fit[ABs1,{1,X},X];
c3a=CoefficientList[g3a[X],{X}];
g33a[X_]=Exp[c3a[[1]]]*Exp[c3a[[2]]*X];
errors3a=Table[0,{Length[acln33]}];
Do[errors3a[[i]]=g33a[i+acln33[[1,1]]-1]-acln33[[i,2]],[i,1,Length[acln33]}];
mse3=Table[0,{Length[acln33]}];
Do[mse3[[i]]=(errors3a[[i]])^2,{i,1,Length[acln33]}];
Do[mser3[[j]]=(1/Length[acln33])*(Sum[mse3[[i]],[i,1,Length[acln33]]]);
Do[coeff3[[j]]=c3a[[2]]];
);
(*facln3[1];
Show[ListPlot[acln3,PlotStyle->{PointSize[0.02],Hue[0.6]}],
Plot[g33[X],{X,First[acln3[[1]]],First[Last[acln3]]},AxesLabel->{"X","Y"}];
Show[ListPlot[acln33,PlotStyle->{PointSize[0.02],Hue[0.6]}],
Plot[g33a[X],{X,First[acln33[[1]]],First[Last[acln33]]},AxesLabel->{"X","Y"}];*);
Do[facln3[j],{j,1,Length[peakvalu]}];
Print["Coefficients3 [Exponent] = ",coeff3];
Print["Mean square error = ",mser3];

```

The parameters extracted from the third acceleration region (acceleration 3) were the exponent and mean square error.

Exponent: This is the exponent of the exponential curve fit. The time constant was calculated from the exponent value.

Mean Square Error (MSE): This shows the variation of the original data from the exponential fit. The lower the mean square error value, the better the fit to the curve.

Figure 3.7 shows an exponential curve fit for the third section of the acceleration region (acceleration 3) for subject S2 for the 4th cycle in a specific cycles session.

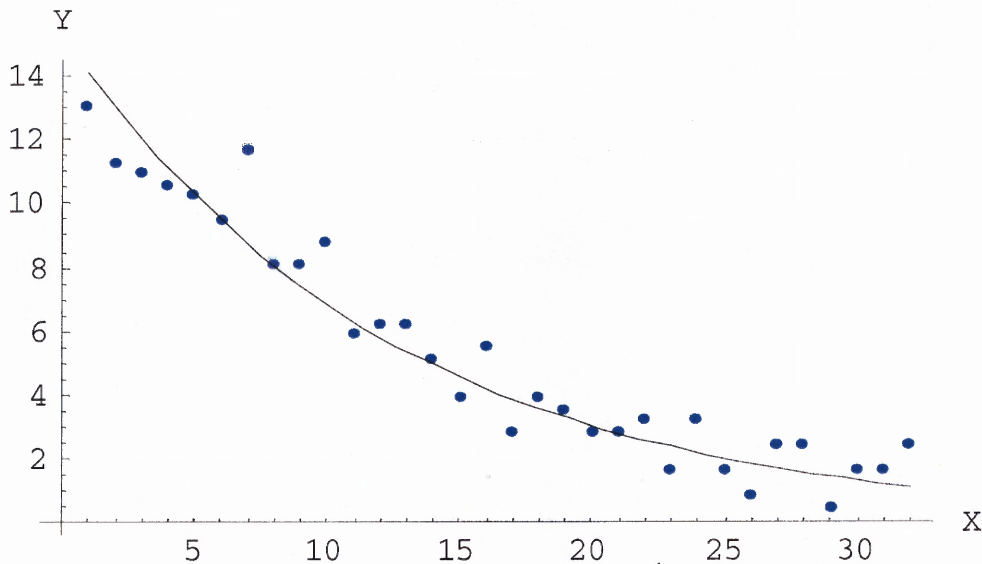


Figure 3.7 An exponential fit to acceleration 3 for 4th cycle in a specific cycles session for subject S2.

Table 3.6 shows the time constant and mean square error for the third portion of acceleration of subject S1 for a specific cycle session.

Table 3.6 Time constant and mean square error for acceleration 3 of subject S1

Cycle Number	Time constant	Mean Square Error
1	16.393	0.75
2	77.520	3.67
3	9.174	2.34
4	13.889	0.93
5	14.492	1.80
6	12.658	1.34

3.3.3 Deceleration Parameters

The deceleration region comprises the region from the peak value point to the deceleration valley point. For analysis purposes, the deceleration region also was divided into three sections just like the acceleration region. The first section, deceleration 1 was fit with an exponential, deceleration 2 was fit with a straight line and deceleration 3 was fit with another exponential. Unlike the acceleration regions, the deceleration regions showed fewer artifacts because the movement artifact has been drastically reduced in these regions since the subjects were sitting quietly during deceleration. Hence the outlier removal part was not included for the deceleration analysis in the program.

Figure 3.8 shows the sketch of the three portions of a deceleration phase.

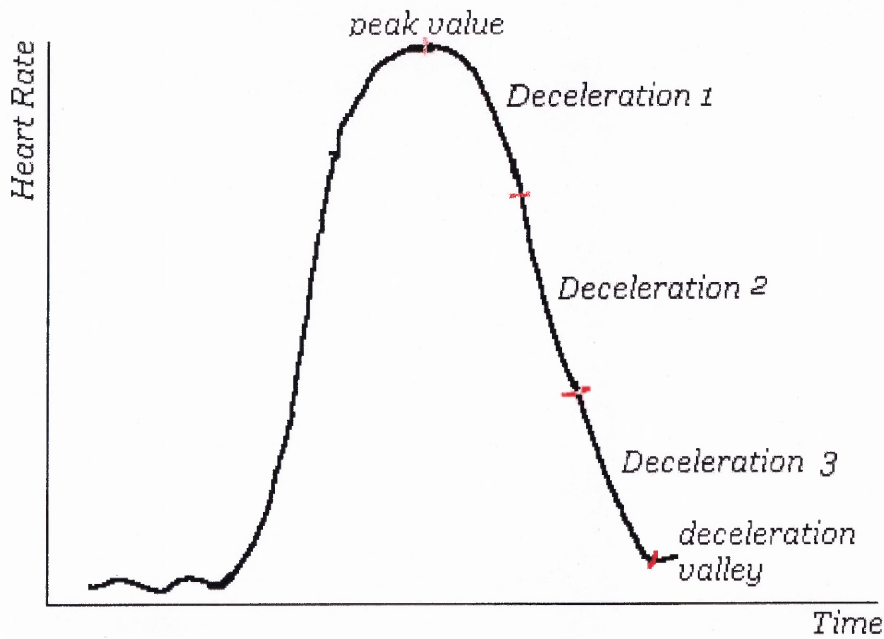


Figure 3.8 Sketch of three deceleration regions.

Deceleration 1:

The first section of the deceleration region, the beginning of the recovery phase (deceleration 1), was fit with an exponential curve $y = 1 - C_3 e^{ht}$. The algorithm did the curve fitting of first portion of the acceleration (acceleration 1) by taking the logarithmic values of the exponential ($C_1 e^{-at}$) to make it linear. Since the curve to the first portion of the deceleration follows the exponential $y = 1 - C_3 e^{ht}$, there is a difficulty to take the logarithm. This difficulty was overcome by adopting the following method to change the original curve that was following the exponential curve $y = 1 - C_3 e^{ht}$ to another curve that was following an exponential curve $C_6 e^{qt}$.

1. Identify the first data point value (according to the index number) of the original curve, $y = 1 - C_3 e^{ht}$.
2. Each data point in that curve was subtracted from the first data point value.
3. The resulting data points produced a curve that followed an exponential curve

$$y' = C_6 e^{qt}.$$

The curve fitting of the first section of deceleration (deceleration 1) was done by taking the logarithmic values of the exponential ($C_6 e^{qt}$) to make it linear. The new data set was fitted with an exponential curve using the *Mathematica* function 'Fit' and the exponent of the exponential curve was extracted. The parameters extracted from the deceleration 1 region were the exponent (q) of the exponential fit and the mean square error. The time constant (1/q) was calculated by inverting the exponent. Since the deceleration regions showed fewer artifacts compared to the acceleration regions the outlier removal part was not included for the deceleration analysis in the program.

The *Mathematica* program segment that did the exponential curve fitting and calculated the exponent and mean square error at the first part of the deceleration region is written below.

```
(****Finding the parameters (exponential and mean square error) for the first section
(dcln1) of deceleration region. It is fitting with an exponential****)
dcoeff1=Table[0,{Length[peakvalu]};
dmser1=Table[0,{Length[peakvalu]};
fdcln1[j_]:=
(dcln1=Take[origcycle1,{peakvalu[[j,2]],peakvalu[[j,2]]+dclnperthird[[j]]});
dcln1rev=Table[0,{Length[dcln1]};
Do[dcln1rev[[i]]=Last[First[dcln1]]-dcln1[[i,2]],{i,1,Length[dcln1]};
q2={};
Do[If[dcln1rev[[i]]>0,q2=Append[q2,dcln1rev[[i]]],{i,1,Length[dcln1rev]};
dcln1=Table[0,{Length[q2]},{n,2}];
Do[dcln1[[i,1]]=i,{i,1,Length[q2]};
Do[dcln1[[i,2]]=q2[[i]],{i,1,Length[q2]};
XYsd=Transpose[{dcln1[[All,1]],Log[dcln1[[All,2]]}];
k1[X_]=Fit[XYsd,{1,X},X];
dc1=CoefficientList[k1[X],{X}];
Do[dcoeff1[[j]]=dc1[[2]]];
k11[X_]=Exp[dc1[[1]]]*Exp[dc1[[2]]*X];
derrors1=Table[0,{Length[dcln1]};
Do[derrors1[[i]]=Abs[k11[i+dcln1[[1,1]]-1]-dcln1[[i,2]]],{i,1,Length[dcln1]};
dmse1=Table[0,{Length[dcln1]};
Do[dmse1[[i]]=derrors1[[i]]*derrors1[[i]],{i,1,Length[dcln1]};
```



```

Do[dmser1[[j]] = (1/Length[dcln1])*(Sum[dmse1[[i]], {i, 1, Length[dcln1]}]);
);
(*fdccln1[3];
Show[ListPlot[dcln1,PlotStyle->{PointSize[0.02],Hue[0.6]}],
Plot[k11[X],{X,First[dcln1[[1]]],First[Last[dcln1]]},
PlotStyle ->{Hue[0]}],AxesLabel -> {"X","Y"}];
Print["Mean square error =", dmser1];
Print["coefficient1=", dcoeff1];*)
Do[fdccln1[j],{j,1,Length[peakvalu]}];
Print["Coefficients1 [Exponent]= ",dcoeff1]
Print["Mean square error = ", dmser1];

```

The parameters extracted from the first deceleration region (deceleration 1) were the exponent and mean square error.

Exponent: This is the exponent of the exponential curve fit. The time constant was calculated from the exponent value.

Mean Square Error (MSE): This shows the variation of the original data from the exponential fit. The lower the mean square error value, the better the fit to the curve.

Figure 3.9 shows an exponential curve fit for the deceleration 1 region for subject S2 for 2nd cycle in a specific cycles session.

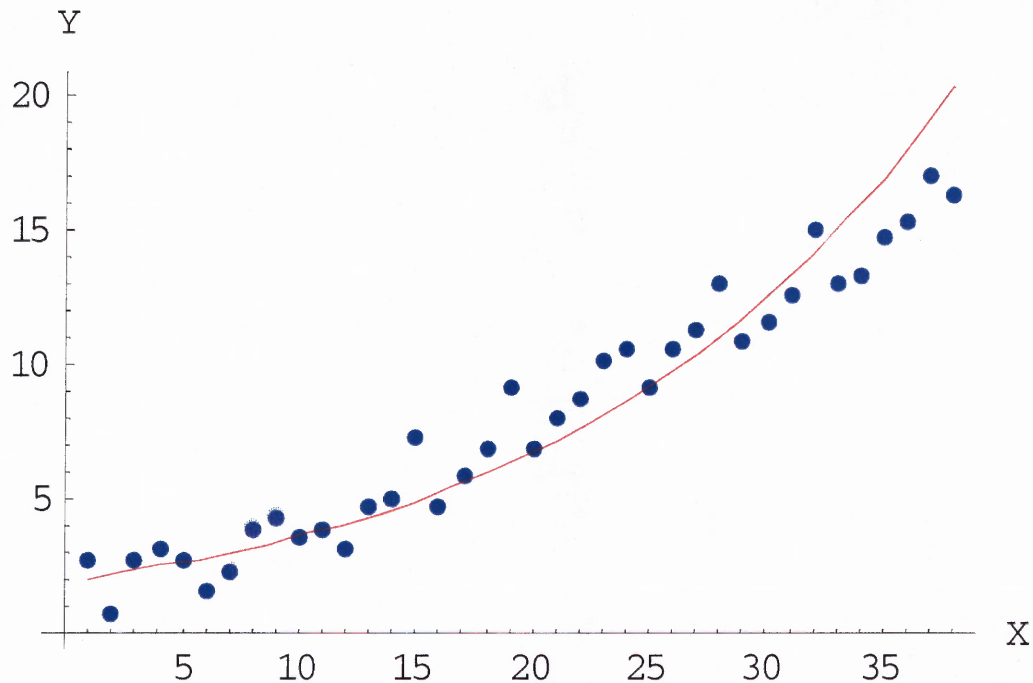


Figure 3.9 An exponential fit to deceleration 1 for 2nd cycle in a specific cycles session for subject S2.

Table 3.7 shows the time constant and mean square error for the first portion of the deceleration for subject S1 for a specific cycle session.

Table 3.7 Time constant and mean square error for deceleration 1 of subject S1

Cycle Number	Time constant	Mean Square Error
1	8.065	8.17
2	5.988	6.44
3	13.698	7.44
4	15.625	3.21
5	23.255	6.62
6	14.925	11.54

Deceleration 2:

The middle section of the deceleration region (deceleration 2) was fit with a straight line ($y = mt + n$) using the *Mathematica* function 'Fit' and the slope of the straight line fit was

extracted. The parameters extracted from the deceleration 2 region were the slope (m) of the straight line fit and the mean square error. Since the deceleration regions showed fewer artifacts compared to the acceleration regions, the outlier removal part was not included for the deceleration analysis in the program.

The *Mathematica* program segment that did the straight-line fitting and calculated the slope and mean square error at the second section of the deceleration region is written below.

(****Finding the parameters -slopes and mean square error- for the middle section (dccln2) of deceleration. It is fitting with a straight line****)

```
dcoeff2=Table[0,{Length[peakvalu]};
dmser2=Table[0,{Length[peakvalu]};
fdcln2[j_]:=
(dccln2=
Take[origcycle1, {(peakvalu[[j,2]]+
dcclnperthird[[j]),(peakvalu[[j,2]]+(2*dcclnperthird[[j]))}];
k2[X_]=Fit[dccln2, {1,X},X];
dc2=CoefficientList[k2[X],{X}];
Do[dcoeff2[[j]]=dc2[[2]]];
derrors2=Table[0,{Length[dccln2]};
Do[derrors2[[i]]=Abs[k2[i+dccln2[[1,1]]-1]-dccln2[[i,2]]],{i,1,Length[dccln2]};
dmse2=Table[0,{Length[dccln2]};
Do[dmse2[[i]]=derrors2[[i]]*derrors2[[i]],{i,1,Length[dccln2]};
Do[dmser2[[j]]=(1/Length[dccln2])*(Sum[dmse2[[i]],{i,1,Length[dccln2]}]);
);
(*fdcln2[3];
Show[ListPlot[dccln2,PlotStyle->{PointSize[0.02],Hue[0.6]}],
Plot[k2[X],{X,First[dccln2[[1]]],First[Last[dccln2]]},
PlotStyle->{Hue[0]}],AxesLabel->{"Index","Heart Rate"},
TextStyle->{FontFamily->"Helvetica",FontSize->13,
FontSlant->"Italic"}];
dmser2*)
Do[fdcln2[j],{j,1,Length[peakvalu]};
Print["Coefficients2 [Slope]= ",dcoeff2];
Print["Mean square error = ", dmser2];
```

The parameters extracted from the second deceleration region (deceleration 2) were the slope and the mean square error.

Slope: This is the slope of the straight-line fit.

Mean Square Error (MSE): This shows the variation of the original data from the straight-line fit. The lower the mean square error value, the better the fit to the curve.

Figure 3.10 shows a straight-line fit to the second section of the deceleration region for 3rd cycle in a specific cycles session for subject S2.

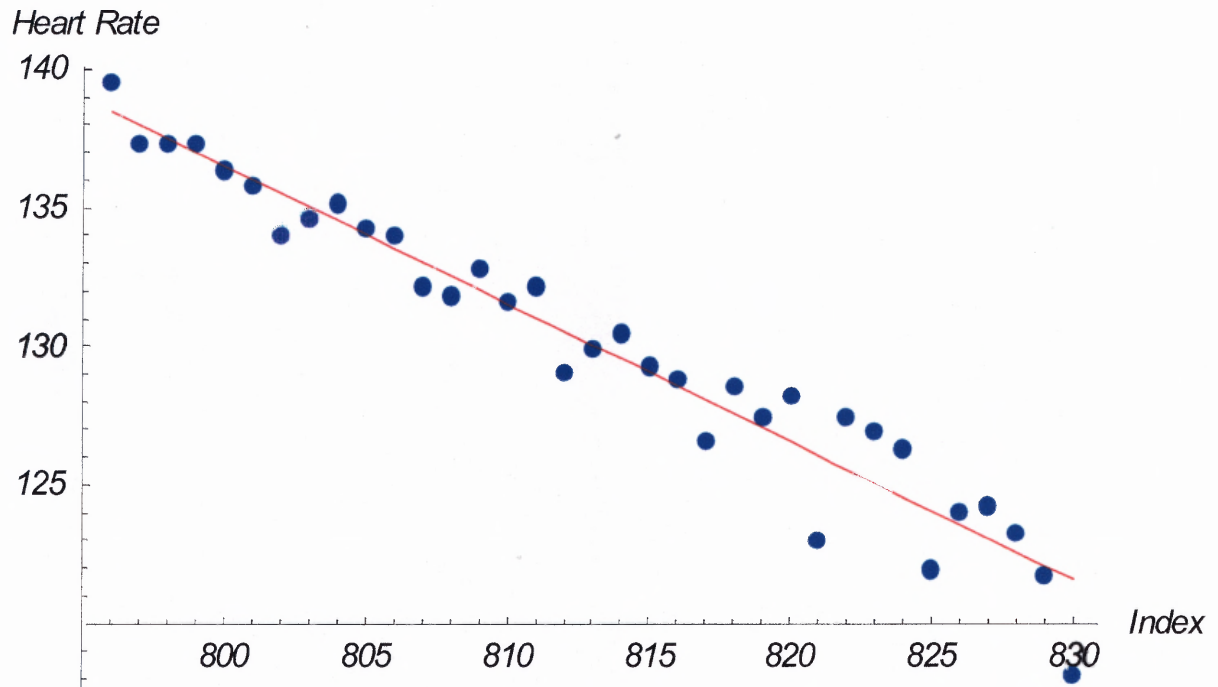


Figure 3.10 A straight line fit to deceleration 2 for 3rd cycle in a specific cycles session for subject S2.

Table 3.8 shows the slope and the mean square error for the second portion of the deceleration for subject S2.

Table 3.8 Slope and mean square error of deceleration 2 of subject S2

Cycle Number	Slope	Mean Square Error
1	-0.628	2.39
2	-0.445	0.68
3	-0.447	1.79
4	-0.594	3.89
5	-0.447	1.13
6	-0.186	4.77

Deceleration 3:

The third section of the deceleration (deceleration 3) was fit with another exponential ($y=C_4e^{-kt}$) using the *Mathematica* function 'Fit' and the exponent of the exponential curve was extracted. The parameters extracted from the deceleration 3 region were the exponent (k) of the exponential fit and the mean square error. The time constant (1/k) was calculated by inverting the exponent value. Since the deceleration regions showed fewer artifacts compared to the acceleration regions the outlier removal part was not included for the deceleration analysis in the program. The *Mathematica* program segment that did the exponential curve fitting and calculated the exponent and mean square error at the third section of the deceleration region is written below.

(****Finding the parameters-exponents and mean square error- for the last section (dccln3) of deceleration. It is fitting with an exponential****)

```
dcoeff3=Table[0,{Length[peakvalu]};
dmser3=Table[0,{Length[peakvalu]};
fdcln3[j_]:=
(dccln3=
Take[origcycle1,{peakvalu[[j,2]]+(2*dcclnperthird[[j]]),dcclnvalley[[j,2]]};
ABsd=Transpose[{dccln3[[All,1]],Log[dccln3[[All,2]]]};
k3[X_]=Fit[ABsd,{1,X},X];
dc3=CoefficientList[k3[X],{X}];
```

```

Do[dcoeff3[[j]]=dc3[[2]]];
k33[X_]=Exp[dc3[[1]]]*Exp[dc3[[2]]*X];
derrors3=Table[0,{Length[dccln3]};
Do[derrors3[[i]]=Abs[k33[i+dccln3[[1,1]]-1]-dccln3[[i,2]]],{i,1,
Length[dccln3]};
dmse3=Table[0,{Length[dccln3]};
Do[dmse3[[i]]=derrors3[[i]]*derrors3[[i]],{i,1,Length[dccln3]};
Do[dmser3[[j]]=(1/Length[dccln3])*(Sum[dmse3[[i]],{i,1,Length[dccln3]}]);
);
(*fdcln3[1];
Show[ListPlot[dccln3,PlotStyle->{PointSize[0.02],Hue[0.6]}],
Plot[k33[X],{X,First[dccln3[[1]]],First[Last[dccln3]]},
PlotStyle->{Hue[0]},AxesLabel->{"Index","Heart Rate"},
TextStyle->{FontFamily->"Helvetica",FontSize->13,FontSlant->"Italic"}];
*)
Do[fdcln3[j],{j,1,Length[peakvalu]};
Print["Coefficients3 [Exponent] = ",dcoeff3];
Print["Mean square error = ", dmser3];

```

The parameters extracted from the third deceleration region (deceleration 1) were the exponent and mean square error.

Exponent: This is the exponent of the exponential curve fit. The time constant was calculated from the exponent value.

Mean Square Error (MSE): This shows the variation of the original data from the exponential fit. The lower the mean square error value, the better the fit to the curve.

Figure 3.11 shows an exponential curve fit for deceleration 3 region for subject S2 for 6th cycle in a specific cycles session.

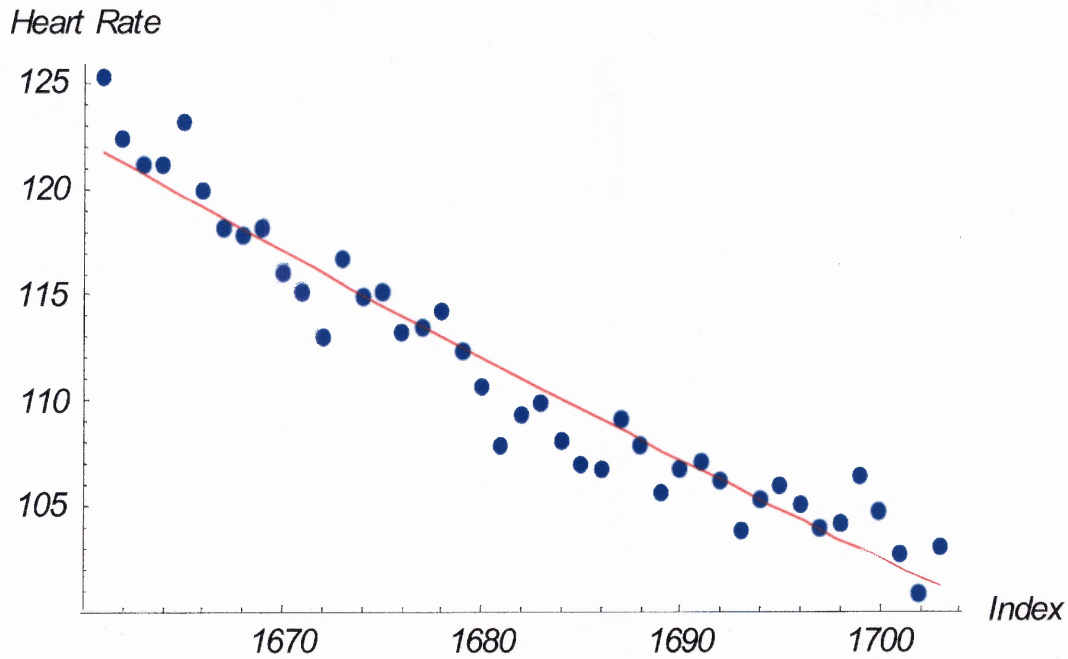


Figure 3.11 An exponential fit to deceleration 3 for subject S2 for 6th cycle in a specific cycles session.

Table 3.9 shows the time constant and the mean square error for the third section of deceleration (deceleration 3) for subject S2 for a specific cycle session.

Table 3.9 Time constant and mean square error for deceleration 3 of subject S2

Cycle Number	Time constant	Mean Square Error
1	200	1.89
2	200	1.29
3	1000	4.06
4	250	1.31
5	500	4.49
6	500	1.38

The results of all the cycles sessions for both the subjects and the discussion were presented in the next chapter.

CHAPTER 4

RESULTS AND DISCUSSION

4.1 Introduction

This chapter discusses the results obtained in this study. The acceleration and the deceleration regions have been identified and divided into three different regions. Each region was fit with different curves, the acceleration 1 region was fit with an exponential curve, the acceleration 2 region was fit with a straight line and the acceleration 3 region was fit with another exponential curve. Similarly, the deceleration 1 region was fit with an exponential curve, the deceleration 2 region was fit with a straight line and the deceleration 3 region was fit with another exponential curve. The time constants for the exponential curves and the slopes for the straight lines were extracted. The mean square error was calculated for each fit to show the variation of the data from the fit. The time constants for different exercise sessions were plotted and analyzed. A linear trendline was fit on the plots and the trend of the slope was analyzed.

The data of two subjects who underwent 4 exercise sessions each were used for the parameter extraction. The number of cycles varied from three to seven. For comparison purposes, in order to include all 4 sessions, the first 3 cycles were used in each session. From each cycle 12 parameters each were extracted, 6 parameters for the acceleration and 6 parameters for the deceleration. The acceleration parameters included the time constant for the acceleration 1 and acceleration 3 regions, the slope for the acceleration 2 region, and their corresponding mean square errors. Similarly the deceleration parameters included the time constant for the deceleration 1 and deceleration

3 regions, the slope for the deceleration 2 region and their corresponding mean square errors. The comparison of parameters was performed within the subjects and between the subjects. Within the subjects the comparison was done between different sessions for comparable cycles. The target heart rate ranges for each subject were calculated as percentages of the peak heart rate determined from their baseline session. The target heart rate goal for each cycle began at the low end of the range and progressively increased in a stepwise incremental fashion to the high end of the range. Therefore the heart rate goal for different cycles in a specific session was different. Hence the same parameters for different cycles in the same session were not a good category for comparison as it was a non-repeated measure. Between the subjects, comparison was performed between comparable cycles.

The Hypothesis: Adaptation to exercise could significantly influence the cardiovascular response to exercise. An observational study done by Goldsmith et al [5] found a significant increase in the heart rate variability after eight weeks of a cyclic exercise program in untrained healthy women. A study done by Hagberg et al [25] found that the increases in oxygen uptake (VO_2), carbon dioxide production (VCO_2), minute ventilation (VE), and heart rate (HR) at the onset of constant load submaximal work, and the decreases in VO_2 , VCO_2 , VE, and HR in recovery were more rapid at both the same absolute and the same relative work rates after training. These results show that the adaptation to endurance exercise training enables an individual to adjust to the energy requirement of constant load submaximal work more rapidly, resulting in a smaller O₂ deficit. The rate of recovery was also more rapid after training, resulting in a smaller O₂ debt. Based on these findings, in this research it has been hypothesized that during the

course of cyclic exercise the body will become adapted to the exercise and there should be an increase in value of the exponent (and hence a decrease in values for the time constant) in the acceleration 1 region from earlier sessions to later sessions. Figure 4.1 shows the sketch of expected results for the acceleration and deceleration regions for a cycle in different exercise sessions.

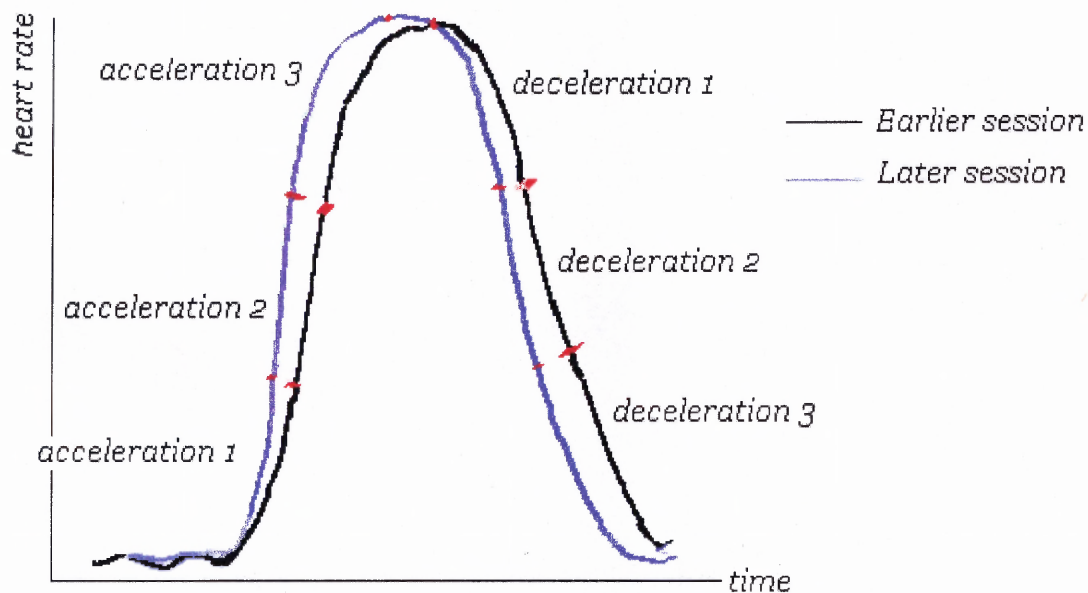


Figure 4.1 Sketch of expected results for a cycle.

After a jump start in the acceleration 1 region the body was expected to maintain that acceleration during the acceleration 2 region. The expected results for the acceleration 2 region were that there should be an increase in the slope value as the cycle session progresses. For the acceleration 3 region it was expected to have a decrease in the value of the time constant which will denote a faster increase in the heart rate in the successive sessions. For the deceleration 1 region it was expected to have a decrease in the time constant which will denote a faster recovery of the heart rate in the successive sessions. For the deceleration 2 region, the slope was expected to be decreasing for the

successive cycles and for the deceleration 3 region, it was expected to have a decrease in the time constant value which would show a faster recovery of the heart rate in the successive sessions.

4.2 Results – Within Subjects

This section shows the acceleration and deceleration results within-subjects.

4.2.1 Acceleration Results

Acceleration 1 Region:

Tables 4.1 and 4.2 show the comparison of the acceleration 1 parameters of 3 cycles. Table 4.1 shows the changes in the time constant and the mean square error (MSE) of the acceleration 1 region for subject S1 through different sessions. Parameters (time constant and mean square error) for the first 3 cycles are shown.

Table 4.1 Acceleration 1 parameters for subject S1

Session	Cycle 1		Cycle 2		Cycle 3	
	Time constant	MSE	Time constant	MSE	Time constant	MSE
04042001S1	250	0.43	100.00	14.84	111.11	2.25
04042201S1	90.91	0.16	166.67	0.63	100	6.40
04042801S1	52.63	9.94	83.33	2.36	83.33	2.57
04050201S1	90.91	0.49	83.33	2.77	90.91	3.08

The following figure shows the graph of the time constant of the acceleration 1 region for different sessions of subject S1 for cycle 1. A trend line is fitted on the graph and the slope is calculated and displayed.

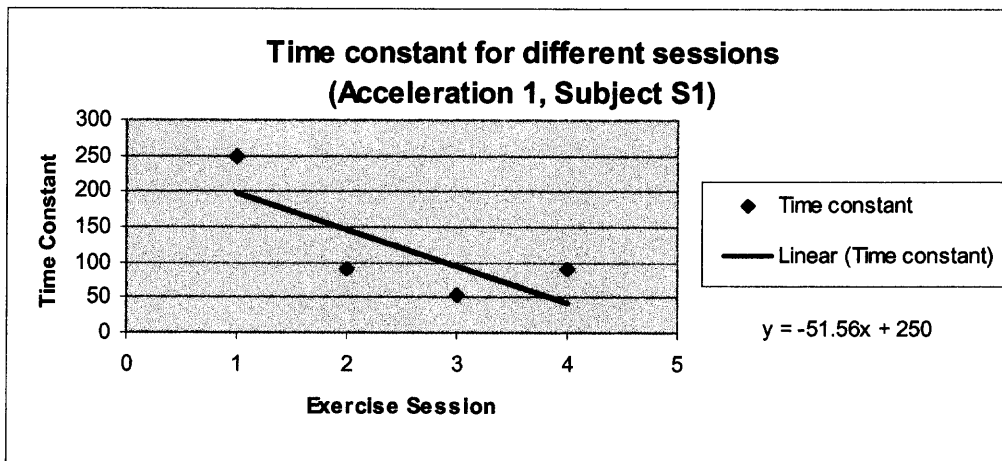


Fig 4.2 Graph showing a decrease in the time constant for subject S1.

There was a negative slope indicating a decrease in the time constant. A decrease in the time constant indicates a more rapid increase in the heart rate as the cycle session progresses. This was true only with subject S1. Table 4.2 shows the changes in time constant of the acceleration 1 region for subject S2 through different sessions. Parameters for first 3 cycles are shown.

Table 4.2 Acceleration 1 parameters for subject S2

Session	Cycle 1		Cycle 2		Cycle 3	
	Time constant	MSE	Time constant	MSE	Time constant	MSE
04042301S2	47.61	7.51	30.30	7.47	34.48	5.84
04042602S2	31.25	35.62	29.41	30.40	66.67	1.96
04051601S2	66.67	16.82	33.33	12.18	125	12.53
04051801S2	55.56	25.30	38.46	24.92	33.33	80.81

For subject S2 there was a positive slope (shown in Figure 4.3) indicating an increase in the time constant and hence a decrease in the heart rate with progress in the cycle session.

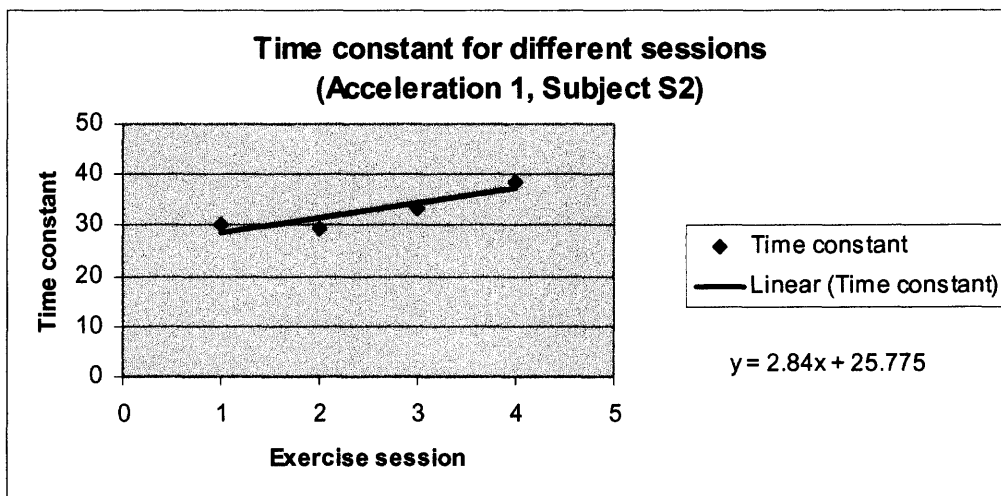


Fig 4.3 Graph showing an increase in the time constant for subject S2.

Mean square error is related to the fit of heart rate data between the curve and the original data points. During the cyclic exercise the heart rate was changing approximately from 60 to 170 beats per minute i.e. the variation was 110 bpm. A $\pm 3.5\%$ of error corresponds to a mean square value (MSE) of 14.8. A MSE of 14.8 or less could be considered as acceptable assuming a $\pm 3.5\%$ error in the variation of the heart rate value.

Discussion: The reason why the time constant is of great importance is because a decrease in magnitude of the time constant indicates the body's ability to become adapted to the exercise. Since this trend happened with only one subject it cannot be concluded that the hypothesis was true. However there were some possibilities by which an increase in the time constant for subject S2 might have happened. In certain cases (for example in session 04042602S2 for subject S2 the time constant was 31.25 and mean square error was 35.62 (shown in Table 4.2)) showing that the data was not properly fit by the curve. As a result the time constant did not exactly correspond to the data and the mean square error calculated was much higher than that of the acceptable value, i. e. 14.8. All such cases were closely investigated and it was found that those errors fall into three major

categories. The first category of error was due to missed data. During the cycles exercise program sometimes pieces of data were missing due to the loss of connectivity between the subject and the heart rate monitor. Figure 4.4 shows an example of a cycle session where data were missed at the beginning of the 3rd cycle.

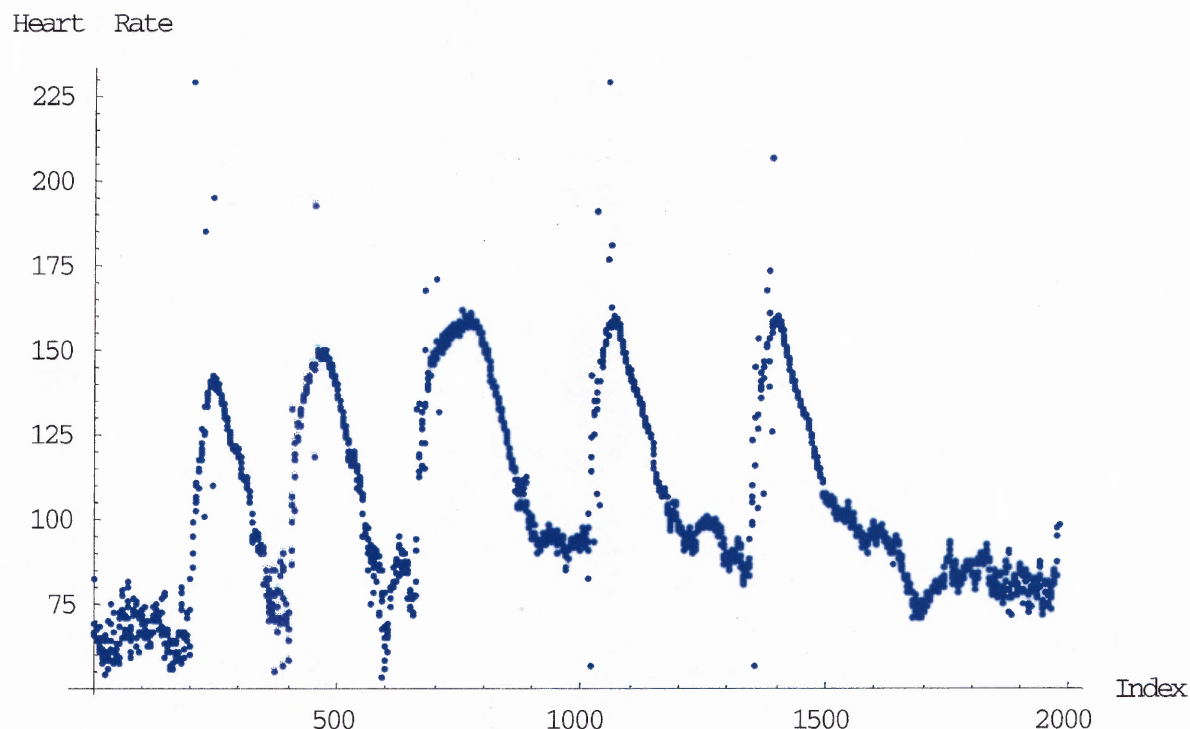


Figure 4.4 Graph of cycles with some missed data in the third cycle.

When the data were lost it led to a particular region (for example acceleration 1 as shown in the above figure) to pick up data points from the next region (acceleration 2), which actually was not a part of that particular region. The resultant curve, in this case acceleration 1, did not correspond to a true exponential curve and the curve fitting did not give the expected results yielding larger values for mean square error. Fig 4.5 shows the exponential curve fitting for acceleration 1 with some missed data (index numbers 19 through 24). The last four points picked up were actually not the part of acceleration 1.

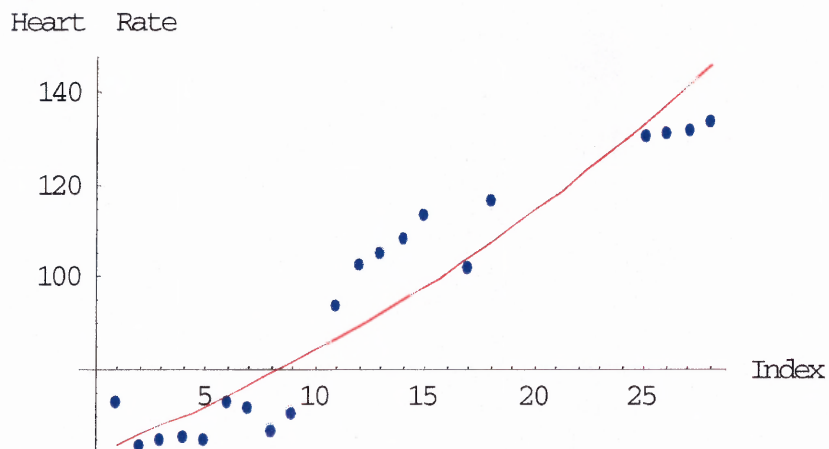


Figure 4.5 Exponential curve fitting in the acceleration 1 region with some missed data.

The second category of error was the extended valley calculation. The *Mathematica* program for valley calculation used the original data points and no smoothing techniques were employed. The valley was determined by back calculating 200 data points from the peak value, dividing them into segments of 15 data points and checking for the condition of heart rate stabilization. Since the valley determination procedure strictly followed the above mentioned algorithm, it sometimes led to the segment past the original valley (as determined by observation) and it yielded an incorrect valley point. Figure 4.6 shows an example of curve fitting for a region (acceleration 1) with the extended valley calculation. The resultant curve, in this case the acceleration 1, did not correspond to a true exponential curve and the curve fitting did not give the expected results yielding larger values for mean square error.

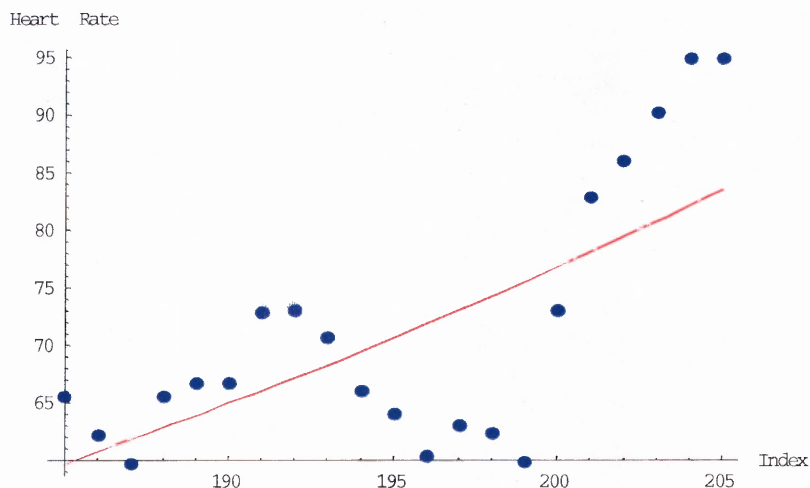


Figure 4.6 Curve fitting for acceleration 1 with extended valley calculation.

The third category of error was the sharp valley. According to the protocol the subjects were asked to rest after each cycle until the heart rate was stabilized (defined as changing at most \pm three beats over 15 seconds). In some cases the subjects did not rest long enough between the cycles and this led to sharp valley formation. Figure 4.7 shows a file with sharp valleys.

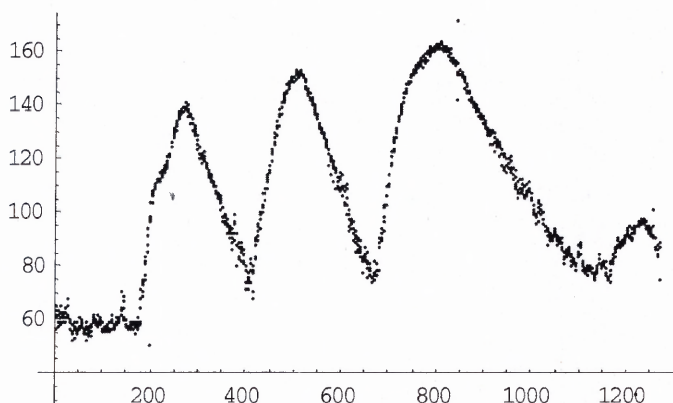


Figure 4.7 Graph of cycles showing sharp valleys.

These sharp valleys also led to incorrect valley calculations and the resultant curve did not correspond to a true exponential curve and the curve fitting did not give the expected results yielding larger values for mean square error. The errors from the first

category (missed data) affected any regions of acceleration or deceleration regions, but the errors from the second category (extended valley calculation) and the third category (sharp valley) mostly affected the first section of the acceleration regions (acceleration 1) and the third sections of the deceleration regions (deceleration 3).

From Table 4.2 it is found that the mean square error for the acceleration 1 region for the file 04042602S2 was 35.62 and for the file 04051801S2 was 25.30. Both these values occurred because of the errors from the second category (extended valley calculation). Mean square error was in the acceptable range (less than 14.8) for the acceleration 1 region only in 75% of the time. Compared to the acceleration 2 and acceleration 3 regions it was very less (acceleration 2 region 95.8% and acceleration 3 region 100%). This indicates that the different category errors mostly affected the acceleration 1 region.

Acceleration 2 region:

Table 4.3 shows the changes in the slope of the acceleration 2 region for subject S1 through different sessions. Parameters for the first 3 cycles (time constant and mean square error) are shown.

Table 4.3 Acceleration 2 parameters for subject S1

Session	Cycle 1		Cycle 2		Cycle 3	
	Slope	MSE	Slope	MSE	Slope	MSE
04042001S1	0.363	0.36	0.366	0.47	0.594	0.66
04042201S1	0.662	0.65	0.716	0.21	0.724	0.81
04042801S1	0.401	0.29	0.862	0.38	0.433	0.63
04050201S1	0.633	0.26	0.802	0.42	0.892	1.74

The following figure shows the graph of the slope of the acceleration 2 region for different sessions of subject S1 for cycle 1. A trend line is fitted on the graph and the slope is calculated and displayed.

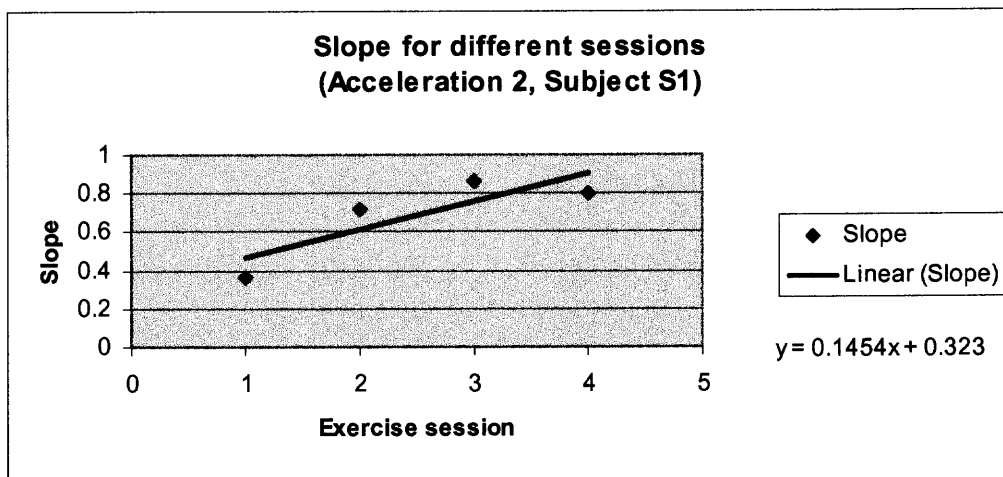


Figure 4.8 Graph showing an increase in the slope for subject S1.

In the acceleration 2 region, for subject S1, in all the three cycles there was a positive slope (for the trend line fit to the slope values) indicating a faster increase in heart rate in successive sessions. This was true only for subject S1. For subject S2 there was a decrease in the slope value in successive cycles (Figure 4.9). Table 4.4 shows the changes in slope of the acceleration 2 region for subject S2 through different sessions.

Table 4.4 Acceleration 2 parameters for subject S2

Session	Cycle 1		Cycle 2		Cycle 3	
	Slope	MSE	Slope	MSE	Slope	MSE
04042301S2	1.434	2.52	0.853	0.51	1.182	1.65
04042602S2	4.004	140.13	1.247	0.39	1.420	1.04
04051601S2	1.431	2.59	0.987	0.45	0.182	1.70
04051801S2	0.908	2.22	0.767	1.10	0.802	1.99

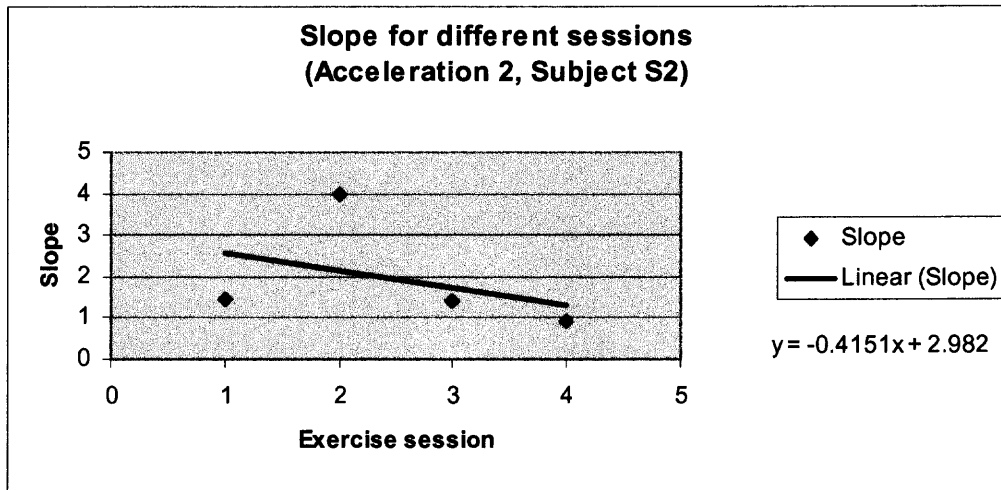


Figure 4.9 Graph showing a decrease in slope for subject S2.

Discussion: A positive slope indicates the body's ability to become adapted to the exercise faster. For subject S1 there was an increase in the slope value for the acceleration 2 region. However for subject S2 the trend line fit to the slope value shows that there was a decrease in the slope value in successive cycles. So it cannot be concluded that the heart rate was increasing faster with successive sessions in the acceleration 2 region. However there were some cases for subject S2 where the data was not exactly fitted by the straight line. The mean square error for the acceleration 2 region for the file 04042602S2 was 140.137. This was due to the first category error (missing data). For the acceleration 2 region 95.8% of the time the value of mean square error were less than 14.8, the acceptable range, showing that the straight line fitted the data properly.

Acceleration 3 region :

This is the third acceleration region and it was fit with an exponential curve. Table 4.5 shows the changes in the time constant of the acceleration 3 region for subject S1 through

different sessions. Parameters for the first 3 cycles (time constant and mean square error) are shown.

Table 4.5 Acceleration 3 parameters for subject S1

	Cycle 1		Cycle 2		Cycle 3	
	Time Constant	MSE	Time Constant	MSE	Time Constant	MSE
04042001S1	8.69	0.95	11.76	0.82	13.89	3.06
04042201S1	16.67	0.74	7.752	3.67	9.17	2.34
04042801S1	13.88	8.68	12.19	2.56	25.64	2.50
04050201S1	12.98	2.18	12.98	3.12	17.54	0.84

The following figure shows the graph of the time constant of the acceleration 3 region for different sessions of subject S1 for cycle 2. A trend line is fitted on the graph and the slope is calculated and displayed.

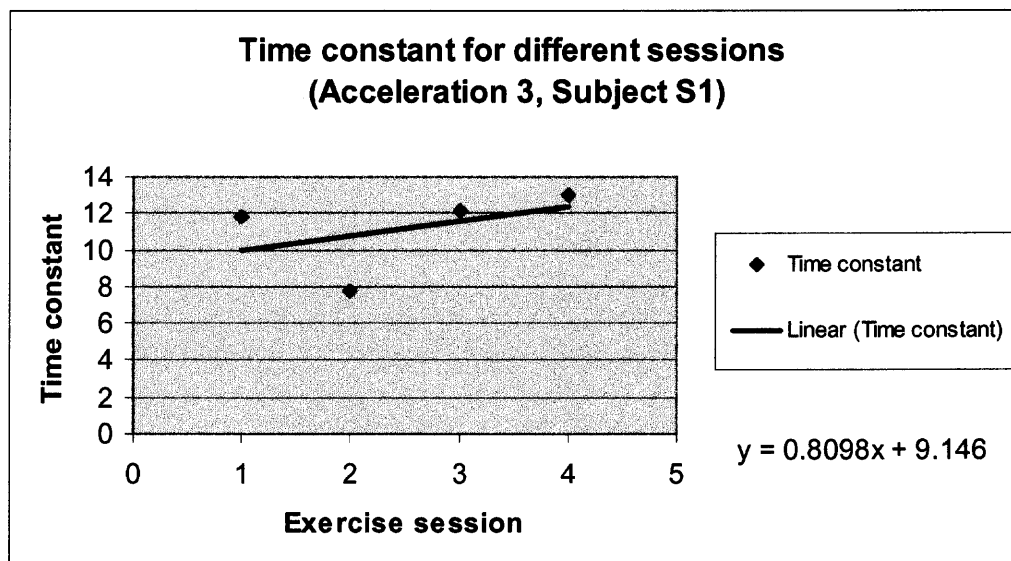


Figure 4.10 Graph showing an increase in the time constant for subject S1.

In the acceleration 3 region it was expected to have a decrease in the value of the time constant which would denote a faster increase in the heart rate in successive sessions. Unlike the expected results, for subjects S1 and S2, all the three cycles show a

positive slope (figure 4.10) indicating a slower increase in the heart rate in successive sessions. So with these results, it cannot be concluded that the heart rate was increasing faster in successive exercise sessions. For subject S2, the values of the time constants were not consistent (Table 4.6). For the acceleration 3 region, for 100% of the data the magnitude of mean square error was less than 14.8, the acceptable range, showing that the exponential curve fitted the data properly.

Table 4.6 Acceleration 3 parameters for subject S2

Session	Cycle 1		Cycle 2		Cycle 3	
	Time Constant	MSE	Time Constant	MSE	Time Constant	MSE
04042301S2	5.23	0.63	8.54	0.48	9.70	1.17
04042602S2	3.11	2.23	3.40	1.00	10.31	1.45
04051601S2	71.32	6.15	125	4.90	32.2	0.53
04051801S2	3.98	0.98	8.00	0.91	71.42	14.00

Discussion (Acceleration Regions): For the acceleration 1 and 2 regions the two subjects have shown different trends (for time constants and slopes) and for the acceleration 3 region, both subjects have shown a similar trend. The fact that the heart rate goal for a specific cycle in different sessions was slightly different might have had an effect on this result. Also the subject's history of physical training prior to the cycles exercise program might have influenced the results. Since the subjects have shown different trends in the acceleration 1 and 2 regions and an opposing trend to the expected results in the acceleration 3 region it cannot be concluded that the hypothesis is true.

The mean square errors were less than 14.8, 75% of the time for the acceleration 1 region, 95.8% of the time for the acceleration 2 region and 100% for the acceleration 3

region showing that the three different category errors affected the first region of acceleration to the most.

4.2.2 Deceleration Results

Deceleration 1 Region:

The deceleration 1 region was fit with an exponential. Table 4.7 shows the changes in time constant of the deceleration 1 region for subject S1 through different sessions. Parameters for the first 3 cycles (time constant and mean square error) are shown.

Table 4.7 Deceleration 1 parameters for subject S1

	Cycle 1		Cycle 2		Cycle 3	
	Time Constant	MSE	Time Constant	MSE	Time Constant	MSE
04042001S1	8.06	8.16	6.02	6.44	11.6	7.43
04042201S1	12.98	2.89	12.05	11.6	12.5	3.09
04042801S1	13.69	1.89	11.49	8.11	12.7	5.35
04050201S1	14.29	9.81	13.16	4.15	111.11	951

The following figure shows the graph of the time constant of the deceleration 1 region for different sessions of subject S1 for cycle 2. A trend line is fitted on the graph and slope is calculated and displayed.

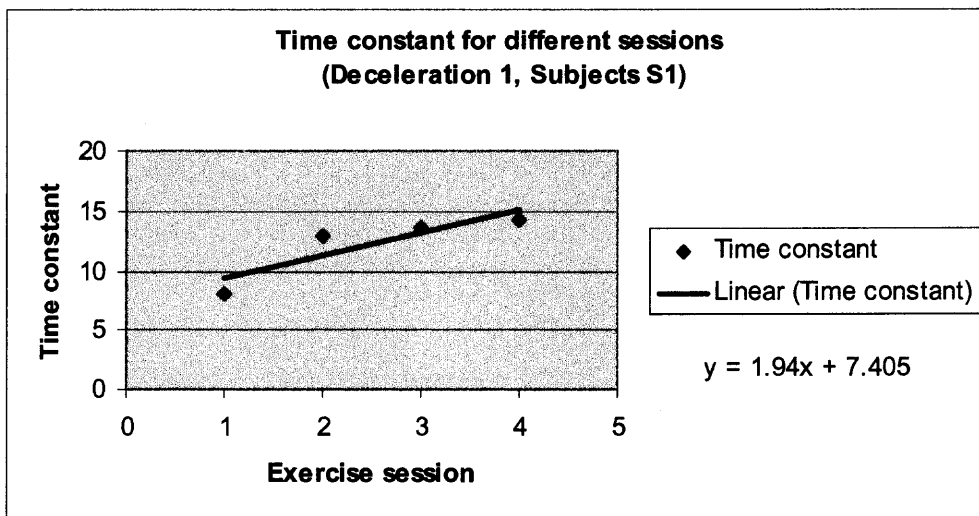


Figure 4.11 Graph showing an increase in the time constant for subject S1.

In the deceleration 1 region it was expected to have a decrease in the time constant which will denote a faster recovery of the heart rate in the successive sessions. Unlike the expected results in the deceleration 1 region all three cycles for subjects S1 and S2 show a positive slope (of the trend line fit) showing an increase in time constant indicating a slower recovery of the heart rate in successive sessions. For file 04050201S1, in the third cycle, the value of time constant was 111.11 and the mean square error was 951 indicating an incorrect fit to the data. For the deceleration 1 region, the mean square error was within the acceptable limits (i.e. a value less than 14.8) 91.6% of the time for subject S1 and 83.3% of the time for subject S2 indicating a proper fit of the exponential curve to the data. For subject S2, there were some exceptional values for the time constant. For example for file 04051601S2 the time constant was 250 for cycle 1 (mean value 70.11) and the mean square value was 32.67 indicating an incorrect fit to the data. This was caused by some missing data. For the same file the time constant for cycle 2 and cycle 3 were 1000 and 1613 showing an incorrect fit to the data. The mean square error also was high (331.36) for this file for the third cycle.

Table 4.8 Deceleration 1 parameters for subject S2

Session	Cycle 1		Cycle 2		Cycle 3	
	Time Constant	MSE	Time Constant	MSE	Time Constant	MSE
04042301S2	13.15	15.14	13.15	2.20	17.86	4.75
04042602S2	7.58	58.75	9.43	11.86	50.0	8.01
04051601S2	250	32.67	1000	25.50	1613	0.88
04051801S2	9.71	6.74	13.69	1.44	149.25	331.26

Discussion: A decrease in the values of time constants indicates a faster recovery of the heart rate in successive sessions. However, subjects S1 and S2 have shown positive slope for the trend line fit to the time constant data indicating a slower recovery of heart rate for successive sessions. Hence it cannot be concluded that the hypothesis was true. For subject S2 there were some exceptional values for the time constant, which was caused by the different category errors.

Deceleration 2 Region:

The deceleration 2 region was fit with a straight line. Table 4.9 shows the changes in slope of the deceleration 2 region for subject S1 through different sessions. Parameters for the first 3 cycles (slope and mean square error) are shown.

Table 4.9 Deceleration 2 parameters for subject S1

	Cycle 1		Cycle 2		Cycle 3	
	Slope	MSE	Slope	MSE	Slope	MSE
04042001S1	-0.222	1.98	-0.355	2.71	-0.001	4.06
04042201S1	-0.157	0.17	-0.514	2.39	-0.006	3.81
04042801S1	-0.414	1.88	-0.557	2.31	-0.002	7.20
04050201S1	-0.401	0.97	-0.516	2.29	-0.004	9.35

The following figure shows the graph of the slope of the deceleration 2 region for different sessions of subject S1 for cycle 2. A trend line is fit on the graph and the slope is calculated and displayed.

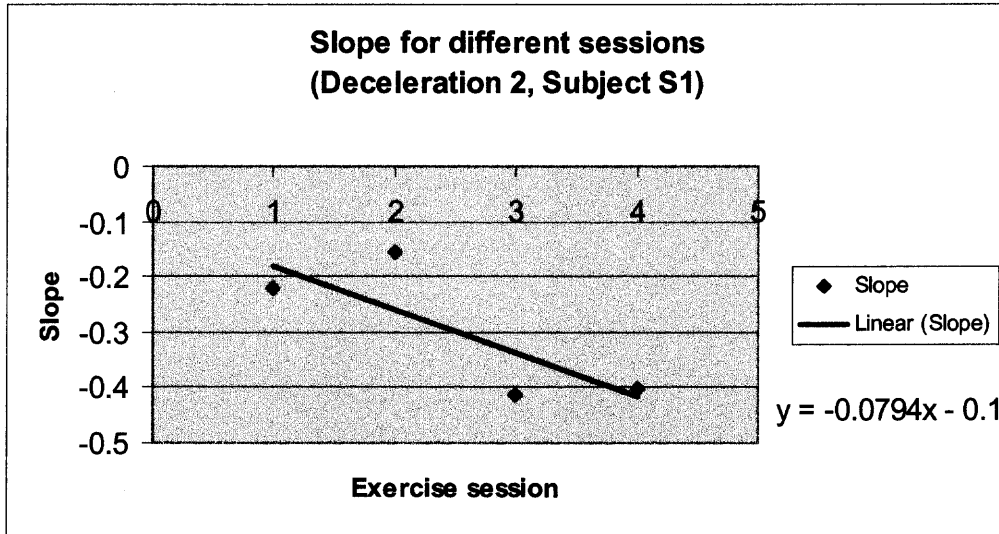


Figure 4.12 Graph showing a decrease in the slope for subject S1.

The negative slope indicates a faster recovery of the heart rate in successive sessions. This was true with subject S1 for all the three cycles. For subject S2 there was an increase in slope (for the trend line fit to the slope for different exercise sessions) indicating a slower recovery of heart rate for successive sessions (Figure 4.13). The mean square error was within the acceptable limit for 100% of the time in the deceleration 2 region.

Table 4.10 Deceleration 2 parameters for subject S2

Session	Cycle 1		Cycle 2		Cycle 3	
	Slope	MSE	Slope	MSE	Slope	MSE
04042301S2	-0.391	3.38	-0.673	3.02	-0.006	7.21
04042602S2	-0.425	0.83	-0.655	3.66	-0.003	9.89
04051601S2	-0.326	1.75	-0.717	0.78	-0.003	10.02
04051801S2	-0.627	2.39	-0.445	0.68	-0.002	8.86

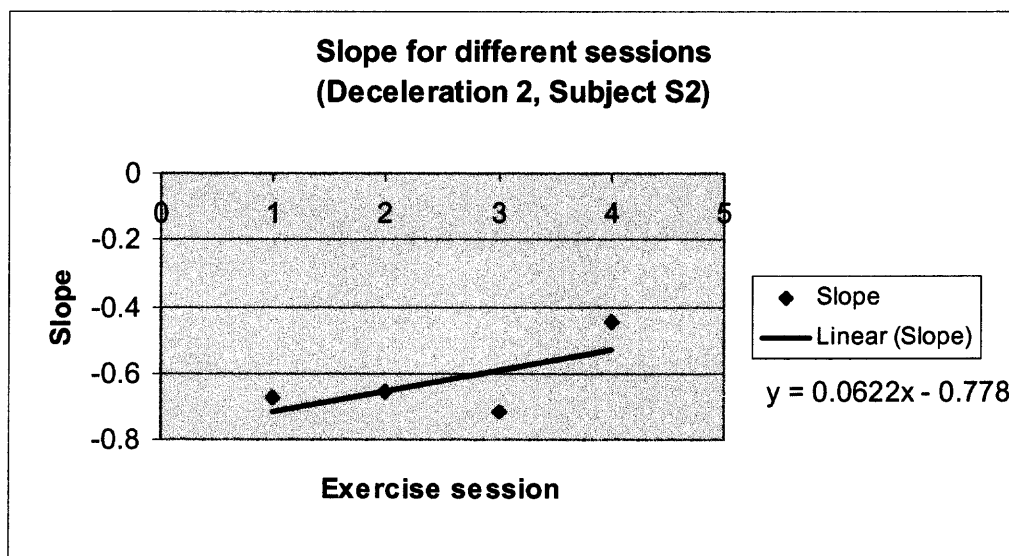


Figure 4.13 Graph showing an increase in the slope for subject S2.

Discussion: The expected result for the deceleration 2 region was that the slope should decrease for successive cycles. Subject S1 has shown a decrease in the slope indicating a faster recovery of heart rate for successive exercise sessions and subject S2 has shown an increase in slope indicating a slower recovery of heart rate for successive exercise sessions. Since the subjects have shown different trends, it cannot be concluded that the hypothesis was true.

The mean square error was within the acceptable limits 100% of the time for the deceleration 2 region indicating a proper fit of a straight line to the data.

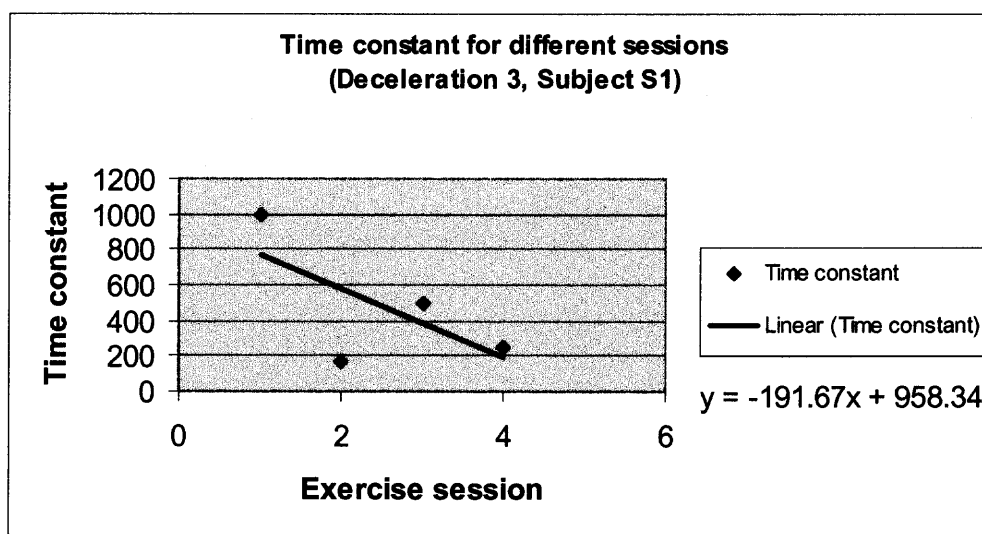
Deceleration 3 Region:

The deceleration 3 region was fit with an exponential curve. Table 4.11 shows the changes in time constant of the deceleration 3 region for subject S1 through different sessions. Parameters for the first 3 cycles (time constant and mean square error) are shown.

Table 4.11 Deceleration 3 parameters for subject S1

	Cycle 1		Cycle 2		Cycle 3	
	Time Constant	MSE	Time Constant	MSE	Time Constant	MSE
04042001S1	200	1.89	166.67	1.29	1000	4.06
04042201S1	200	1.13	250	18.40	166.67	3.81
04042801S1	200	1.98	250	11.30	500	7.20
04050201S1	333	6.45	166.67	2.82	250	9.35

The following figure shows the graph of the time constant of the deceleration 3 region for different sessions of subject S1 for cycle 3. A trend line was fit on the graph and the slope was calculated and displayed.

**Figure 4.14** Graph showing a decrease in the time constant for subject S1.

The expected result for the deceleration 3 region was that the time constant should decrease for successive cycle sessions indicating a faster recovery. This was true with subject S2 for only one cycle. For the rest of the cycles for subject S2 and for subject S1 there was an increase in the slope (for the trend line fit to the time constant data) indicating a slower recovery in successive cycle sessions (Figure 4.15). Hence it cannot

be concluded that the hypothesis was true. The mean square error was within the acceptable limits 83.3% of the time for the deceleration 3 region indicating a proper fit of straight line to the data. For subject S2, the mean square error for second cycle for the file 04042301S2 was 76.25. This was caused by some missing data.

Table 4.12 Deceleration 3 parameters for subject S2

Session	Cycle 1		Cycle 2		Cycle 3	
	Time Constant	MSE	Time Constant	MSE	Time Constant	MSE
04042301S2	142.86	11.65	111.11	76.25	166.67	7.21
04042602S2	142.86	6.84	200	1.79	333.33	9.89
04051601S2	142.86	6.85	125	7.71	333.33	10.02
04051801S2	588.23	1.70	142.86	1.61	500	8.86

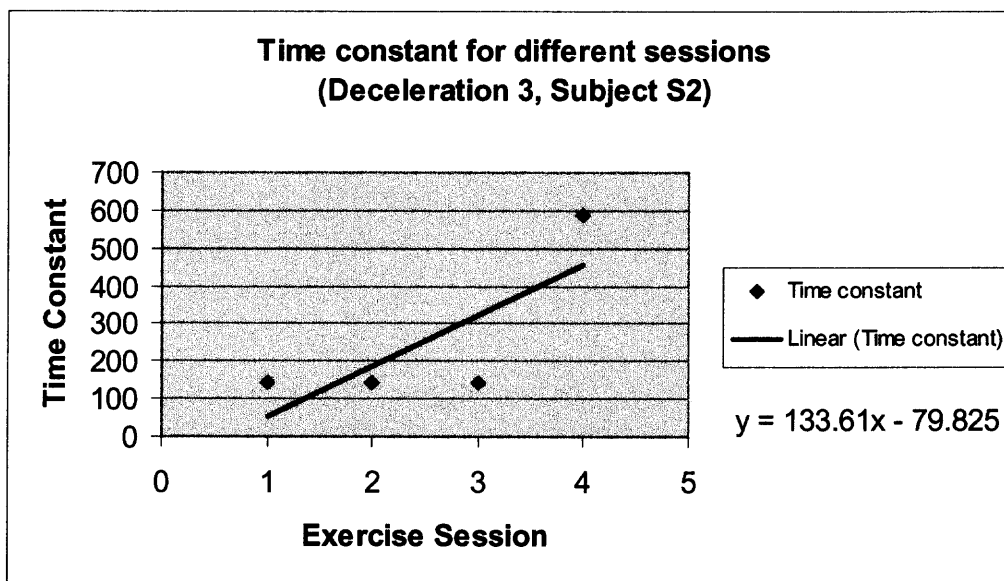


Figure 4.15 Graph showing an increase in time constant for subject S2.

Discussion (Deceleration Regions): For the deceleration 1 region subjects have shown an opposing trend to the expected results. For the deceleration 2 and 3 regions the

subjects showed different trends for the values of time constants and slopes. Hence it cannot be concluded that the hypothesis is true. The different category errors affected the deceleration regions. The mean square errors were less than 14.8, 87.5% of the time for the deceleration 1 region, 100% of the time for the deceleration 2 region, and 91.67% of the time for the deceleration 3 region indicating that the three different category errors affected the deceleration 1 region the most.

4.3 Results - Between Subjects

The time constant and slopes have been compared between the subjects for comparable files (04042201S1 and 04042301S2; 04042801S1 and 04042602) based on the date of exercise session.

4.3.1 Acceleration Results

Table 4.13 shows the changes in parameters (time constants and slopes) of both subjects for the acceleration 1, 2, and 3 regions for files 04042201S1 and 04042301S2 and Table 4.14 shows the same comparison for the files 04042801S1 and 04042602.

Table 4.13 Comparison of acceleration parameters between the subjects

File Name	Acceleration 1 (Time Constant)			Acceleration 2 (Slope)			Acceleration 3 (Time Constant)		
	Cycle 1	Cycle 2	Cycle 3	Cycle 1	Cycle 2	Cycle 3	Cycle 1	Cycle 2	Cycle 3
04042201S1	90.91	166.67	100	0.662	0.716	0.724	16.67	7.75	9.17
04042301S2	47.61	30.3	34.48	1.43	0.853	1.18	5.23	8.54	9.7

For the acceleration 1 region, subject S2 has shown a lower value for the time constant than subject S1 indicating a faster increase in the heart rate during exercise for

subject S2 than subject S1. For the acceleration 2 region, subject S2 has shown a higher value for the slope than subject S1 indicating a faster increase in heart rate during exercise. For the acceleration 3 region, subject S2 shows a higher value for the time constant than subject S1 indicating a slower increase in the heart rate during exercise for subject S2 compared to subject S1. The result shows the difference in individual body response to the exercise. However the trend for different regions of acceleration was not consistent for subject S2 compared to subject S1.

Table 4.14 Comparison of acceleration parameters between the subjects

File Name	Acceleration 1 (Time Constant)			Acceleration 2 (Slope)			Acceleration 3 (Time Constant)		
	Cycle 1	Cycle 2	Cycle 3	Cycle 1	Cycle 2	Cycle 3	Cycle 1	Cycle 2	Cycle 3
04042801S1	52.63	83.33	83.33	0.401	0.862	0.433	13.88	12.19	25.64
04042602S2	31.25	29.41	66.67	4	1.247	1.42	3.11	3.4	10.31

Table 4.14 shows that for the acceleration 1 region, subject S2 has a lower value for the time constant than subject S1 indicating a faster increase in heart rate during exercise for subject S2. For the acceleration 2 region, subject S2 has shown a higher value for the slope than subject S1 indicating a faster increase in heart rate during exercise for subject S2. For the acceleration 3 region, subject S2 shows an lower value for the time constant than subject S1 indicating a faster increase in the heart rate during exercise. The results show the difference in individual body response to the exercise.

4.3.2 Deceleration Results

Tables 4.15 and 4.16 shows the comparison of deceleration parameters between subjects S1 and S2.

Table 4.15 Comparison of deceleration parameters between the subjects

File Name	Deceleration 1 (Time Constant)			Deceleration 2 (Slope)			Deceleration 3 (Time Constant)		
	Cycle 1	Cycle 2	Cycle 3	Cycle 1	Cycle 2	Cycle 3	Cycle 1	Cycle 2	Cycle 3
04042201S1	12.98	12.05	12.5	-0.157	-0.154	-0.006	200	250	166.67
04042301S2	13.15	13.15	17.86	-0.391	-0.673	-0.006	142.86	111.11	166.67

Table 4.16 Comparison of deceleration parameters between the subjects

File Name	Deceleration 1 (Time Constant)			Deceleration 2 (Slope)			Deceleration 3 (Time Constant)		
	Cycle 1	Cycle 2	Cycle 3	Cycle 1	Cycle 2	Cycle 3	Cycle 1	Cycle 2	Cycle 3
04042801S1	13.69	11.49	12.7	-0.414	-0.557	-0.002	200	250	500
04042602S2	7.58	9.43	50	-0.425	-0.655	-0.003	142.86	200	333.33

For the deceleration 1 region, subject S1 has lower values for the time constant than subject S2 indicating a faster recovery of the heart rate after exercise for subject S1. For the deceleration 2 region, subject S2 has shown a lower value for the slope than subject S1 indicating a faster recovery in the heart rate after exercise for subject S2. For the deceleration 3 region also, subject S2 shows a lower value for the time constant than subject S1 indicating a faster recovery in the heart rate after exercise. The results show the difference in individual body response to the exercise.

Discussion: Adaptation to exercise acquired by physical training can significantly influence the cardiovascular response to exercise [25]. A subject's history of physical training might have affected the results. Also the results show the difference in individual body response to the exercise. The results indicate that 83.33% of the time subject S2 has shown a faster increase in heart rate during exercise and faster recovery after exercise

than subject S1. Hence the parameters of the fit (time constant and slope) could be used as a marker for health.

CHAPTER 5

CONCLUSION, LIMITATIONS AND FUTURE PROGRESS

5.1 Conclusion

An algorithm for the analysis of acceleration and deceleration region of cycles has been developed. The cyclic exercise program yielded a series of cyclic waves of cardiovascular exercise and recovery. The acceleration and the deceleration regions of these waves have been identified. Since different sections of the acceleration and deceleration regions were following different curves, these regions were then divided into three sections and each section was fit with appropriate curves. The *Mathematica* program, then extracted the parameters (exponents, slopes and mean square errors) for the different curves. The values for the mean square errors indicated that the curves are being fitted properly. Subjects have shown different trends in the time constant and slope values for the acceleration and deceleration regions. The expected results for the acceleration 1 and 3 regions and the deceleration 1 and 3 regions were that there should be a decrease in the time constant indicating a faster increase in heart rate during exercise (acceleration) and faster recovery after exercise (deceleration) in successive sessions. The expected results for the acceleration 2 region was that there should be an increase in the slope indicating a faster increase in heart rate and for the deceleration 2 region was that there should be a decrease in slope indicating a faster recovery after exercise in successive sessions. Since the subjects have shown different trends for the time constant and slope values for the acceleration and deceleration regions it cannot be concluded that the hypothesis was true.

5.2 Limitations

There are a number of limitations in the study. Since the data came from an on going pilot study, sometimes the protocol was not followed exactly and hence there were problems encountered during data analysis especially because it led to the incorrect valley calculations. One subject did not rest long enough before the start of cyclic exercise. Hence the calculation of the acceleration valley point was not possible and all the data had to be dropped. Also the subjects in some of the sessions did not wait long enough for the heart rate to stabilize between the cycles, which also affected the calculation of acceleration and deceleration valley points. Also, if the connectivity between the subject and the Polar heart rate monitor was lost, the data was not recorded and hence pieces of data were missing. The instrument sometimes produced sudden burst of heart rate values, which led to larger values of mean square error. The number of subjects also was an issue. With two subjects a statistical analysis was not possible.

Adaptation to exercise acquired by physical training can significantly influence the cardiovascular response to exercise [25]. This study did not take consideration of subject's history of physical training and this fact might have affected the results. The variation of the time constants and slopes between the subjects show that there was an individual difference in the level of adaptation to the exercise.

Also, the heart rate parameters are to a large extent influenced by breathing pattern. The cyclic exercise program designed for this study did not attempt to control the breathing pattern.

If the above-explained limitations are overcome, the algorithm can be used for the quantitative analysis of health of an individual, as the parameters of the fit could be used as a marker for the health.

5.3 Future Progress

The next step of this study is to implement the cyclic exercise program for a group of people having disease (specifically diseases related to the heart) and a group of healthy individuals and see if there is any significant difference in parameters of the fit for the two groups. The algorithm could be modified in order to avoid some of the errors it produced in the valley calculation. The extended valley calculation could be avoided by adding more criteria to the valley selection. Methods should be implemented in the algorithm to identify the data loss. Also a modification in the algorithm can be made to exactly follow the protocol for heart rate stabilization, which could lead to a more accurate valley calculation. The criteria for heart rate stabilization was that the heart rate should be varying less than \pm three beats over 15 seconds. Currently the program is checking 15 data points.

APPENDIX

MATHEMATICA PROGRAM

Introduction

This section discusses the *Mathematica* program used for cycles data analysis. The program calculates the peak value, acceleration valley, and deceleration valley for the heart rate data. The program then identifies the acceleration and deceleration regions and divides them into three sections. Different sections were then fit with appropriate curves and the parameters of curves were extracted.

The Mathematica program follows.

```

(***** This mathematica program for cycles analysis was originally
written by Dr. Stanley Reisman and was modified by Jeena Vadi*****)
data = Import["04051601S1.hrm", "Text"];
cycleb = data;
c = StringDrop[cycleb, (Part[Part[StringPosition[cycleb, "[HRData]", 1], 2] + 1)];
b = StringToStream[c]; a = ReadList[b, Number];
Close[b]; cycle = {}; cyclea = {};
Do[If[a[[i]] == 9999, 0, cycle = Append[cycle, a[[i]]], {i, 1, Length[cycleb]}];
a1 = N[60000 / a]; cycleb = a1;

(*remove points outside the range 29-231*)
Do[If[cycleb[[i]] > 28 ^ cycleb[[i]] < 232, cyclea = Append[cyclea, cycleb[[i]]],
{i, 1, Length[cycleb]}]; cycle = cyclea;

(*program the time counter*)
tj = Table[0, {Length[cycle]}];
N[tj[[1]] = 60 / cycle[[1]];
Do[tj[[n]] = tj[[n - 1]] + 60 / cycle[[n]], {n, 2, Length[cycle]}];
ti = N[tj];

(*Spike Detector*)
cycle[[1]] = N[1 / 8] * Sum[cycle[[i]], {i, 2, 9}];
cycle2d = Table[0, {i, Length[cycle]}, {j, 2}];
Do[cycle2d[[i, 1]] = i, {i, Length[cycle]}];
Do[cycle2d[[i, 2]] = cycle[[i]], {i, Length[cycle]}];
spst = {First[cycle2d]};
Do[If[(cycle[[i]] - cycle[[i - 1]]) > 60, spst = Append[spst, cycle2d[[i]]],
{i, 2, Length[cycle]}];
spst1 = Drop[spst, 1];
spend = Table[0, {Length[spst1]}];
fend[j_] := (Catch[Do[i;
If[cycle[[i]] != spst1[[j, 2]], Throw[i]], {i, spst1[[j, 1]], Length[cycle]}]]];
Do[spend[[j]] = fend[j], {j, 1, Length[spst1]}];
freplace[j_] := (For[i = spst1[[j, 1]], i < spend[[j]],
i++, cycle2d[[i, 2]] = cycle2d[[spst1[[j, 1]] - 1, 2]]];
Do[freplace[j], {j, 1, Length[spst1]}];
Do[cycle[[i]] = cycle2d[[i, 2]], {i, Length[cycle2d]}];
cycle3d = Table[0, {i, Length[cycle]}, {j, 3}];
Do[cycle3d[[i, 1]] = i, {i, Length[cycle]}];
Do[cycle3d[[i, 2]] = cycle[[i]], {i, Length[cycle]}];
Do[cycle3d[[i, 3]] = ti[[i]], {i, Length[cycle]}]; m = Floor[N[Length[cycle] / 5]];
origcycle = cycle;
(*Max Detector*)
(*take average of every five points*)
fifth = Table[0, {m}];
Do[fifth[[i]] = 0.2 * (cycle[[5 * i - 4]] + cycle[[5 * i - 3]] + cycle[[5 * i - 2]] +
cycle[[5 * i - 1]] + cycle[[5 * i]]), {i, 1, m}];
cycle = fifth;
smooth = Table[0, {Length[cycle]}];
l = Length[cycle] - 11;
(* smoothing for peak value determination. Take average of 21 points*)

```

```

Do[ smooth[[j]] = N[1/21] * Sum[cycle[[i]], {i, j - 10, j + 10}], {j, 11, 1}];
smooth1 = Take[smooth, {11, 1 - 10}];
ld = Table[0, {Length[smooth1]};
Do[ld[[i]] = smooth1[[i]] - smooth1[[i - 6]], {i, 6, Length[smooth1]};
ld1 = Drop[ld, 6];
mx = Max[ld1];
mn = Min[ld1];
test = Table[0, {i, Length[ld1]}, {j, 2}];
Do[test[[i, 1]] = i, {i, Length[ld1]};
Do[test[[i, 2]] = ld1[[i]], {i, Length[ld1]};
pd = First[test];
Do[If[test[[i, 2]] > 0.4 * mx, pd = Append[pd, test[[i]]], {i, 1, Length[test]}];
If[Length[pd] < 3, Goto[skip1]];
pd1 = Drop[pd, 2];
nd = First[test];
Do[If[test[[i, 2]] < 0.4 * mn, nd = Append[nd, test[[i]]], {i, 1, Length[test]}];
If[Length[nd] < 3, Goto[skip1]];
nd1 = Drop[nd, 2];
p1 = Table[0, {Length[pd1]};
Do[p1[[i]] = pd1[[i, 1]], {i, 1, Length[pd1]};
n1 = Table[0, {Length[nd1]};
Do[n1[[i]] = nd1[[i, 1]], {i, 1, Length[nd1]};
p = {First[p1]};
Do[If[(p1[[i + 1]] - p1[[i]]) > 20, p = Append[p, p1[[i]]], {i, 1, Length[p1] - 1}];
If[p1[[Length[p1]]] - p1[[Length[p1] - 1]] > 20, p = Append[p, p1[[Length[p1]]]];
p = Append[p, p1[[Length[p1]]];
n = {First[n1]};
Do[If[(n1[[i + 1]] - n1[[i]]) > 20, n = Append[n, n1[[i]]], {i, 1, Length[n1] - 1}];
If[n1[[Length[n1]]] - n1[[Length[n1] - 1]] > 20, n = Append[n, n1[[Length[n1]]]];
n = Append[n, n1[[Length[n1]]];
p = Drop[p, 1];
n = Drop[n, 1];
(* P and n contains the index values of max's and min's*)
pp = Join[p, {9999}];
n2 = {0};
p2 = {0};
Do[If[(pp[[j]] < n[[i]]) ^ (pp[[j + 1]] > n[[i]]) ^ (n[[i]] - pp[[j]] < 100),
  p2 = Append[p2, pp[[j]]], {i, 1, Length[n]}, {j, 1, Length[pp] - 1}];
p = Drop[p2, 1];
Do[If[(pp[[j]] < n[[i]]) ^ (pp[[j + 1]] > n[[i]]) ^ (n[[i]] - pp[[j]] < 100),
  n2 = Append[n2, n[[i]]], {i, 1, Length[n]}, {j, 1, Length[pp] - 1}];
n = Drop[n2, 1];
mxx = Table[0, {Length[p]};
cycle1 = Table[0, {i, Length[cycle]}, {j, 2}];
Do[cycle1[[i, 1]] = i, {i, Length[cycle]};
Do[cycle1[[i, 2]] = cycle[[i]], {i, Length[cycle]};
fmx[j_] := (test1 = Take[cycle1, {p[[j]], n[[j]]}; test12 = Table[0, {Length[test1]};
  Do[test12[[i]] = test1[[i, 2]], {i, 1, Length[test1]}; mx1 = Max[test12];
  mx2 = Catch[Do[i, If[mx1 == test12[[i]], Throw[i]], {i, 1, Length[test12]}];
  mxk[[j]] = test1[[mx2]]);
Do[fmx[j], {j, 1, Length[p]};
mx = Table[0, {Length[mxx]};

```

```

Do[mx[[i]] = mxx[[i, 2]], {i, 1, Length[mx]}];
mx1 = Max[mx];
mx2 = {First[mxx]};
Do[If[mxx[[i, 2]] > 0.7 * mx1, mx2 = Append[mx2, mxx[[i]]], {i, 2, Length[mxx]}];
mx3 = {First[mx2]};
Do[If[(mx2[[i + 1, 1]] - mx2[[i, 1]]) > 500, Break[], mx3 = Append[mx3, mx2[[i + 1]]],
  {i, 1, Length[mx2] - 1}];
(* mx3 give the value and index of peaks of 5 point average*)
m = Table[0, {Length[mx3]}];
Do[m[[i]] = mx3[[i, 2]], {i, Length[mx3]}];
maxcycle = Max[m];
peakval = mx3[[All, 2]];
(*peakval has peak values from 5 pt average data*)
peakindex = mx3[[All, 1]];
origpeakindex = peakindex * 5;
val7 = Table[0, {i, Length[origpeakindex]}, {j, 2}];
Do[val7[[i, 1]] = Range[origpeakindex[[i]] - 3, origpeakindex[[i]] + 3],
  {i, 1, Length[origpeakindex]}];
origcycle1 = Table[0, {i, Length[origcycle]}, {j, 2}];
Do[origcycle1[[i, 1]] = i, {i, Length[origcycle]}];
Do[origcycle1[[i, 2]] = origcycle[[i]], {i, Length[origcycle]}];
ListPlot[origcycle1, PlotStyle -> {Hue[0.6]}, AxesLabel -> {"Index", "Heart Rate"}]
Do[val7[[i, 2]] = Take[origcycle1[[All, 2]],
  {origpeakindex[[i]] - 3, origpeakindex[[i]] + 3}], {i, 1, Length[origpeakindex]}];
(* val7 gives the 3 values left and right of 5 point average peak*)
(* peakvalu gives the peaks of all cycles *)
peakvalu = Table[0, {i, Length[val7]}, {j, 2}];
Do[peakvalu[[i, 1]] = Max[val7[[i, 2]]], {i, 1, Length[val7]}];
aaa1 = Table[0, {Length[val7]}];
aaa2 = Table[0, {Length[val7]}];
Do[aaa2[[i]] = Position[val7[[i, 2]], peakvalu[[i, 1]], {i, 1, Length[val7]}];
Do[aaa1[[i]] = First[aaa2[[i]]], {i, 1, Length[val7]}];
aaa2 = Flatten[aaa1];
Do[peakvalu[[i, 2]] = aaa2[[i]], {i, 1, Length[val7]}];
aaa3 = Table[0, {Length[val7]}];
aaa3 = val7[[All, 1]];
aaa4 = Table[0, {Length[val7]}];
Do[aaa4[[i]] = Take[aaa3[[i]], {aaa2[[i]], aaa2[[i]]}], {i, 1, Length[val7]}];
aaa3 = Flatten[aaa4];
Do[peakvalu[[i, 2]] = aaa3[[i]], {i, 1, Length[val7]}];

(*Valley point calculation. From peakvalu go back 200 data points. Make
  them sets of 15 points. Check the middle, max and min values and if
  beat to beat difference (middle-max and middle-min) is less than 3,
  pick it as valley. Also the value of valley should be less than 100*)
throwvalue1 = Table[0, {Length[peakvalu]}];
fvalcalc[j_] :=
  (val1 = Take[origcycle1, {peakvalu[[j, 2]], peakvalu[[j, 2]] - 200, -1}];
  val2 = Table[0, {Length[val1]}];
  Do[val2[[i]] = val1[[i, 2]], {i, 1, Length[val1]}];
  val15 = Partition[val2, 15, 1];
  meanval = Table[0, {Length[val15]}];

```

```

Do[meanval[[i]] = val15[[i, 8]], {i, 1, Length[val15]};
maxval = Table[0, {Length[val15]};
Do[maxval[[i]] = val15[[i, 1]], {i, 1, Length[val15]};
minval = Table[0, {Length[val15]};
Do[minval[[i]] = val15[[i, 15]], {i, 1, Length[val15]};
valdiff1 = Table[0, {Length[val15]};
Do[valdiff1[[i]] = Abs[(meanval[[i]] - maxval[[i]])], {i, 1, Length[val15]};
valdiff2 = Table[0, {Length[val15]};
Do[valdiff2[[i]] = Abs[(meanval[[i]] - minval[[i]])], {i, 1, Length[val15]};
Do[throwvalue1[[j]] = Catch[Do[i; If[(valdiff1[[i]] < 3) ^ (valdiff2[[i]] < 3) ^
(minval[[i]] < 100), Throw[i]], {i, 1, Length[val15]}]];
);
Do[fvalcalc[j], {j, 1, Length[peakvalu]};
peak = peakvalu[[All, 2]];
valleyindex = Table[0, {Length[peakvalu]};
Do[valleyindex[[i]] = peak[[i]] - throwvalue1[[i]] + 1, {i, 1, Length[peakvalu]};
Clear[valley];
acclnvalley = Table[0, {i, Length[peakvalu]}, {j, 2}];
Do[acclnvalley[[i, 2]] = valleyindex[[i]], {i, 1, Length[peakvalu]};
Do[acclnvalley[[i, 1]] = origcycle1[[valleyindex[[i], 2]],
{i, 1, Length[peakvalu]}];
Print["ACCELERATION"];
Print["Peakvalues = ", peakvalu];
Print["Acceleration Valleys = ", acclnvalley];
Print["COEFFICIENT LISTS FOR ACCELERATION"];
(* accleration: getting values from peak to valley *)
accln = Table[0, {Length[peakvalu]};
Do[(accln[[i]] = Take[origcycle1, {acclnvalley[[i, 2]], peakvalu[[i, 2]]}],
{i, 1, Length[peakvalu]}];
acclnperthird = Table[0, {Length[peakvalu]};
(* dividing accleration into 3 portions*)
Do[acclnperthird[[i]] = Round[Length[accln[[i]]] / 3 // N], {i, 1, Length[peakvalu]};
(*Finding the parameters-exponent and mean square error-
for the first part (accln1) It is fitting with an exponential*)
coeff1 = Table[0, {Length[peakvalu]};
mser1 = Table[0, {Length[peakvalu]};
faccln1[j_] :=
(
accln1 =
Take[origcycle1, {acclnvalley[[j, 2]], acclnvalley[[j, 2]] + acclnperthird[[j]]};
SD6 = Table[0, {Length[accln1]};
Do[SD6[[n]] = accln1[[n, 2]], {n, 1, Length[accln1]};
XYS = Transpose[{accln1[[All, 1]], Log[accln1[[All, 2]]]};
g1[X_] = Fit[XYS, {1, X}, X];
c1 = CoefficientList[g1[X], {X}];
g11[X_] = Exp[c1[[1]]] * Exp[c1[[2]] * X];
errors1 = Table[0, {Length[accln1]};
Do[errors1[[i]] = g11[i + accln1[[1, 1]] - 1] - accln1[[i, 2]], {i, 1, Length[accln1]};
SD5 = errors1;
Do[SD4 =  $\frac{1}{\text{Length}[SD5]}$  * (Sum[SD5[[n]], {n, 1, Length[SD5]}]); (*mean of errors*)

```



```

SD3 = Table[0, {Length[SD5]};
Do[SD3[[n]] = (SD5[[n]] - SD4)^2, {n, 1, Length[SD5]};

Do[SD2 =  $\frac{1}{\text{Length}[SD5]} * (\text{Sum}[SD3[[n]], \{n, 1, \text{Length}[SD5]\}])$ ];
Do[SD1 = Sqrt[SD2]]; (*standard deviation of errors*)
SD = {};
Do[If[(SD5[[n]] < (SD4 + SD1)) && (SD5[[n]] > (SD4 - SD1)), SD = Append[SD, n]],
{n, 1, Length[SD5]};
acln11 = Table[0, {Length[SD]};
Do[acln11[[p]] = SD6[[SD[[p]]]], {p, 1, Length[SD]};
acln1 = Table[0, {Length[acln11]}, {n, 2};
Do[acln1[[i, 1]] = SD[[i]], {i, 1, Length[acln11]};
Do[acln1[[i, 2]] = acln11[[i]], {i, 1, Length[acln11]};
XYS1 = Transpose[{acln1[[All, 1]], Log[acln1[[All, 2]]]};
g1a[X_] = Fit[XYS1, {1, X}, X];
c1a = CoefficientList[g1a[X], {X}];
g11a[X_] = Exp[c1a[[1]]] * Exp[c1a[[2]] * X];
errors1a = Table[0, {Length[acln1]};
Do[errors1a[[i]] = g11a[SD[[i]]] - acln1[[i, 2]], {i, 1, Length[acln1]};
mse1 = Table[0, {Length[acln1]};
Do[mse1[[i]] = (errors1a[[i]])^2, {i, 1, Length[acln1]};
Do[mser1[[j]] =  $\frac{1}{\text{Length}[acln1]} * (\text{Sum}[mse1[[i]], \{i, 1, \text{Length}[acln1]\}])$ ];
Do[coeff1[[j]] = c1a[[2]]];
);
(*faccln1[1];
Show[ListPlot[accln1, PlotStyle->{PointSize[0.02], Hue[0.6]}],
Plot[g11[X], {X, First[accln1[[1]]], First[Last[accln1]]}, PlotStyle->{Hue[0]}],
AxesLabel->{"Index", "Heart Rate"}];
Show[ListPlot[acln1, PlotStyle->{PointSize[0.02], Hue[0.6]}],
Plot[g11a[X], {X, First[acln1[[1]]], First[Last[acln1]]}, PlotStyle->{Hue[0]}],
AxesLabel->{"Index", "Heart Rate"}];
*)
Do[faccln1[j], {j, 1, Length[peakvalu]};
Print["Coefficients1 [Exponent]= ", coeff1]
Print["Mean square error = ", mser1];

(****Finding the slope and mean square error for the middle part
(accln2) of acceleration region.It is fitting with a straight line****)
coeff2 = Table[0, {Length[peakvalu]};
mser2 = Table[0, {Length[peakvalu]};
faccln2[j_] :=
{accln2 = Take[origcycle1, {(acclnvalley[[j, 2]] + acclnperthird[[j]]),
(acclnvalley[[j, 2]] + (2 * acclnperthird[[j]]))}];
ASD6 = Table[0, {Length[accln2]};
Do[ASD6[[n]] = accln2[[n, 2]], {n, 1, Length[accln2]};
g2[X_] = Fit[accln2, {1, X}, X];

```

```

c2 = CoefficientList[g2[X], {X}];
errors2 = Table[0, {Length[accln2]}];
Do[errors2[[i]] = g2[i + accln2[[1, 1]] - 1] - accln2[[i, 2]], {i, 1, Length[accln2]}];
ASD5 = errors2;
Do[ASD4 =  $\frac{1}{\text{Length}[ASD5]} * (\text{Sum}[ASD5[[n]], \{n, 1, \text{Length}[ASD5]\}])$ ]; (*mean of errors*)
ASD3 = Table[0, {Length[ASD5]}];
Do[ASD3[[n]] = (ASD5[[n]] - ASD4)2, {n, 1, Length[ASD5]}];
Do[ASD2 =  $\frac{1}{\text{Length}[ASD5]} * (\text{Sum}[ASD3[[n]], \{n, 1, \text{Length}[ASD5]\}])$ ];
Do[ASD1 = Sqrt[ASD2]];
(*standard deviation of errors*)
ASD = {};
Do[If[(ASD5[[n]] < (ASD4 + ASD1)) && (ASD5[[n]] > (ASD4 - ASD1)), ASD = Append[ASD, n]],
{n, 1, Length[ASD5]}];
acln22 = Table[0, {Length[ASD]}];
Do[acln22[[p]] = ASD6[[ASD[[p]]]], {p, 1, Length[ASD]}];
acln2 = Table[0, {Length[acln22]}, {n, 2}];
Do[acln2[[i, 1]] = ASD[[i]], {i, 1, Length[acln22]}];
Do[acln2[[i, 2]] = acln22[[i]], {i, 1, Length[acln22]}];
g2a[X_] = Fit[acln2, {1, X}, X];
c2a = CoefficientList[g2a[X], {X}];
errors2a = Table[0, {Length[acln2]}];
Do[errors2a[[i]] = g2a[ASD[[i]]] - acln2[[i, 2]], {i, 1, Length[acln2]}];
mse2 = Table[0, {Length[acln2]}];
Do[mse2[[i]] = (errors2a[[i]])2, {i, 1, Length[acln2]}];
Do[mser2[[j]] =  $\frac{1}{\text{Length}[acln2]} * (\text{Sum}[mse2[[i]], \{i, 1, \text{Length}[acln2]\}])$ ];
Do[coeff2[[j]] = c2a[[2]]];
);

(*faccln2[1];
Show[ListPlot[accln2, PlotStyle->{PointSize[0.02], Hue[0.6]}],
Plot[g2[X], {X, First[accln2[[1]]], First[Last[accln2]]}, PlotStyle->{Hue[0]}],
AxesLabel->{"Index", "Heart Rate"}, TextStyle->{FontFamily->"Helvetica",
FontSize->13, FontSlant->"Italic", FontColor->RGBColor[0, 0, 0]}];
Show[ListPlot[acln2, PlotStyle->{PointSize[0.02], Hue[0.6]}],
Plot[g2a[X], {X, First[acln2[[1]]], First[Last[acln2]]}, PlotStyle->{Hue[0]}],
AxesLabel->{"Index", "Heart Rate"}, TextStyle->{FontFamily->"Helvetica",
FontSize->13, FontSlant->"Italic", FontColor->RGBColor[0, 0, 0]}];
Print["Coefficients2 [Slope]= ", coeff2];
Print["Mean square error = " , mser2];*)
Do[faccln2[j], {j, 1, Length[peakvalu]}];
Print["Coefficients2 [Slope]= ", coeff2];
Print["Mean square error = " , mser2];

(****Finding the exponent and mean square error for the last part (accln3) of
acceleration. The shape of the curve is inverted for calculation purpose****)
coeff3 = Table[0, {Length[peakvalu]}];
mser3 = Table[0, {Length[peakvalu]}];

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faccln3[j_] :=
(
accln3 =
Take[origcycle1, {acclnvalley[[j, 2]] + (2 * acclnperthird[[j]]), peakvalu[[j, 2]]}];
accln3rev = Table[0, {Length[accln3]}];
Do[accln3rev[[i]] = Last[Last[accln3]] - accln3[[i, 2]], {i, 1, Length[accln3]}];
q1 = {};
Do[If[accln3rev[[i]] > 0, q1 = Append[q1, i]], {i, 1, Length[accln3rev]}];
acln3 = Table[0, {Length[q1]}, {n, 2}];
Do[acln3[[i, 1]] = q1[[i]], {i, 1, Length[q1]}];
Do[acln3[[i, 2]] = accln3rev[q1[[i]]], {i, 1, Length[q1]}];
ABs = Transpose[{acln3[[All, 1]], Log[acln3[[All, 2]]]}];
g3[X_] = Fit[ABs, {1, X}, X];
c3 = CoefficientList[g3[X], {X}];
g33[X_] = Exp[c3[[1]]] * Exp[c3[[2]] * X];
errors3 = Table[0, {Length[acln3]}, {n, 2}];
Do[errors3[[i, 1]] = acln3[[i, 1]], {i, 1, Length[acln3]}];
Do[errors3[[i, 2]] = g33[i + acln3[[1, 1]] - 1] - acln3[[i, 2]], {i, 1, Length[acln3]}];
AASD6 = Table[0, {Length[acln3]}];
Do[AASD6[[p]] = acln3[[p, 2]], {p, 1, Length[acln3]}];
AASD5 = errors3[[All, 2]];
Do[AASD4 =  $\frac{1}{\text{Length}[AASD5]} * (\text{Sum}[AASD5[[n]], \{n, 1, \text{Length}[AASD5]\}])$ ];
AASD3 = Table[0, {Length[AASD5]}];
Do[AASD3[[n]] = (AASD5[[n]] - AASD4)^2, {n, 1, Length[AASD5]}];
Do[AASD2 =  $\frac{1}{\text{Length}[AASD5]} * (\text{Sum}[AASD3[[n]], \{n, 1, \text{Length}[AASD5]\}])$ ];
Do[AASD1 = Sqrt[AASD2]];
AASD = {};
Do[If[(AASD5[[n]] < (AASD4 + AASD1)) && (AASD5[[n]] > (AASD4 - AASD1)),
AASD = Append[AASD, n], {n, 1, Length[AASD5]}];
acln33 = Table[0, {Length[AASD]}, {n, 2}];
Do[acln33[[i, 1]] = AASD[[i]], {i, 1, Length[AASD]}];
Do[acln33[[i, 2]] = acln3[[AASD[[i]], 2]], {i, 1, Length[AASD]}];
ABs1 = Transpose[{acln33[[All, 1]], Log[acln33[[All, 2]]]}];
g3a[X_] = Fit[ABs1, {1, X}, X];
c3a = CoefficientList[g3a[X], {X}];
g33a[X_] = Exp[c3a[[1]]] * Exp[c3a[[2]] * X];
errors3a = Table[0, {Length[acln33]}];
Do[errors3a[[i]] = g33a[i + acln33[[1, 1]] - 1] - acln33[[i, 2]],
{i, 1, Length[acln33]}];
mse3 = Table[0, {Length[acln33]}];
Do[mse3[[i]] = (errors3a[[i]])^2, {i, 1, Length[acln33]}];
Do[mser3[[j]] =  $\frac{1}{\text{Length}[acln33]} * (\text{Sum}[mse3[[i]], \{i, 1, \text{Length}[acln33]\}])$ ];
Do[coeff3[[j]] = c3a[[2]]];
);
(*faccln3[1];
Show[ListPlot[acln3, PlotStyle->{PointSize[0.02], Hue[0.6]}],
Plot[g33[X], {X, First[acln3[[1]], First[Last[acln3]]}], AxesLabel->{"X", "Y"}];

```

```

Show[ListPlot[acIn33, PlotStyle -> {PointSize[0.02], Hue[0.6]}],
  Plot[g33a[X], {X, First[acIn33[[1]], First[Last[acIn33]]}, AxesLabel -> {"X", "Y"}];
*)
Do[facIn3[j], {j, 1, Length[peakvalu]};
Print["Coefficients3 [Exponent] = ", coeff3];
Print["Mean square error = ", mser3];

(****Valleys calculated for deceleration*****)
Print[""];
Print["DECELERATION"]
throwvalue2 = Table[0, {Length[peakvalu]};
fvalcalc2[j_] :=
  (val1a = Take[origcycle1, {peakvalu[[j, 2]], peakvalu[[j, 2]] + 500}];
  val2a = Table[0, {Length[val1a]};
  Do[val2a[[i]] = val1a[[i, 2]], {i, 1, Length[val1a]};
  val15a = Partition[val2a, 15, 1];
  meanvala = Table[0, {Length[val15a]};
  Do[meanvala[[i]] = val15a[[i, 8]], {i, 1, Length[val15a]};
  maxvala = Table[0, {Length[val15a]};
  Do[maxvala[[i]] = val15a[[i, 1]], {i, 1, Length[val15a]};
  nextmaxa = Table[0, {Length[val15a]};
  Do[nextmaxa[[i]] = val15a[[i, 4]], {i, 1, Length[val15a]};
  minvala = Table[0, {Length[val15a]};
  Do[minvala[[i]] = val15a[[i, 15]], {i, 1, Length[val15a]};
  nextmina = Table[0, {Length[val15a]};
  Do[nextmina[[i]] = val15a[[i, 12]], {i, 1, Length[val15a]};
  valdiff1a = Table[0, {Length[val15a]};
  Do[valdiff1a[[i]] = Abs[(meanvala[[i]] - maxvala[[i]])], {i, 1, Length[val15a]};
  valdiff2a = Table[0, {Length[val15a]};
  Do[valdiff2a[[i]] = Abs[(meanvala[[i]] - minvala[[i]])], {i, 1, Length[val15a]};
  valdiff3a = Table[0, {Length[val15a]};
  Do[valdiff3a[[i]] = Abs[(meanvala[[i]] - nextmaxa[[i]])], {i, 1, Length[val15a]};
  valdiff4a = Table[0, {Length[val15a]};
  Do[valdiff4a[[i]] = Abs[(meanvala[[i]] - nextmina[[i]])], {i, 1, Length[val15a]};
  Do[throwvalue2[[j]] = Catch[Do[i, If[(valdiff1a[[i]] < 3) ^ (valdiff2a[[i]] < 3) ^
    (minvala[[i]] < 100), Throw[i]], {i, 1, Length[val15a]}]];
  );
Do[fvalcalc2[j], {j, 1, Length[peakvalu]};
Print["Throwvalue = ", throwvalue2];
valleys2 = Table[0, {Length[peakvalu]};
Do[If[throwvalue2[[i]] < 1, valleys2[[i]] = valleyerror,
  valleys2[[i]] = throwvalue2[[i]] + peakvalu[[i, 2]], {i, 1, Length[peakvalu]}]
Print["Deceleration Valleys = ", valleys2];
dcclnvalley = Table[0, {i, Length[peakvalu]}, {j, 2}];
Do[dcclnvalley[[i, 2]] = valleys2[[i]], {i, 1, Length[peakvalu]};
Do[dcclnvalley[[i, 1]] = origcycle1[[valleys2[[i], 2]], {i, 1, Length[peakvalu]};
Print["Peakvalues = ", peakvalu];
Print["Deceleration Valleys = ", dcclnvalley];
Print["COEFFICIENT LISTS FOR DECELERATION"];
(* deceleration: getting values from peak to valley *)
dccln = Table[0, {Length[peakvalu]};

```

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Do[{dccln[[i]] = Take[origcycle1, {peakvalu[[i, 2]], dcclnvalley[[i, 2]]}],
  {i, 1, Length[peakvalu]}}];
dcclnperthird = Table[0, {Length[peakvalu]};
(* dividing deceleration into 3 portions*)
Do[dcclnperthird[[i]] = Round[Length[dccln[[i]]] / 3 // N], {i, 1, Length[peakvalu]};
(****Finding the parameters for the first part of
  deceleration (dccln1). It is fitting with an exponential****)
dcoeff1 = Table[0, {Length[peakvalu]};
dmser1 = Table[0, {Length[peakvalu]};
fdcccln1[j_] :=
  (
    dccln1 = Take[origcycle1, {peakvalu[[j, 2]], peakvalu[[j, 2]] + dcclnperthird[[j]]}];

    dccln1rev = Table[0, {Length[dccln1]};
    Do[dccln1rev[[i]] = Last[First[dccln1]] - dccln1[[i, 2]], {i, 1, Length[dccln1]};
    q2 = {};
    Do[If[dccln1rev[[i]] > 0, q2 = Append[q2, dccln1rev[[i]]],
      {i, 1, Length[dccln1rev]};
    dcln1 = Table[0, {Length[q2]}, {n, 2}];
    Do[dcln1[[i, 1]] = i, {i, 1, Length[q2]};
    Do[dcln1[[i, 2]] = q2[[i]], {i, 1, Length[q2]};
    XYsd = Transpose[{dcln1[[All, 1]], Log[dcln1[[All, 2]]]};
    k1[X_] = Fit[XYsd, {1, X}, X];
    dc1 = CoefficientList[k1[X], {X}];
    Do[dcoeff1[[j]] = dc1[[2]]];
    k11[X_] = Exp[dc1[[1]]] * Exp[dc1[[2]] * X];
    derrrors1 = Table[0, {Length[dcln1]};
    Do[derrrors1[[i]] = Abs[k11[i + dcln1[[1, 1]] - 1] - dcln1[[i, 2]]],
      {i, 1, Length[dcln1]};
    dmser1 = Table[0, {Length[dcln1]};
    Do[dmser1[[i]] = derrrors1[[i]] * derrrors1[[i]], {i, 1, Length[dcln1]};
    Do[dmser1[[j]] =  $\frac{1}{\text{Length}[dcln1]} * (\text{Sum}[dmser1[[i]], \{i, 1, \text{Length}[dcln1]\}])$ ];
  );
(*fdcccln1[3];
Show[ListPlot[dcln1, PlotStyle->{PointSize[0.02], Hue[0.6]}],
  Plot[k11[X], {X, First[dcln1[[1]], First[Last[dcln1]]}, PlotStyle->{Hue[0]}],
  AxesLabel->{"X", "Y"}];
Print["Mean square error =", dmser1];
Print["coefficient1=", dcoeff1];*)
Do[fdcccln1[j], {j, 1, Length[peakvalu]};
Print["Coefficients1 [Exponent]= ", dcoeff1];
Print["Mean square error = ", dmser1];

(*Finding the parameters for the middle part of
  deceleration (dccln2). It is fitting with a straight line*)
dcoeff2 = Table[0, {Length[peakvalu]};
dmser2 = Table[0, {Length[peakvalu]};
fdcccln2[j_] :=
  (
    dccln2 = Take[origcycle1, {(peakvalu[[j, 2]] + dcclnperthird[[j])},

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    (peakvalu[[j, 2]] + (2 * dcclnperthird[[j]]));
k2[X_] = Fit[dccln2, {1, X}, X];
dc2 = CoefficientList[k2[X], {X}];
Do[dcoeff2[[j]] = dc2[[2]];
derrors2 = Table[0, {Length[dccln2]}];
Do[derrors2[[i]] = Abs[k2[i + dccln2[[1, 1]] - 1] - dccln2[[i, 2]]],
  {i, 1, Length[dccln2]}];
dmse2 = Table[0, {Length[dccln2]}];
Do[dmse2[[i]] = derrors2[[i]] * derrors2[[i]], {i, 1, Length[dccln2]}];
Do[dmser2[[j]] =  $\frac{1}{\text{Length}[dccln2]}$  * (Sum[dmse2[[i]], {i, 1, Length[dccln2]}]);
);
(*fdccln2[3];
Show[ListPlot[dccln2, PlotStyle->{PointSize[0.02], Hue[0.6]}],
  Plot[k2[X], {X, First[dccln2[[1]]], First[Last[dccln2]]}, PlotStyle->{Hue[0]}],
  AxesLabel->{"Index", "Heart Rate"},
  TextStyle->{FontFamily->"Helvetica", FontSize->13, FontSlant->"Italic"}];
dmser2*)
Do[fdccln2[j], {j, 1, Length[peakvalu]}];
Print["Coefficients2 [Slope]= ", dcoeff2];
Print["Mean square error = ", dmser2];

(*Finding the parameters for the last part
(dccln3) od deceleration. It is fitting with an exponential*)
dcoeff3 = Table[0, {Length[peakvalu]}];
dmser3 = Table[0, {Length[peakvalu]}];
fdccln3[j_] :=
  (dccln3 = Take[origcycle1,
    {peakvalu[[j, 2]] + (2 * dcclnperthird[[j]]), dcclnvalley[[j, 2]]});
  ABsd = Transpose[{dccln3[[All, 1]], Log[dccln3[[All, 2]]]}];
  k3[X_] = Fit[ABsd, {1, X}, X];
  dc3 = CoefficientList[k3[X], {X}];
  Do[dcoeff3[[j]] = dc3[[2]];
  k33[X_] = Exp[dc3[[1]]] * Exp[dc3[[2]] * X];
  derrors3 = Table[0, {Length[dccln3]}];
  Do[derrors3[[i]] = Abs[k33[i + dccln3[[1, 1]] - 1] - dccln3[[i, 2]]],
    {i, 1, Length[dccln3]}];
  dmse3 = Table[0, {Length[dccln3]}];
  Do[dmse3[[i]] = derrors3[[i]] * derrors3[[i]], {i, 1, Length[dccln3]}];
  Do[dmser3[[j]] =  $\frac{1}{\text{Length}[dccln3]}$  * (Sum[dmse3[[i]], {i, 1, Length[dccln3]}]);
);
(*fdccln3[6];
Show[ListPlot[dccln3, PlotStyle->{PointSize[0.02], Hue[0.6]}],
  Plot[k33[X], {X, First[dccln3[[1]]], First[Last[dccln3]]}, PlotStyle->{Hue[0]}],
  AxesLabel->{"Index", "Heart Rate"},
  TextStyle->{FontFamily->"Helvetica", FontSize->13, FontSlant->"Italic"}];

```

```
dmser3*)  
Do[fdcc1n3[j], {j, 1, Length[peakvalu]}];  
Print["Coefficients3 [Exponent] = ", dcoeff3];  
Print["Mean square error = ", dmser3];
```

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