FATIGUE RELATED EMG POWER SPECTRUM CHANGES DURING DYNAMIC CONTRACTIONS IN FEMALE ROWERS

by

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ABSTRACT

The Surface Electromyography (SEMG) signal allows a good assessment of neuromuscular activity as a noninvasive tool. While muscle fatigue is a complex multifaceted phenomenon, in sedentary subjects it is characterized by changes of spectral parameters. If these criteria are also valid for athletes, monitoring training and performance development as well as scientific research on muscular adaptations during intense physical exercise will be facilitated.

For this purpose, ten healthy female rowers of the Turkish National Team were selected. SEMG recordings were obtained from the muscles Vastus Lateralis (VL). The fatigue test with 80 % Maximum Voluntary Contraction (MVC) consisted of two identical tests. First, the subjects performed repetitive auxotonic knee extensions to maintain for as long as possible (till exhaustion). After a five-minute rest, the exercise protocol was repeated. The power spectrum was derived from the raw SEMG signal using the Fast Fourier Transform (FFT) algorithm. For the active phase of each contraction cycle the Median Frequency (MDF) and the Mean Frequency (MNF) were computed from the EMG signal. In addition, the Borg's Category-Ratio Scale (CR-10) was used to measure the perceived muscle exertion.

The results of this study show that the inter-individual fatigue profiles differ in power spectrum. Differences are also noted for the first and the second experiments in terms of spectral values. But, the MDF and MNF graphics of both experiments are greatly similar. What is common for all the subjects is that there are periodic decreases and increases in their MDF and MNF values. Recruitment of larger motor units with higher discharge rates or cyclic recruitment of motor units during sustained auxotonic contractions may be the cause for these interesting findings. This result may represent a special muscular adaptation of elite rowers to intense muscular training.

Keywords: EMG, sports, fatigue, contraction, median frequency, mean frequency, power spectral analysis, elite rowers.

BAYAN KÜREKÇİLERİN DİNAMİK KONTRAKSİYONLARDA YORGUNLUĞA BAĞLI EMG GÜÇ DAĞILIMI DEĞİŞİMLERİ

ÖZET

Yüzeyel Elektromiyografi (YEMG), iğnesiz bir yöntem olarak nöromusküler aktiviteyi değerlendirmenin avantajlı bir yoludur. Kas yorgunluğu her ne kadar kompleks bir olguysa da, spor yapmayan deneklerde spektral ölçütlerde değişim ile tanımlanabilmektedir. Bu kriterler elit atletler için de geçerli ise, antrenman ve performans gelişimi ile yoğun fiziksel egzersiz sırasındaki kassal uyumla ilgili bilimsel araştırmalar ivme kazanacaktır.

Bu amaçla, çalışmalar Türk milli takımından seçilen 10 bayan kürekçi üzerinde yapıldı. EMG kayıtları dominant bacaktaki Vastus Lateralis kasından alındı. Bu çalışma % 80 MVC ile yapılan birbirinin aynısı iki testten oluşmuştur. İlk olarak, denekler yorulana kadar oksotonik diz ekstansiyonlarına devam ettiler ve beş dakika dinlenmeden sonra deney protokolü ikinci kez tekrarlandı. Güç dağılımı değerleri, Fast Fourier Dönüşümü (FFD) ile ham EMG sinyalinden hesaplandı. Gürültüler temizlenerek sadece aktif kas kontraksiyonlarının Ortanca Frekans (OCF) ve Ortalama Frekans (OMF) değerleri hesaplanmıştır. Buna ek olarak, Borg Kategori Oran Skalası (CR-10) algılanan kas yorgunluğunu ölçmek için kullanılmıştır.

Çalışmanın sonucunda, yorgunluk profillerine bakıldığı zaman güç dağılımı değerleri bireyler arasında farklıdır. Ayrıca birinci ve ikinci testlerde güç spektrumu değerleri her bir denek için değişik olmaktadır. Ancak her iki test için OCF ve OMF değerleri genelde benzerlik arz etmektedir. Deney süresince tüm deneklerde OCF ve OMF değerlerinde periyodik artma ve azalmalar göstermiştir. Yüksek uyarı oranlarıyla büyük motor birimlerin kontraksiyona katılımı veya motor birimlerin değişmeli olarak oksotonik kontraksiyonları sürdürmeleri bu sonuçların nedeni olabilir. Bu ilginç sonuçlar, yoğun antrenman yapan elit kürekçilerin özel kas adaptasyonlarının bir göstergesi olabilir.

Anahtar Sözcükler: EMG, spor, kontraksiyon, yorgunluk, ortanca frekans, ortalama frekans, güç dağılımı analizi, elit kürekçiler.

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LIST OF ABBREVIATIONS

CR-10	Borg's Category Ratio Scale.
EMG	Electromyography.
FFT	Fast Fourier Transforms.
MVC	Maximum Voluntary Contraction.
MNF	Mean Frequency.
MDF	Median Frequency.
MU	Motor Unit.
MUAP	Motor Unit Action Potential.
SEMG	Surface Electromyography.
MFCV	Muscle Fiber Conduction Velocity.

1. INTRODUCTION

The surface electromyographic signal allows a good assessment of neuromuscular activity as a noninvasive tool. During recent decades, there is a growing interest in studying the behavior of spectral parameters with respect to physiological, anatomical, and biochemical events within a muscle. Analyses of the Surface Electromyography (SEMG) have been widely utilized for prediction of force, quantification of muscle fatigue and used as a diagnostic tool in rehabilitation medicine, ergonomy and sports physiology.

Neuromuscular fatigue with respect to the motor unit physiology, is defined as the changes in the nerve and muscle physiology and biomechanical processes used to produce muscle force that eventually result in the inability to maintain a contraction [1]. Fatigue during voluntary muscular contractions is a complex multifaceted phenomenon and may be caused by central nervous factors as well as changes in peripheral sites of neuromuscular system [2,3,4,5]. Moreover, causing fatigue may be dependent on the type and intensity of muscular activity. Fatigue is a frequent problem encountered during rehabilitation and exercise physiology, it can limit the performance of both patients and athletes.

Methods for assessing the electrical manifestations of muscle fatigue during isometric, constant-force contractions are reported with many papers [1,6,7,8]. But isometric contractions may not be representative of muscle activity and fatigue development during human locomotion. Most movements of muscles in daily life are dynamic contractions. Although fatigue is most often the consequence of movement (sports training, rehabilitation etc.), relatively few studies were carried out to quantify muscle fatigue resulting from dynamic contractions [9,10]. The principal causes for this situation are movement artifacts of the Electromyography (EMG) signal and the problem of stationary of spectral analysis. But it is important to clarify the change of EMG parameters during dynamic contraction for quantitative analyses of fatigue in sports and labor. The performances of daily activities by an individual involve dynamic muscle contractions where muscle force and geometry are changing. Dynamic contractions, which include the stretching and shortening of a muscle, should enhance blood flow by enhanced venous return from the contracting muscle. The enhanced blood flow removes metabolic by products and contributes to the inhibition of the decrease in intracellular pH [11]. Thus,

dynamic muscle contractions produce non-stationary myoelectric signal. This variability of the intracellular state may affect the changes in Muscle Fiber Conduction Velocity (MFCV), Median frequency (MDF) and Mean frequency (MNF). In addition to this, most of the research in the literature is conducted on healthy and sedentary subjects [11,12,13,14]. Only few reports deal with specific trained subjects [6] and elite athletes [15,16].

In this context the reproducibility (reliability) of the assessment is crucial for the interpretation of research findings and has been investigated in several studies [8,17]. In addition to this, simulation of the competition of a particular sport, like rowing, may involve repetition of the exercise. Therefore, we repeated our measurements after a short interval of rest and compared both measurements.

It is accepted that elite athletes can accurately perceive the level of evolving fatigue. Assessment of this subjective perception by the Borg's Category Ratio Scale (CR-10) [18] and comparison with EMG spectral parameters may provide a tool for validation of fatigue.

Attempts to extend spectral analytical tools to dynamic contractions have been reported recently. However, analyses of dynamic contractions in elite athletes are very few [15,16]. Also the type of dynamic contractions employed in these studies, like isokinetic or isotonic ones, are not very representative of the natural movement pattern of sports. Therefore, we chose auxotonic contractions, which are characterized by the simultaneous change of force and muscle length, to simulate the natural movement pattern of a particular sports. We used a simple spring system for this purpose.

These considerations determined the choice of rowing and rowers for the analysis of EMG spectral parameters in our study. The movement pattern in rowing is characterized by auxotonic extensions in the knee. The increase in force in the quadriceps muscle during the rowing stroke can easily be simulated by compression of a spring. Furthermore, rowing is unique for analysis of fatigue, because rowers are able to maintain 75-80 % of maximal power output during the entire race, which lasts approximately 6 to 7 minutes. Therefore in

this study we tested the suitability of median frequency (MDF) and mean frequency (MNF) as a criterion of fatigue by examining the EMG findings of elite female rowers.

It will be of great importance, if a non-invasive tool like the Surface Electromyography (SEMG) should provide a criterion for determination of muscle fatigue. This criterion would be ideally suited for monitoring training and performance development as well as for scientific research on muscular adaptations during intense physical exercise. To put it precisely, in this study we investigated; (1) whether there is a decrease in the EMG spectral parameters (MDF and MNF) due to the fatigue in elite athletes as it has been observed for sedentary subjects, (2) whether these EMG changes can be used for the evaluation of athletic performances and (3) whether these EMG changes may be suitable for the online and offline observation of training induced changes.

1.1 Thesis Outline

The remaining chapters are organized as follows. Chapter 2 gives brief information on the nervous system (neuron, electrical activity in the neurons). Chapter 3 explains muscular control of movement (muscle physiology, muscle contraction types, fiber types, and muscle fatigue). Chapter 4 consists of fatigue in Surface Electromyography (SEMG), studies related to SEMG and brief information on power spectrum.

Chapter 5 contains methodology of this study; these are subjects, test design, data acquisition system, the Borg's Category Ratio Scale (R-10), calculation of the Median Frequency (MDF) and Mean Frequency (MNF). Chapter 6 includes the results of the study. The results are discussed and in further detail concluded in Chapter 7.

2. NERVOUS SYSTEM

The nervous system is the body's means of perceiving and responding to events in the internal and external environments. Receptors capable of sensing touch, pain, temperature and chemical stimuli send information to the Central Nervous System (CNS) concerning changes in our environment. The CNS responds by either voluntary movement or a change in the rate of release of some hormone from the endocrine system, depending on which response is appropriate.

Anatomically, the nervous system can be divided into two main parts: the CNS and the Peripheral Nervous System (PNS). The CNS is that portion of the nervous system contained in the skull (brain) and the spinal cord; the PNS consist of nerve cells (neurons) outside the CNS [19].

2.1 Structure of Neuron

The functional unit of the nervous system is the neuron. Anatomically, neurons can be divided into three regions: (1) cell body, (2) dendrites, and (3) axon (Figure 2.1) [19,20]. The center of operation for the neuron is the cell body or soma, which contains the nucleus. Narrow, cytoplazmic attachments extend from the cell body and are called dendrites. Dendrites serve as a receptive area that can conduct electrical impulses toward the cell body. The axon (also called nerve fiber) caries the electrical message away from the cell body toward another neuron or effectors organ. Each neuron has only one axon; however, the axon can divide into several collateral branches that terminate at other neurons neuron, muscle cells or glands. Contact points between an axon of one neuron and the dendrites of another neuron are called synapses.

The axons are covered with an insulating layer of cells called Schwann cells. The membranes of Schwann cells contain a large amount of a lipid-protein substance called myelin, which forms a discontinuous sheath that covers the outside of the axon. The gaps between the myelin segments along the axon are called nodes of ranvier and play important role in neural transmission. Generally, the larger the diameter of the axon is the greater the

speed of neural transmission. Thus, those axons with large myelin sheaths conduct impulses faster than small non-myelinated fiber [19].

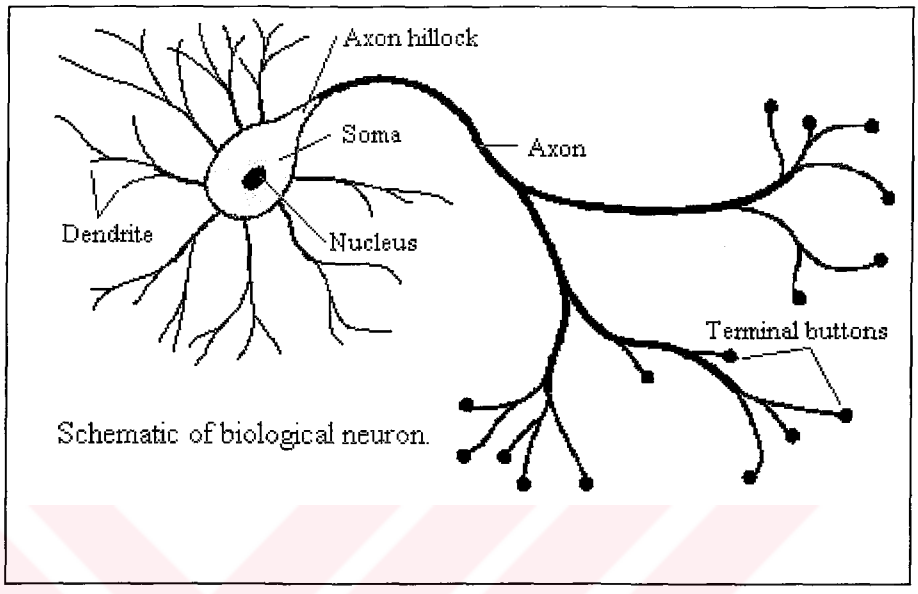

Figure 2.1 The parts of a neuron [20].

2.2 Electrical Activity in Neurons

Neurons are considered "excitable tissue" because of their specialized properties of irritability: the ability of the dendrites and neuron cell body to respond to a stimulus and convert it to a neural impulse. Conductivity refers to the transmission of the impulse along the axon. A nerve impulse can be thought of as an electrical signal carrying the length of the axon. This electrical signal is initiated via some stimulus that causes a charge in the normal electrical charge of the neuron [19,21].

At rest, all cells are negatively charged on the inside of the cell with respect to the charge on the exterior of the cell. This negative charge is the result of an unequal distribution of charged ions across the cell membrane. This balance is achieved by the permeability of the cell membrane to sodium (Na) and the potassium (K) ions. Thus, a neuron is polarized and this electrical charge difference is called the resting membrane potential. When, a neuron membrane is excited by an outside stimulus, changes in potential occur along the cell membrane. When the membrane potential becomes more negative, the cell is referred to as depolarized [19,21].

A neural message is generated when a stimulus of sufficient strength reaches the neuron membrane and opens sodium gates, which allows sodium ions to diffuse into the neuron, making the inside more and more positive. When depolarization reaches a critical value called "threshold", the sodium gates open wide and action potential or nerve impulse is formed (Figure 2.2). Repolarization occurs immediately following depolarization due to an increase in membrane permeability to potassium and a decreased permeability to sodium.

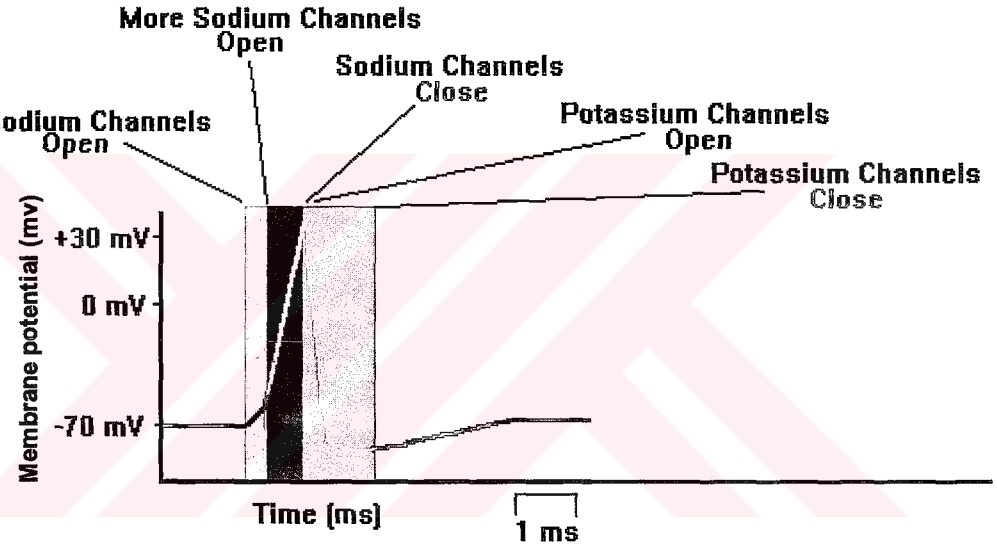

Figure 2.2 An action potential is produced by an increase in sodium conductance into the neuron. As sodium enters the neuron the chance becomes more and more positive and an action potential is generated [19,21].

Neurons communicate with other neurons at junctions called synapses. Synaptic transmission occurs when sufficient amount of a specific neurotransmission are released from the pre-synaptic neuron (Figure 2.3). Upon release, the neurotransmitter gets bound to a receptor on the postsynaptic membrane (Figure 2.4).

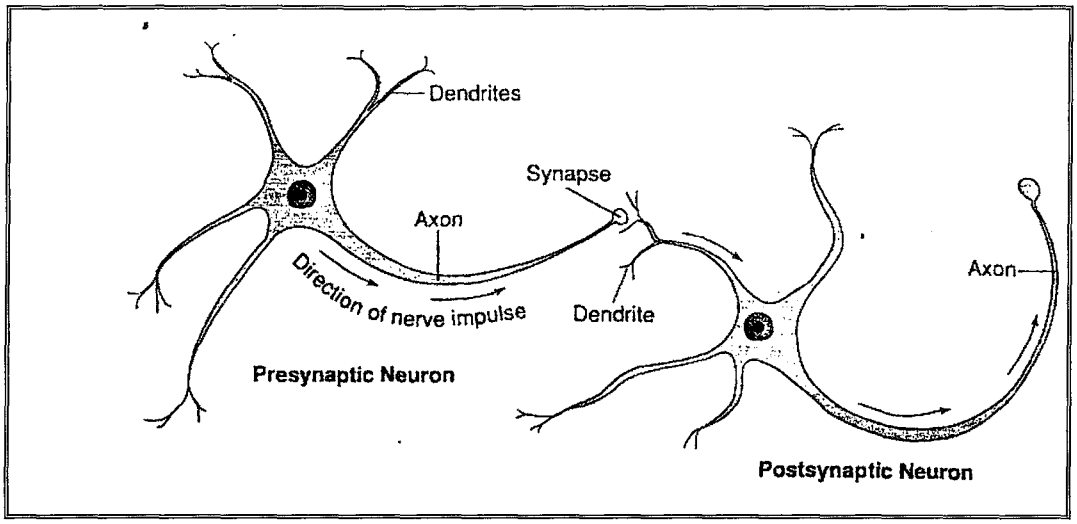

Figure 2.3 An illustration of synaptic transmission. For a nerve impulse to continue from one neuron to another, it must cross the synaptic cleft at a synapse [19].

Neurotransmitters can be excitatory or inhibitory. An excitatory transmitter increases neuronal permeability to sodium and results in excitatory postsynaptic potentials (EPSPs). Inhibitory neurotransmitters cause the neuron to become more negative (hyperpolarized). This hyperpolarization of the membrane is called an inhibitory postsynaptic potential (IPSPs) [19].

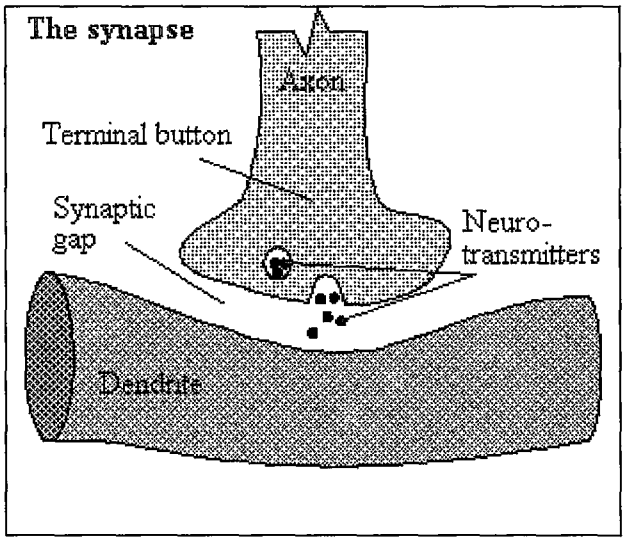

Figure 2.4 The basic structure of a chemical synapse [20].

3. MUSCULAR CONTROL OF MOVEMENT

The muscular system consists of three muscle types: cardiac muscle, which composes the heart; smooth (involuntary) muscle, which lines the hollow internal organs; and skeletal (striated or voluntary) muscle, which is attached to skeleton via the tendons and cause it to move [22].

The human body contains over four hundred skeletal muscles, which constitute 40%-50% of the total body weight. The muscles provide strength and protection to the skeleton by distributing loads and absorbing shock and they enable the bones to move at the joints. Such movement usually represents the action of muscle groups rather than of individual muscles.

Skeletal muscle performs three important functions (1) dynamic work; force generation for locomotion, the positioning of the body segments in space and breathing, (2) static work; force generation for postural support and (3) heat production during periods of cold stress. The most obvious function of skeletal muscle is to enable an individual to move freely and breathe. There are different movements, which depend on the type of joint and muscles involved. Muscles that decrease joint angles are called flexors; while muscles tat increase joint angles are called extensors [19,22].

3.1 Structure of Skeletal Muscle

Skeletal muscle is composed of several tissue types (Figure 3.1) displays the relationship between muscle and the various connective tissues [23]. The structural unit of skeletal muscle is fiber. Each fiber is encompassed by a loose connective tissue called the endomysium and the fibers are organized into various-sized bundles or fascicles, which are in turn, encased connective tissue sheet known as the premysium. Surrounding the entire muscle is a fascia of fibrous connective tissue called the epimysium.

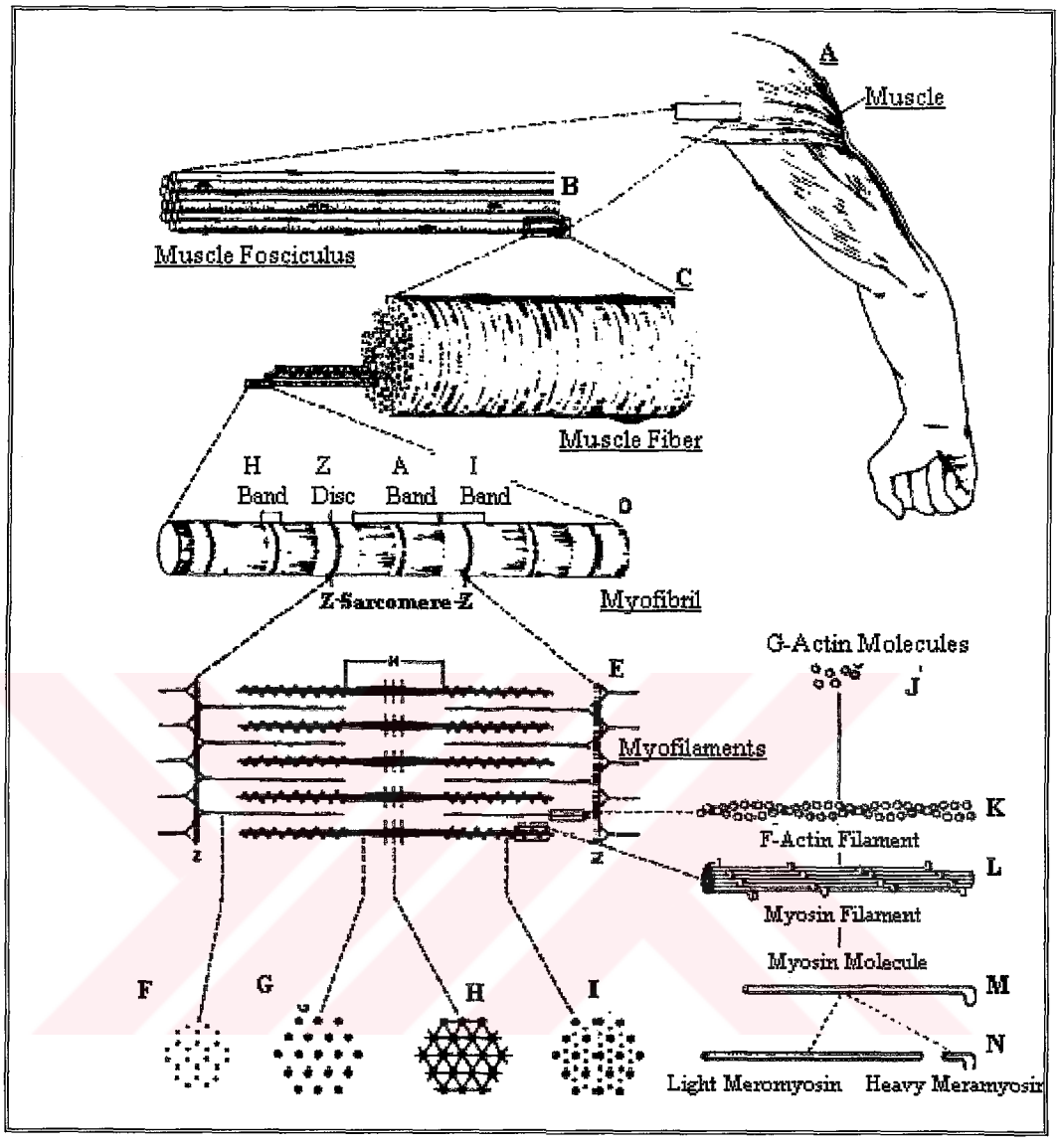

Figure 2.3 An illustration of synaptic transmission. For a nerve impulse to continue from one neuron to another, it must cross the synaptic cleft at a synapse [19].

The cell membrane surrounding the muscle cell is called the sarcolemma. Beneath the sarcoplazm (cytoplasm), which contains the cellular proteins, organelles and myofibrils. Each myofibril is composed of fibrous filaments of two types: thin filaments are composed of the protein actin and thick filaments are composed of protein myosin. Located on the actin molecule itself are two additional proteins, troponin and tropomyosin. These proteins make up small portion of the muscle, but play important role in regulation of the contractile process.

Myofibrils can be further subdivided into individual segments called sarcomeres. Sarcomeres are divided from each other with a thin sheet of structural proteins called a Z line. Myosin filaments are located primarily within the dark portion of he sarcomere, which is called the A band, while actin filaments occur principally in the light region of the sarcomere there is apportion of the myosin filament with no overlap the actin. This is the H zone [19,22].

3.2. Neuromuscular Junction

Each skeletal muscle is connected to a nerve fiber branch coming from a nerve cell. These nerve cells are called motor neurons and extend outward from the spinal cord [19]. The functional unit of skeletal muscle is the motor unit, which includes a single motor neuron and all of the muscle fibers innervated by it. This unit is the smallest part of the muscle that can be made to contract independently. When stimulated, all muscle fibers in the motor unit respond as one. The fibers of a motor unit are said to show an all-or-none response to stimulation: they either contract maximally or not at all [22]. Stimulation from motor neurons initiates the contraction process. The site where the motor neuron and muscle cell meet is called the neuromuscular junction (Figure 3.2). At this junction the sarcolemma forms a pocket that is called the motor end plate [19].

The fibers of each motor unit are dispersed throughout the muscle with fibers of other units. Thus, if a single motor is stimulated, a large portion of the muscle appears to contract. If additional motor units of the nerve innervating the muscle are stimulated, the muscle contracts with greater force. The calling in of additional motors units in response to greater stimulation of the motor nerve is called recruitment [22].

The end of the motor neuron does not physically make contact with the muscle fiber, but is separated by a short gap called the neuromuscular cleft. When a nerve impulse reaches the end of the motor nerve, the neurotransmitter acetyclholine is released and diffuses across the synaptic cleft to bind with receptor sites on the motor end plate. This causes an increase in the permeability of the sarcollema to sodium, resulting in a depolarization called the end-plate potential (EPP). The EPP is always large enough to exceed threshold and is the signal to begin the contractile process [19].

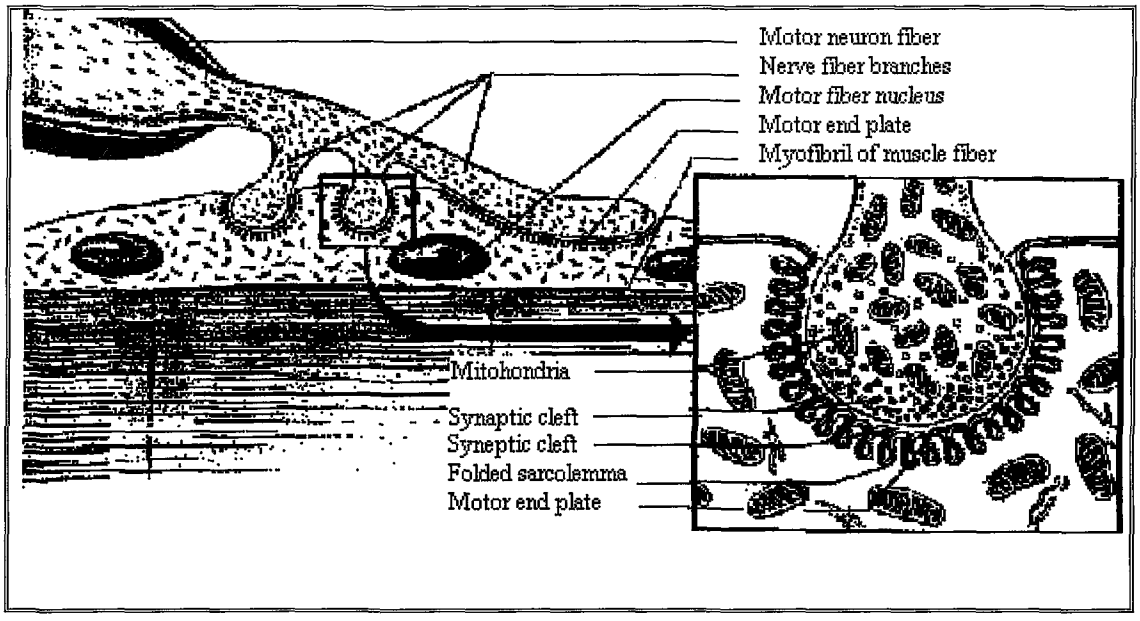

Figure 3.2 The connecting point between a motor neuron and a single muscle fiber is called the neuromuscular junction. The neurotransmitter acetylcholine is stored in synaptic vesicles at the end of the nerve fiber [19].

3.3 Muscular Contraction

Muscular contraction can be explained with the sliding filament model. Muscle fibers contract by a shortening of their myofibrils due to actin sliding over the myosin. This results in a reduction in the distance from Z line to Z line.

The generation of an action potential in a motor neuron causes the release of acetylcholine into the neuromuscular junction. Acetylcholine is bound to with receptors on the motor end-plate potential that leads to a depolarization. If the cell is sufficiently depolarized, an action potential is fired and muscle action occurs [19].

The action potential travels along the sarcolemma, then through the tubule system and eventually causes stored calcium ions to be released from the sarcoplazmic reticulum. Calcium ions is bound to with troponin and then troponin lifts the tropomyosin molecules off the active sites to allow the myosin heads to bind strongly with them. Once a strong binding is established with actin filament so that two slide across each other. The tilting of the myosin head is the power stroke. Energy is required before muscle action can occur. The myosin head binds to ATP and ATPase found on the head splits ATP into ADP and Pi

(inorganic phosphate), releasing the energy to fuel the contraction. The energy released from this break down of ATP is used to bind the myosin head to the actin filament. Thus, ATP is the chemical source of energy for muscle action [24].

Muscle action continues until the calcium is depleted. Calcium is then pumped back into the sarcoplazmic reticulum, where it is stored until a new nerve impulse arrives at the muscle fiber membrane. Calcium is returned to the sarcoplazmic reticulum by active calcium – pumping system. This is another energy – demanding process that also relies on ATP. Thus, energy is required for both the action and relaxation phases. When the calcium is removed troponin and tropomyosin are deactivated. This blocks the linking of the myosin cross-bridges and actin filaments and stops the use of ATP. As a result, the myosin and actin filaments return to their original relaxed state [24].

3.4 Types of Muscle Contractions

During contraction, the force exerted by a contracting muscle on the bony lever(s) to which it is attached is known as the muscle tension and the external force exerted on the muscle is known as the resistance or load. As the muscle exerts its force, it generates a turning effect or moment (torque) on the involved joint, as the line of application of the muscle force usually lies at a distance from the center of motion of the joint. The moment is calculated as the product of the muscle force and the perpendicular distance between its point of application and the center of motion. Muscle contractions can be classified according to the relationship between either the muscle tension and the resistance to be overcome or the muscle moment generated and the resistance to be overcome (Figure 3.3) [22].

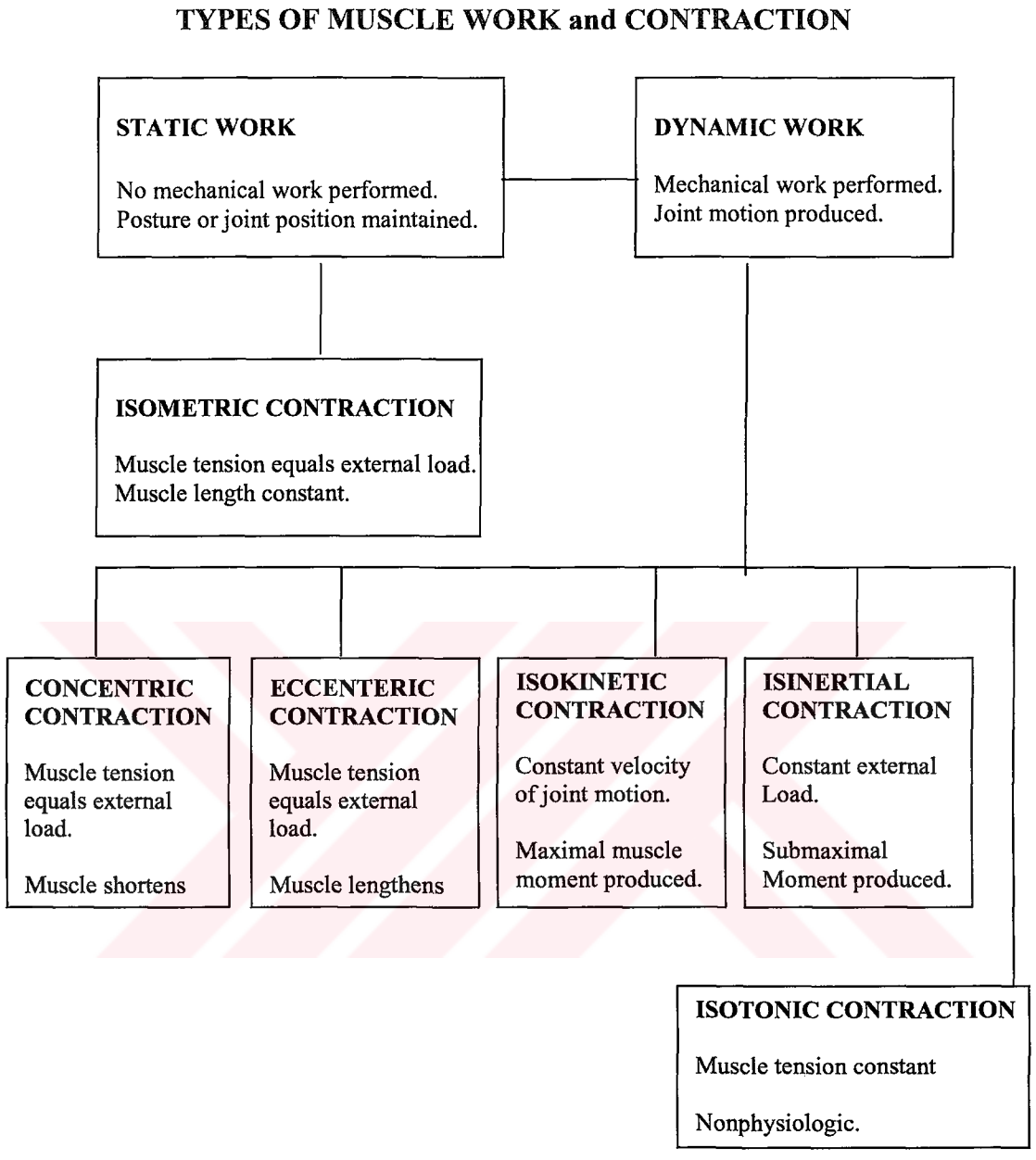

Figure 3.3 Types of Muscle Work and Contraction [22].

3.5 Force Production in the Muscle

The total force that a muscle can produce is influenced by its mechanical properties, which can be described by the length - tension, load - velocity and force - time relationship of the muscle. Both active (contractile) and passive (series and parallel elastic) components influence the length - tension relationship in a whole muscle. The velocity of shortening of a muscle contracting concentrically is inversely related to the external load applied. The

velocity of shortening is greatest when the external load is zero, but as the load increases the muscle shortens more and slowly. The force generated by a muscle is proportional to the contraction time: the longer contraction time, the greater developed force is up to the point of maximum tension. Slower contraction leads to greater force production because time is allowed for the tension produced by the contractile elements to be transmitted through the parallel elastic components to the tendon. Other factors that increase force production are prestreching of the muscle, a rise in muscle temperature and becoming muscle fatigue. Muscle fatigue occurs when the ability of the muscle to synthesize ATP is insufficient to keep up with the rate of ATP breakdown during contraction [22].

The amount of force exerted during muscular contraction a group of muscles is complex and dependent on these factors [19,24]:

- The number and types motor units recruited (activated)
- The muscle's initial length when activated
- The size of the muscle
- The angle of the joint
- The muscle speed of action
- The nature of neural stimulation of the motor units

To achieve athletic success in some disciplines (e.g., rowing competition) high power output (force x speed) must accompany good endurance. This complex dimension of muscle performance is called force-endurance [25]. The enhancement of "force-endurance" or prevention of fatigue is the aim of discipline specific training programs. Especially the following 3 parameters determine "force-endurance" of an athlete:

1- amount of force,
2- frequency of movement,
3- velocity of muscle contraction.

3.6 Fiber Types

The fiber types are mainly distinguished by the metabolic pathways by which they can generate ATP and the rate at which its energy is made available to the contractile system of the sarcomere, which determines the speed of contraction. The three fibers types are termed: type I; slow – twitch oxidative (SO) fibers, type IIA; fast - twitch oxidative - glycolitic (FOG) fibers and type IIB; fast-twitch glycolitic (FG) fibers [19, 22, 24, 26] (Table 3.1).

Table 3.1

Types of Muscle Fibers

Fiber Types	**Type I**	**Type II A**	**Type II B**
Twitch and Fatigue Characteristics	Slow (S)	Fast resistant (FR)	Fast fatigue (FF)
Twitch and enzymatic properties	Slow oxidative (SO)	Fast oxidative - glycolytic (FOG)	Fast glycolitic (FG)
Properties of Muscle Fibers			
Resistance to fatigue	High	High	Low
Oxidative enzymes	High	High	Low
Phosphorylase (glycolytic)	Low	High	High
Adenosine triphosphate	Low	High	High
Twitch speed	Low	High	High
Twitch tension	Low	High	High
Characteristics of Motor Units			
Size of cell body	Small	Large	Large
Size of motor unit	Small	Large	Large
Diameter of axons	Small	Large	Large
Conduction velocity	Low	High	High
Threshold for recruitment	Low	High	High
Firing frequency	Low	High	High
Frequency of miniature (EPP)	Low	High	High

Slow Fibers: Type I (SO) fibers are characterized by a low activity of myosin ATPase in the muscle fiber and therefore, a relatively slow contraction time. The glycolitic (anaerobic) activity is low in this fiber type, but a high content of mitochondria produces a high potential potential for oxidative (aerobic) activity. Type I fibers are very difficult to fatigue, as the high rate of blood flow to these fibers delivers oxygen and nutrients at a sufficient rate to keep up with the relatively slow rate of ATP breakdown by myosin ATPase. Thus, the fibers are well suited for prolonged, low-intensity work.

Fast Fibers: two subtypes of fast fibers exist in humans; Type II A and Type II B.Type IIA (FOG) fibers are considered intermediate between type IA and type IIB, because their fast contraction time is combined with a moderately well developed capacity for both aerobic (oxidative) and anaerobic (glycolytic) activity. These fibers also have well developed blood supply. They can maintain their contractile activity. They can maintain their contractile activity for relatively long periods; however, at high rates of activity, the high rate of ATP splitting exceeds the capacity of both oxidative phosphorylation and glycolysis to supply ATP and these fibers eventually fatigue.

Type IIB (FG) fibers rely primarily on glycolitic (anaerobic) activity for ATP production. Few capillaries are found in the vicinity of these fibers and because they contain little myoglobin they often referred to as white muscle. Although type IIB fibers are able to produce ATP rapidly, they fatigue very easily and as their high rate of ATP splitting quickly depletes the glycogen needed for glycolysis. These fibers generally are of large diameter and are thus able to produce great tension but for only short periods before they fatigue [22].

3.7. Fiber Types and Athletic Success

In low intensity activity, most muscle force is generated by ST fibers. As the intensity increases, FTa fibers are recruited and at the higher intensities, the FTb fibers are activated. The same pattern of recruitment is followed in case of long duration.

In elite athletes, the relative percentage of fiber types differs from that in the general population and appears to depend on whether the athlete's principal activity requires a

short, explosive, maximal effort or involves sub-maximal endurance [22]. Knowledge of the composition and use of muscle fibers suggest that athletes with high percentage of ST fibers might have an advantage in prolonged endurance events, whereas those with a predominance of FT fibers could be better suited for short –term and explosive activities [24].

Descriptive studies have demonstrated several interesting acts concerning the percentages of fast and slow muscle fibers found in humans. First, there are no apparent sex or age differences in fiber distribution. Secondly, the average sedentary man or woman possesses approximately 47%-53% slow fibers. Thirdly, it is commonly believed that successful power athletes (e.g., sprinters, fullbacks, etc) possess a large percentage of fast fibers, where as endurance athletes generally have a high percentage of slow fibers [19]. In the study of Tesch and Karlson [15], the athletes were examine during or at the end of their competitive season Both runners and kayakers possessed a greater percentage of ST fibers in the trained muscle compared with the untrained muscle. The %ST of the vastus was higher in runners than wrestlers, flat-water, kayakers, middle and long distance runners, olympic weight, power lifters and physical education students. Their data show a difference in fiber type distribution between the trained and non-trained muscles of endurance athletes. This pattern may reflect the adaptive response to long- term endurance training.

World champion in the marathon are reported to possess 93% to 99% ST fibers in their gastrocnemius muscles World - class sprinters, however, have only about 25 % ST fiber sprinters this muscle. The fiber composition of muscles in distance runners and sprinters is markedly different. However, it may be a bit risky to think we can select champion distance runners and sprinters solely on the basis of predominant muscle fiber type. Other factors, such as cardiovascular function, motivation, training and muscle size, also contribute to success in such events of endurance, speed and strength. Thus, fiber composition alone is not a reliable factor to athletic success [24].

It is generally, but not universally, accepted that fiber types are genetically determined. The genetically determined fiber typing may be responsible for the natural selective process by which athletes are drawn to the type of sports for which they are

determined by the nerve that innervates the muscle fiber. There may be some cortical control of these innervations that influences an athlete to choose the sport in which he or she is genetically able to excel [22].

3.8. Alteration of Muscle Fiber Types by Exercise Training

Recent investigations using improved techniques to study myosin isoforms have shown that rigorous exercise training results in alterations in muscle fiber types. Interestingly, both endurance training and resistance (weight) training result in a shift from a fast to a slower fiber type. Note, however, that the training induced changes in fiber type are often small and do not result in a complete conversion of Type IIB to Type I fibers and an increase in the percent of Type IIA fibers (IA). The transformation of a Type IIB into a Type IIA fiber is considered a fast to slow fiber shift because the movement is from the fastest fiber type (i.e., Type IIB) toward a slower fast fiber type (i.e., Type IIA) [19].

The relative proportions of the different skeletal muscle fiber types vary considerably between individuals. This large inter-individual variation may be consequence of genetic and/or training influence. Other possible factor behind inter-individual variation may be aging and sex. Glenmarc and Hedberg [27] were to investigate longitudinally whether the muscle fiber type composition changes over an 11-year period from adolescence to adulthood in a reasonably large group of subjects, including both women and men. In the fiber type composition was similar in women and men at the age of 16. With increased age there was a shift in fiber type distributions with a tendency to increase type I percentage and decreased type IIA +IIB percentages increased. A reverse shift in fiber type distribution with age was found in the men: type I percentage decreased and type IIA+IIB percentages increased. The fiber areas remained unchanged in both sexes. It is suggested that there is a sex related fiber adaptation to increased age. Sale and Macdougall [28] reported that percent of ST fibers in vastus lateralis increased after ~5 month of strength and endurance training in the young women and men. In the study of Hakkınen and Kraeme [29], they examined electromyographic activity areas of type I, II a and II b of vastus lateralis, the resistance training program (6 months) also led to significant increases in the mean fiber areas of type I elderly women and of type II in

women of middle and elderly groups, while the changes in the male groups did not reach statistically significant levels.

In order to investigate the time course of skeletal muscle adaptation in men and women Staron and Karapondo performed an 8-wk progressive resistance- training program for the lower extremity twice a week. Resistance training also caused a significant decrease in the percentage of type IIb fibers after 2 wk in women and 4 weak in men. These data maybe show that the muscles need not to be active for extremely long periods to cause an alteration in fiber type composition (type IIb→IIa). The time course for the alteration of the phenotypic expression of specific contractile proteins appears to be an adjustment that can occur after only a few workouts. According to their parameters, skeletal muscle adaptations that may contribute to strength gains of the lower extremity are similar for men and women during the early phase of resistance training and with the exception of fast fiber type composition, that they gradually. However one gender difference may be reflected in possible hormonal mechanism muscle. Growth for the men, increased testosterone and decreased cortisol levels favor an environment for increased protein synthesis [30].

Muscle fiber types in rats have changed in response to 15 wk of high - intensity treadmill training, resulting in an increase in ST and FTa fibers and decrease in FTb fibers. The transition of fibers from FTb to FTa and from FTa to ST was confirmed by several different histochemical techniques. Above studies indicate that training induced change in fiber type occurs in a stepwise fashion, which proceeds in the following order: Type IIb → IIa→I. That is, a Type IIb fiber cannot be converted to a Type IIa fiber prior to becoming a Type I fiber [19,24].

3.9 Muscle Fatigue

Short term, high intensity exercise or prolonged sub maximal exercise can result in a decline in muscle force production. This decrease in muscle force production and a reduced ability to perform work is known as fatigue [9,19]. Muscular fatigue has been defined as " the failure to maintain the required (expected) force or an ability to regenerate the original force in the presence of an increased perception of effort" [9,31].

Fatigue also has been classified as being either central or peripheral origin **(1) Central fatigue** is described as a reduction in neural drive or motor command to the muscle resulting in a decline in force or tension development [9]. Central factors in the study of muscle fatigue are those physiological processes that occur within the Central Nervous System (CNS). This includes the ability to generate a sufficient and appropriate central command for the task, faithful transmission of the command to the involved motor neuron pools and sustain activation of the muscle by the motor neurons [31].

The recruitment of muscle depends, in part, on conscious control. The psychological trauma of exhaustive exercise may consciously or subconsciously inhibit the athlete's willingness to tolerate further pain. The CNS may slow the exercise pace to a tolerable level to protect the athlete. Indeed, researches generally agree that the perceived discomfort of fatigue precedes the onset of a physiological limitation within the muscles. Unless they are highly motivated, most individuals terminate exercise before their muscles are physiologically exhausted. To achieve peak performance, athletes train to learn proper pacing and tolerance for fatigue [24, 31].

(2) Peripheral fatigue is defined as a decrease in the force generating capacity of the skeletal muscle due to action potential failure, excitation contraction coupling failure or impairment of cross-bridge cycling in the presence of unchanged or increased neural drive [9].

The cause of muscle fatigue varies and depends upon type of exercise performed. For example, fatigue resulting from high intensity exercise (e.g., sprinting 400 meters) appears to be due to an accumulation of inorganic phosphate and hydrogen ions within the muscle fiber. Accumulation of these metabolites interacts with the contractile proteins and reduces muscle force production. In contrast, fatigue resulting from prolonged exercise (e.g., running a marathon) may involve the failure of excitation – contraction coupling; this is likely due to reduction in the release of calcium from the sarcoplazmic reticulum. Reduced calcium release results in fewer myosin cross-bridges in the strong binding state (i.e., force generating state) and therefore reduced muscle force production.

The ability of the muscle membrane to conduct an action potential may be related to fatigue in activities demanding a high frequency of stimulation. Repeated stimulation of the sarcollemma can result in a reduction in the size and frequency of action potentials, however, shifts in the optimal frequency needed for muscle activation preserves force output. Under certain conditions an action potential block can occur in the t-tubule to result in reduction in calcium release from the sarcoplazmic reticulum [19]

4. FATIGUE IN ELOCTROMYOGRAPHY

Electromyography records changes in electrical potential of a muscle when it is caused to contract by a motor nerve impulse. Each efferent alpha – motoneuron (or motor neuron) innervates a number of muscle fibers. The motor neuron forms a neuromuscular junction, or motor end plate. The term motor unit is used to refer to a motor neuron and all of the muscle fibers that it innervates, which can spread over a wide area of the muscle. The motor unit can be considered as the fundamental functional unit of neuromuscular control. Each nerve impulse causes all of the muscle fibers of the motor unit to contract fully and almost simultaneously. The stimulation of the muscle fiber at the motor end plate results in a reduction of the electrical potential of the cell and spread of the action potential trough the muscle fiber.

A muscle Fiber Action Potential (MFAP), which is a fundamental component contributing to a detected EMG signal, results from the propagation of an action potential along the excitable membrane of a muscle fiber [32]. The Motor Unit Action Potential (MUAP) can be thought as the summation of the individual potentials of all the muscle fibers comprising a single motor unit [33]. The MUAP trains that contribute to an EMG signal provide information regarding the temporal behavior and morphological layout of motor units that are active during muscle contraction. Such information can assist in the diagnosis of various neuromuscular disorders and in the development of a better understanding of healthy, pathological, ageing or fatiguing neuromuscular systems [32].

Surface and intra-muscular electrodes have been used mainly to detect and analyze myoelectric activities of individual muscles. Studies indicate that there was gross variation between individuals when needle electrodes were used because of different depths of muscle, the changing position of the needle tip within some muscles (e.g. quadriceps). SEMG measurements is an excellent method of obtaining summated activity, can be used during maximum voluntary contraction, can be repeated as often as necessary and carries no risk of cross-infection and surface electrodes provide good co-operation of young children with the absence of needles. Therefore, surface electrodes have several advantages, for example, noninvasive, easy to adhere to the skin and to detect the total

activities of the muscle, they have been widely used to investigate neuromuscular functions of the extremities and/ or body trunk of healthy subjects as well as patients [34,35].

The kinesiological disciplines are the major group of SEMG users regarding voluntary contractions. Clinical evaluations require movement analyses techniques suitable for detecting modifications and functional compensation due to the pathologic situations and their evaluation with treatment. SEMG is a very promising technique in this regard because it can provide, in a noninvasive way, information about the global activity of the muscle under the study [36,37]. The rehabilitation sciences are the largest field of kinesiology, which SEMG is used [27,38,39,40,41]. Closely related is the study of labor circumstances and ergonomics. During recent decades, there has been a remarkable change in the characteristics of work loads in industry from heavy dynamic muscular loads to highly repetitive light work or light static loading of the neck and shoulder muscles [37, 42]. In these work circumstances, SEMG used to estimate the activity of individual muscles in terms of their contribution to complex, mostly deviant and / or harmful co-ordination patterns and associated reactions to fatigue [36,37]. Exercise and sport physiologists also routinely use SEMG in their scientific work [36,43,44,45]. In this area, SEMG has been used frequently to study motion techniques or skills, body position, material or equipment used, training-methodology and learning processes in sports and ergonomics. In addition to this, co-ordination aspect in terms of movement optimization, as well as muscle fatigue, is estimated by means of SEMG parameters. It is well recognized that the measured parameters or variables should predict performance or function in an objective manner.

The SEMG signal detected during a voluntary muscle contraction is realization of a non-stationary stochastic process [46,47]. Any variable of the signal, computed over a given time interval, is intrinsically an estimate of the true variable with an associated variance and bias, which depend on the window length and on the estimator used. A specific feature of the signal may in fact be indicated by a number of different estimators. For example, amplitude may be indicated by the average rectified value or the root mean square value while spectral features may be value while spectral features may be indicated by the mean spectral frequency or the median spectral frequency [46].

Most studies of neuromuscular activity and fatigue have evaluated isometric contractions [1,6,7,8]. But isometric contractions may not be representative of muscle activity and fatigue development during human locomotion [9]. Although the analysis myoelectric signal detected under stationary conditions have not yet been thoroughly explored in clinics, it is evident that isometric contractions are not usual in most daily activity [47]. In particular, movements in sports and most of the labor activities are fast and dynamic. Therefore, when attempting to evaluate the degree of muscular fatigue during dynamic exercises, it must be established a technique for reliably measuring EMG signals and also must evaluate the detected signals appropriately [11,13].

During dynamic exercises, the relative position of detection electrodes with respect to the underlying muscle changes with time. This change may alter the waveform of EMG signals and their spectral characteristics. Moreover, during fast dynamic exercise, phasic MU is activated, compared with tonic MU activated during static contractions. Muscle fiber conduction velocity (MFCV) is related to the size principle of MU and tends to be faster for larger MU recruited at higher contraction force. Consequently, MFCV during dynamic exercises may become much higher than the values obtained during static contractions. Therefore, before estimating muscular fatigue, we must determine the influence of contraction force and contraction speed, on the EMG variable [13].

In the previous studies, in the investigation of fatigue was searched by using the isometric contraction, because of the easiness of experiments and the spectral analyses. For example, Hagberg showed that the endurance time for sustained isometric exercise (right angle elbow flexion) and dynamic exercise (continues concentric and eccentric elbow flexions) was measured at different contraction level nine male volunteers. There were significant differences between the regressions of endurance time vs. the contraction level for the sustained isometric exercise. The development of muscle fatigue was well correlated to changes of the myoelectric Root-Mean-Square amplitude and the MNF differences in exercise did not significantly effect the relation between the time constant of the MNF decrease and the endurance time [14].

In the last ten years, the complexity of the SEMG has led to the development of a multiplicity of measurement protocols and processing methods. Based on theoretical

models, and understanding of the information carried by this signal requires a description of its characteristics using several parameters. This characteristic is supposed to provide useful information neuromuscular function. Some researches about muscle fatigue, which were made with dynamic (eccentric, concentric and isokinetic actions) exercise, are presented below the technology review.

Linnamo et al. [48] examined acute effects of explosive (EE) and heavy resistance (HRE) concentric leg press exercise on muscle force, EMG from vastus medialis and blood lactate from vastus lateralis. They found that MNF and MDF were higher during EE than during HRE. MNF and MDF increased during EE as the exercise progressed (%40, %55 and %70), where as during HRE no change or even slight decreases were observed. Signs of fatigue after pure concentric work were not observed after EE, and even after HRE, possibly due to the small range of motion and short duration of action time, the fatigue was not extensive.

At the study of Gerdle and et al. [49], twenty-one healthy volunteers performed 100 isokinetic knee extensions at 90 degree. EMG signals were recorded from the vastus lateralis, rectus femoris and vastus medialis of the right high by surface electrodes. MNF and RMS of the EMG together with peak torque were determined for each contraction. At he individual level MNF generally in contrast to Root Mean Square (RMS) showed good criterion validity with respect to biomechanical fatigue during dynamic maximum contractions.

Ament and et al. [50], EMG median power frequency of the calf muscles was investigated during an exhausting treadmill exercise. The exercise was an uphill run, the average endurance time was1.5 min. Median power frequency of the calf muscles declined by more than 10% during this exercise.

Jammes and colleagues [51] examined the changes in M wave and SEMG (RMS and MDF) in vastus lateralis during progressive dynamic exercise above the aerobic threshold in the well-trained cyclist and untrained university students. No significant MF changes were measured during exercise and recover RMS value increased progressively during exercise in their subjects.

Conwit et al. [1] who examined motor unit changes during the development of fatigue in healthy subjects. Automated decomposition - enhanced spike - triggered averaging was used to characterize motor unit size and firing rate in dominant in the vastus medialis during maintained contractions at %10 and 30% of MVC. Surface electromyogram and surface detected motor unit amplitude increases during sub-maximal MVC fatiguing contractions, while mean firing rates decreased. A motor unit index, indicating the degree of motor unit pool activation, increased similarity to motor unit action potential amplitude (S-MUAP) size, implying that new and larger motor units were recruited to maintain the contraction. Repeated contractions led to earlier motor unit changes and fatigue.

Eight untrained volunteers performed two bouts 50 voluntary maximal eccentric contractions of the knee extensors of one leg 3 weeks apart. During maximal voluntary isometric contractions performed at intervals after each bout, EMG mean power frequency declined after bout one, whereas integrated EMG did not change after either bout. These results suggest that unaccustomed eccentric contractions produce a temporary reduction in mean muscle activation frequency during subsequent maximal isometric contractions [52].

Felici and colleagues [53] suggest that MDF is suitable for the early and non-invasive detection of SEMG changes induced by eccentric exercise (EC). Six sedentary adult subjects performed two rounds of 35 EC with the biceps brachii of non-dominant arm, the other arm being used as control for five consecutive days. They found that firstly, spectral parameters are less sensitive to error introduced by electrodes repositioning than time domain parameters, and are more sensitive to EC-induced SEMG changes than RMS. Secondly, a significant shift of MDF power spectra towards lower frequencies at 80% and 50 % was evident as early as after EC on the exercised arm and MDF follows the evaluation of muscle damage.

In the study of Linnamo and colleagues [54], eight male subjects performed EE and CE consisting of 100 maximal eccentric and concentric actions with elbow flexors during two separate exercise session during the recovery period of 1 week. They found that MDF decreased immediately after both exercises, which may be at least partly related to elevated blood lactate concentration.

Kay and colleagues investigated the neuromuscular fatigue profiles. Twelve subjects performed isometric concentric, eccentric maximal voluntary contractions and 100 s endurance trials on an isokinetic dynamometer. There were no significant differences between eccentric, concentric and isometric peak torque output during maximal contractions and their data demonstrated distinct neuromuscular fatigue profiles for different types of muscle contraction. Whereas eccentric activity was largely fatigue resistant, isometric and concentric contractions displayed different neuromuscular fatigue profiles [9].

4.1 EMG Changes of Power Spectrum During Fatigue

Surface electromyographic signal processing techniques allow a good assessment of muscle activity. The amplitude and frequency characteristics of the SEMG have been used for quantification of muscle fatigue [55]. However, SEMG signal depends on a large number of physiological factors such as MFCV, the recruitment process is varying the number, firing rates, sizes, types and synchronization of motor units, the action potential propagation velocity, volume conductor geometry changes, muscle length and muscle architecture. All factors change during a fatiguing contraction and EMG signals sensitive to all these factors. Furthermore, experimental factors affect EMG signal such as positioning of electrodes with respect to innervations zone and tendon and electrode-to-muscle distance [7,17,55,56,57].

Most of the studies [7,54,58,56,36,59,14,60] stated that exercise - induced fatigue leads to decreased strength output accompanied by decreases in electromyographic activity measured from the muscles in MVC and prolonged exercise. During sustained fatiguing both isometric and dynamic contractions, the EMG frequency spectrum is observed to shift towards the lower frequencies. These spectral changes are generally progressive decrease in muscle fiber conduction velocity (MFCV), which also contributes to an increase in the amplitude of the surface EMG signal.

MFCV is a basic physiological parameter that greatly affects the myoelectric signal. Mean and median frequencies of an EMG power spectrum are often used as indicator a of muscle fatigue. In recent years, MFCV has also been used as a fatigue indicator. Sakamoto

and Mito [61] founded that the MFCV at different electrode locations declined gradually during the loads of sustained isometric contractions of 30, 50, and 70% of the MVC. The degree of the decrease of the MFCV was extremely intense during a sustained contraction of 70 % MVC for biceps brachii in the ten healthy male. In the same manner, Broman et al. showed the consistent decrease of average myoelectric spectral parameters in the same muscle (tibialis anterior) during a high-force-level (80% MVC) isometric contraction [62]. The exact cause of this decrease has not yet fully established, although, it has been suggested that a build up of hydrogen ions and acidic metabolites, such as pyruvic and lactic acid, causes a decrease in membrane excitability, which is directly linked to the fiber conduction velocity during the muscle fatigue. As conduction velocity decrease, the observed motor unit action potentials expand along the time axis, causing the frequency content of the EMG signal to shift toward the lower end of the spectrum [61,62,63]. In contrast, some researchers have studied the dependence of CV and force. They found an increase of MFCV during isotonic [13,64] and isometric [6] contraction with force for biceps brachii, vastus lateralis and tibialis anterior muscles. The increase in CV is considered to be partly due to the size principle of motor units (MU) in that larger MU with higher recruitment threshold tending to have faster CV. The second cause may be that muscle fiber shortening during contraction relates to a lower inner electrical resistance or a change in membrane channel configuration, resulting in a higher MFCV. The relationship of muscle fiber shortening and CV is controversial.

On the other hand, Increase in MDF and MNF with increase in torque output were reported steady isometric contractions as well as in the case of linearity increasing (or ramp) isometric contractions [12,65,66,67] and dynamic contractions [48,68]. The relationships consists of a shift MDF and MNF parameters towards to higher frequencies as a result of the recruitment of progressively larger and faster motor units with correspondingly higher conduction velocity of the active muscle fibers [12,65,67,69]. Researchers found that the increasing average conduction velocity during orderly recruitment of motor units was the major contributor to variations in the MDF, whereas a change of the firing rate had a negligible effect, establishing the relationships between orderly recruitment and increasing MDF [65,70,71].

Daud and Walsh found that the longest muscle length is associated with the lowest frequency components with non-isometric contractions in the normal male subjects and they showed a greater reduction in EMG center frequency at shortest muscle length relative to the longest muscle length for the biceps brachii [72]. In contrast to this investigate, several studies show that the velocity of excitation propagation decreases with the muscle elongation and a highly significant linear relationship was observed between the relative increase in measured muscle length and relative decline in conduction velocity and MDF for the vastus lateralis and biceps brachii [12,57,73]. Besides, the rate of chance of MDF was not affected by electrode location. Estimates of conduction velocity were most stable in a region between the distal tendon and the adjacent innervation zone. This region also provided the best linear fit when comparing conduction velocity to MDF estimates [74].

Muscle temperature can affect conduction velocity [6] and can be affect the frequency component of power spectrum. Although it has been show that MNF decreased due to cooling but remained unchanged with heating [48]. The contractile properties of a muscle also become slow when muscle temperature is reduced. However, Bigland et al. found that in the case of cooled muscles, there was no significant change in the rate of motor neuron firing [75]. Zhou et al. show that the increased muscle temperature might contribute to 20-25 % of the electromechanical delay elongation found during the fatiguing intermittent isometric exercise and MFCV was impaired after the fatigue exercise while the muscle temperature was elevated [76]. Therefore muscle temperature is one of the important factors that can affect power spectrum in the fatiguing contractions.

Another important parameters; inter-electrode distance and sampling rate which affect of power spectrum. Melaku et al. [77] demonstrated that there is a significant effect of muscle contraction (50 and 80% MVC) and inter-electrode distance on the RMS value of the SEMG recorded from the biceps brachii muscle. Larger inter-electrode spacing results in an increase in the magnitude of the RMS of the SEMG then would smaller separation. Sadhukhan and et al. [78] showed linear relationship between sampling rate and the MNF. But, there was no distinct effect of sampling rate on MNF and RMS of digitized signal.

It is stated that the position of electrodes along active muscle fiber of finite length affects the power spectrum as well as the sensitivity of MNF and MDF to variation of propagation velocity and duration of intracellular action potential. Hogrel, et al. [79] observed that the power spectral density of the SEMG is modified according to the electrode location, not only in its initial characteristics but also in its changes during a fatiguing effort.

4.2 Frequency Analysis

The electrical activation of the muscle tissue during voluntary contractions can be registered using SEMG. Root Mean Square (RMS) and Mean Frequency (MNF) or Median Frequency (MDF) is commonly used to describe signal energy and frequency content of the signal, respectively. The behavior of the surface EMG during various protocols of fatigue has been extensively investigated generally during static contractions [17,22,53,79].

It has been proposed that the RMS and MDF provide information relative to the number and location of the active motor units, the recruitment of motor units, the shape of the motor unit action potentials, the mean firing rate of the individual motor units, and the extent of superposition of action potentials from concurrently active motor units [53]. Because there is a linear relation ship between the median frequency (MDF) computed from the power spectrum and the average conduction velocity of recruited muscle fibers, the MDF is at times used as an estimator of the muscular conduction velocity. The MDF generally is can be used to study their patterns of recruitment during isometric contractions performed at different force levels [80]. However there is an apparent shortage of information concerning the validity of MNF or MDF at the individual level during dynamic contractions. The question of validity is complex as pointed out by some investigators. Criterion validity can be determined by correlating the variables under investigation with a gold standard, which is considered as the "truth'. At group level some studies of maximal or high submaximal levels indicate validity between MNF or MDF and output. However, some researches based upon static contractions, strongly questioned that MNF or MDF could be applied during dynamic conditions both for individual analysis and group analysis [22].

4.2.1 Mean and Median Frequency

To obtain the power density spectrum (P) of the EMG signal, calculation is performed using the Fast Fourier Transform (FFT) algorithm and the muscle fatigue was estimated by means of FFT after windowing with EMG signal the Hanning or Hamming window [37,56]. De Luca et al. [82] have investigated various parameters of the power density spectrum and found that the median and mean frequency parameters are two most reliable with respect to frequency compression. As a MDF shift due to the muscle fatigue, the MDF of power spectrum curve into two equal parts. This condition may be stated as mathematically:

$$\int_0^{f_{med}} P(f)\,df = \int_{f_{med}}^{\infty} p(f)\,df = \tfrac{1}{2}\int_0^{\infty} P(f)\,df \qquad (4.1)$$

The MNF of the power spectral density P (f) is defined in below:

$$f_{mean} = \frac{\int_0^{\infty} f.P(f)\,df}{\int_0^{\infty} P(f)\,df} \qquad (4.2)$$

Where, the median frequency (MF), P (*f*) is power spectral density in the EMG power spectrum estimated by FFT method. The majority of the literature [47,60,67,81] is stated that MDF and MNF (Figure 4.1) [82] is most reliable spectral parameter in monitoring changes in the muscle fiber propagation, muscle temperature, muscle fatigue and muscle fiber type. In addition to this, researches are demonstrated that the power spectrum of the EMG signal was found to shift toward the lower band during prolonged muscle contraction when the localized muscular fatigue occurs.

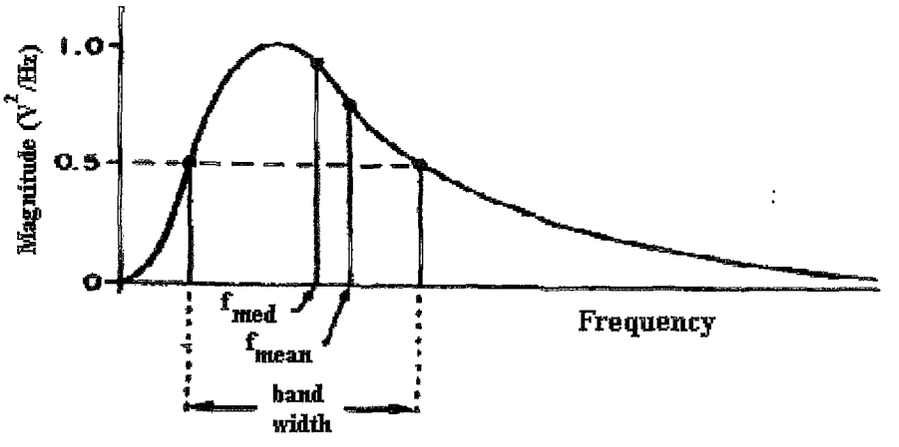

Figure 4.1 An idealized version of the frequency spectrum of the EMG signals. Three convenient and useful variables: the median frequency $f_{med;}$ the mean frequency, f_{mean}; and bandwidth are indicated [82].

5. EXPERIMENTAL METHODS

5.1. Test subjects

The subjects are composed of a total of ten healthy female athletes between 16-21 years of age. They are all national rowers in Turkey. All subjects attended the study voluntarily and gave consent prior to the study. Demographic data of subjects are presented in Table 5.1 and statistical values are showed in Table 5.2. The athletes were examined during or at the end of the competitive season. Therefore, they were all in fit condition.

Table 5.1

Subjects Demographic Data

		Age	Weight	Height (cm)	Years	Branch
1	**Bur**	23	60	168	3	Rowing
2	**Cey**	16	54	162	3	Rowing
3	**Ebr**	17	65	169	3	Rowing
4	**Fat**	20	59	172	5	Rowing
5	**Hal**	19	54	160	5	Rowing
6	**Hav**	19	55	165	3	Rowing
7	**İre**	22	60	175	7	Rowing
8	**Mah**	17	57	172	3	Rowing
9	**Pin**	19	54	167	3	Rowing
10	**Zeh**	22	61	173	6	Rowing

Table 5.2

Statistical Values of Subjects Demographic Data

	Number	Minimum	Maximum	Mean	Standard Deviation
AGE	10	16,00	23,00	19,40	2,36
WEIGH	10	54,00	65,00	57,90	3,72
HEIGH	10	160,00	175,00	168,30	4,90
VAR	10	3,00	7,00	4,10	1,52

The Vastus Lateralis (VL) muscle of the dominant leg was chosen for the recordings. Although, in all subjects the dominant extremity was the right leg, for only one

subject (Ebr), the experiment was carried out with the left leg because she had a meniscus injury in her right leg. The VL muscle particularly has been chosen because of its special morphology and superficial location suitable for SEMG measurements [13,17,79,83].

This study was conducted at the Department of Physiology of Istanbul Medical School. Before the testing began, the subjects were given details concerning the protocol of the test. Their verbal permission was taken and test applications were applied. The subjects were informed of the purpose, the protocol of experiment and practiced for the voluntary contraction before the tests.

5.2. Testing Protocol

Experimental set up was designed in accordance to the rowing sport [84]. Subjects were seated in a proper chair to enable adequate and comfortable fixture. While the hip joints for all the subjects were brought to a 100° flexion, the knee joints were brought to a 90° flexion. The range of the knee joint angle during the movement was set from 90 to 105° for each subject. This 15° range of motion of the knee joint was kept the same for each repetitive contraction.

Prior the experiment, the Maximum Voluntary Contraction (MVC) force was determined using the instrumentation set up within a few trials. The maximal value of MVC was used as the reference value to determine a load of 80 % of MVC for each subject. For every contraction the subjects managed to close the spring, which while at rest had strength of 3000 N/m. As a result each contraction closing distance of the spring was in the range of at 4-5cm (Figure 5.1).

The fatigue test with 80% MVC consisted of two identical tests. First, the subjects performed repetitive auxotonic knee extension (30/min-60/min) to maintain force as long as possible (till exhaustion). Exhaustion was defined as the point, when subjects were no longer able to sustain the required power output to close the spring at 80% MVC. After a five-minute rest, the exercise protocol was repeated. During all procedures, the same investigator did verbal encouragement during the tests for all subjects.

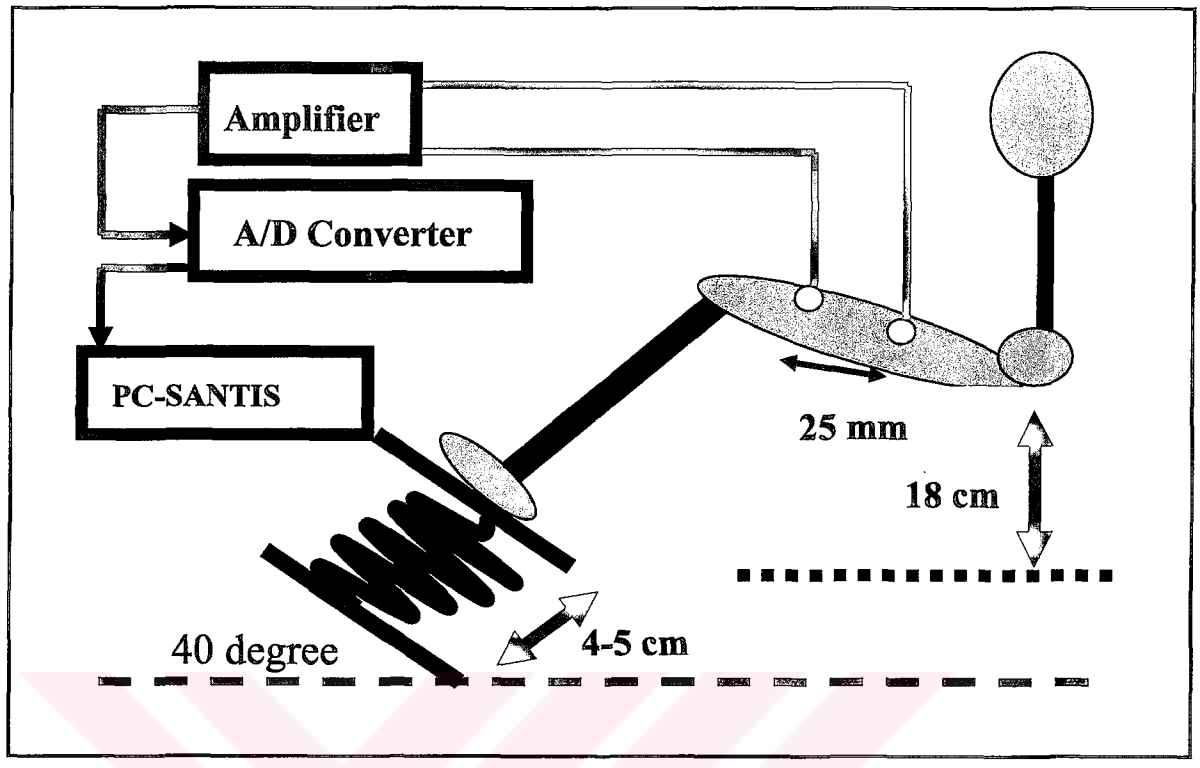

Figure 5.1 Schematic illustrations of the apparatus for the experiment; The VL muscle is represented with a large oval shape. Distance and angle values are chosen according to rowing ergonomics.

5.3. Measurement of Perceived Exertion

Borg's category-ratio scale (CR-10) was used to measure the perceived muscle exertion. The subjects have to rate their perceived musculoskeletal exhaustion ranging from 0 to 10. It is shown CR-10 in Table 5.3 This scale may be a useful tool in both clinical and research settings for evaluating perceived exertion [85]. Therefore Borg's category-ratio scale (CR-10) was used to evaluate fatigue subjectively in comparison with objective EMG measurements in recent studies [42,85,86,87]. The use of this scale has been found to correlate positively with increasing levels of lactate accumulation. Furthermore, qualitative changes in motor unit recruitment may be perceived. Before the experiments, detailed information about this scale was given to the subjects. During the dynamic contractions, subjects were asked to "think about the feelings in their VL muscle". The subject from the numerical 10-point category chose fatigue degree in accordance to their perceived exertion. Subject's degree of fatigue and the time of fatigue were also recorded during the tests. Fatigue points were marked on the "frequency-time

graphics" of MDF and MNF changes over time as drawn in run Figure 6.1. At these time points the mean of ten nearest consecutive contractions were taken for the calculation of spectral parameters.

Table 5.3

Borg's Category-Ratio Scale (CR-10)

BORG'S CATEGORY RATIO SCALE	
0	Nothing at all
0.5	Extremely weak (just noticeable)
1	Very weak
2	Weak
3	Moderate
4	
5	Strong
6	
7	Very strong
8	
9	
10	Extremely strong
*	Maximal

5.4. Recording of EMG

EMG data were recorded from the VL muscle with silver-silver chloride (Ag-AgCl) surface disk electrodes. The diameters of the disk electrodes were 10 mm, and the inter-electrode distance (center to center) between the bipolar electrodes was set to 25 mm. The reference electrode was placed over the tuberositas tibia of the left leg, according to the recommendation by SENIAM [88]. The European concerted action SENIAM (surface EMG for a non-invasive assessment of muscles) was started in 1996. Besides having the general; goal of creating more collaboration among the various European groups, the specific goal was formulated to develop recommendations on key items to enable more useful exchange of data obtained with SEMG, including sensors, sensor placement, signal processing and modeling. Electrodes were placed longitudinally in the direction of muscle

fibers approximately halfway from the motor point area to the distal part of the muscle by observing muscle contraction during knee extension.

In order to ensure the same localization throughout the exercise sessions, the position of electrode array was carefully marked on the skin to prevent displacement. Before the electrodes were placed, the skin was abraded, shaved and cleaned with alcohol in order to reduce impedance between the electrode and skin. We then applied a minimal amount of conductive paste. The electrodes were attached to the leg with adhesive tape.

The SEMG signals were directly fed to a computer-driven data acquisition system. The SEMG signal was increased 1000 times using a differential amplifier and filtered through an analog band pass filter between 5-500 Hz. Signals were digitized by a 12-bit A/D (analog-to-digital) converter and stored on the hard disk of the PC. It is well known that the bandwidth of the EMG signals from surface EMG signals is less than 1000 Hz. The EMG signals were therefore sampled at a rate of 2000 Hz. Noise during the experiment was eliminating by using a Notch filter at 50 Hz. Before each recording the transformer send off sinusoidal calibration signal with 100 mV amplitude at 8 Hz. Data analysis was performed off-line using MATLAB 6.0 software. The power spectrum was derived from the raw EMG signal after convolving with a Hamming windowing (to reduce the side-lobe leakage) and using the Fast Fourier Transform (FFT) algorithm. The median frequency (MDF) and the mean frequency (MNF) of the power spectrum were computed from the EMG signal for the active phase of the contraction cycle. For each contraction during the experiment electrophysiological data were analyzed in time domain with consecutive 200 ms windows. This short duration was chosen in order to remain in a wide-sense stationary region of the EMG signal.

6. RESULTS

Two tests were performed separated by an interval of 5 minutes. The first test lasted until the athlete was fatigued until exhaustion. After the break the second test was performed exactly with identical conditions.

The period of time that each subject could continue the experiment varied. Also first and second trials of each experiment had different period of time. Generally, the subjects could continue second experiment for a longer period the same with %80 MVC.

The horizontal axis shows the time the subjects can maintain 80 % maximum voluntary contraction (MVC) during the tests.

The vertical axes show the Median Frequency (MDF) and Mean Frequency (MNF) during the tests.

The circular murky indicate the corresponding Borg category Ratio Scale (CR-10) fatigue score. The graphs start with degree 0 and continue stepwise by 1 point. For each level of fatigue 10 consecutive contractions were used to estimate the MDF (or MNF) value for that degree. Unless, otherwise specified the Borg Scale levels of Table 5.2 are in the same sequence as drawn in run Figure 6.1.

If we look at the graphs, at time points when subject notify their fatigue level according to the Borg Scale, we observed periodic increases and decreases of MDF and MNF values. These increases and decreases of MDF and MNF values did not show any consistent pattern and were independent of subjective feelings of fatigue.

The graphics show all the experiment performed in this study. The following 40 figures depict the 20 MDF and 20 MNF studies analyses of 10 subjects.

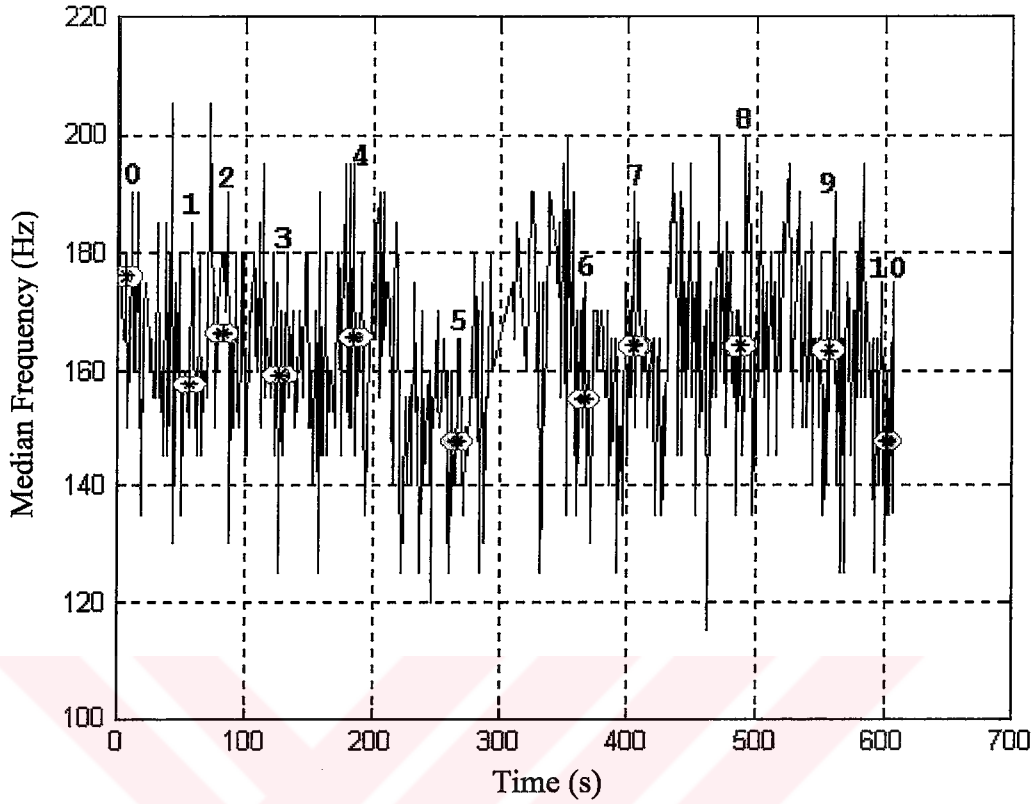

Figure 6.1 MDF of subject Bur_1 for experiment I.

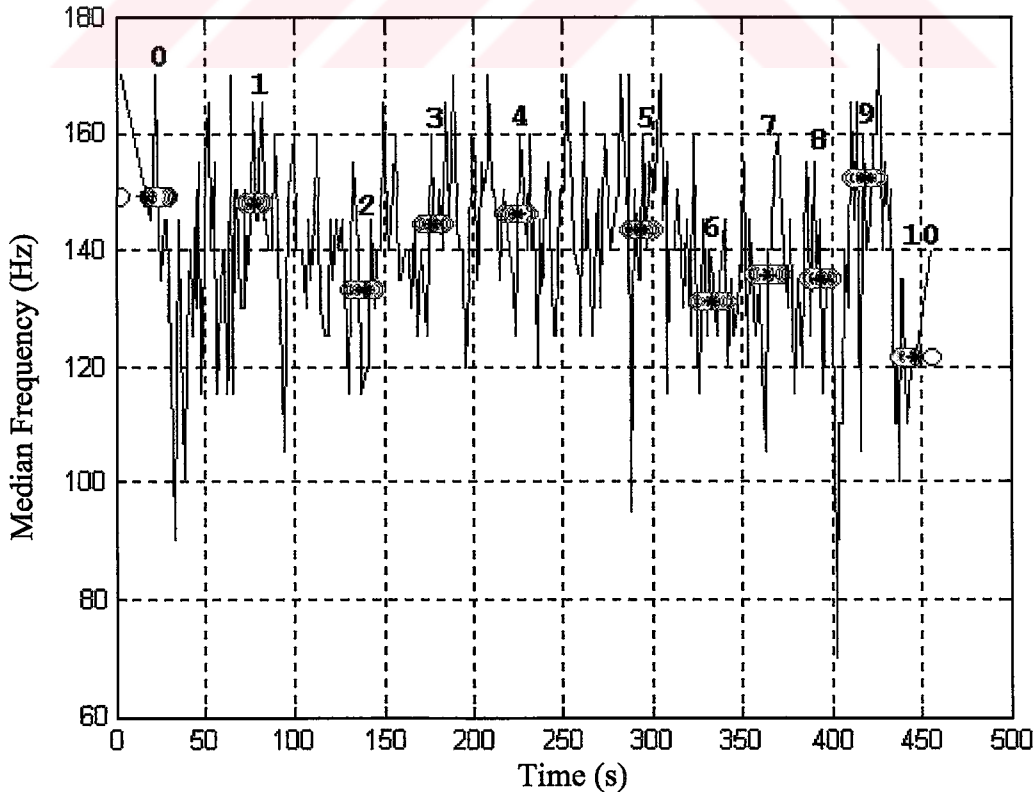

Figure 6.2 MDF of subject Bur_2 for experiment II.

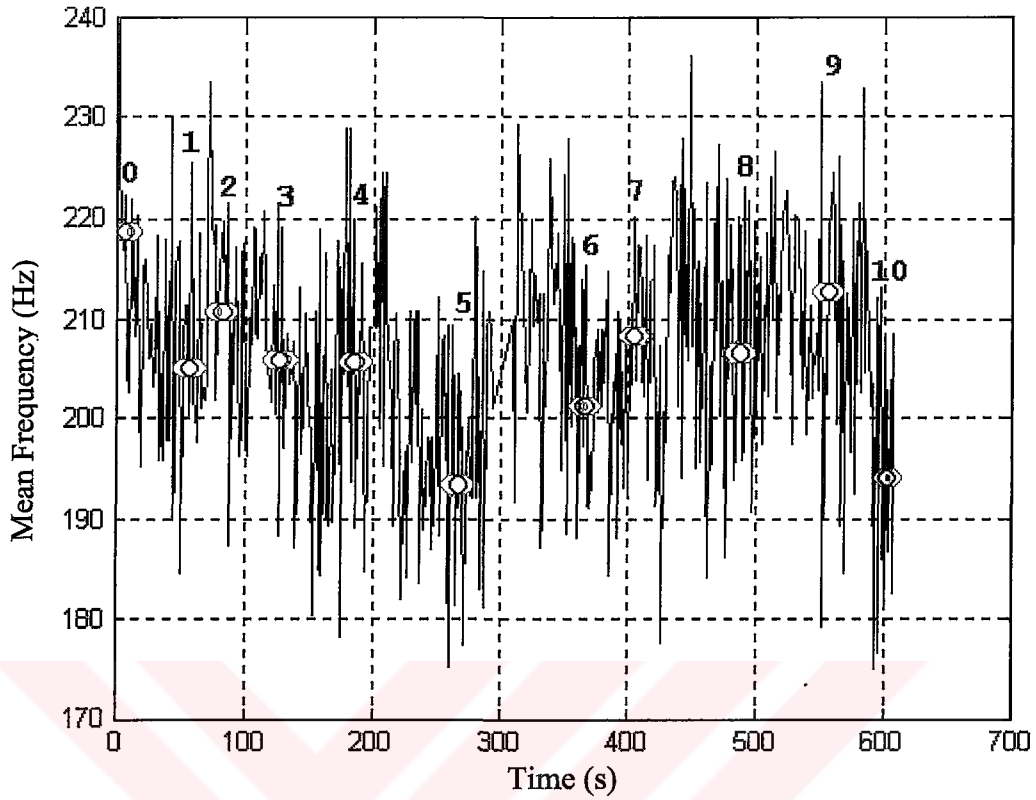

Figure 6.3 MNF of subject Bur_1 for experiment I.

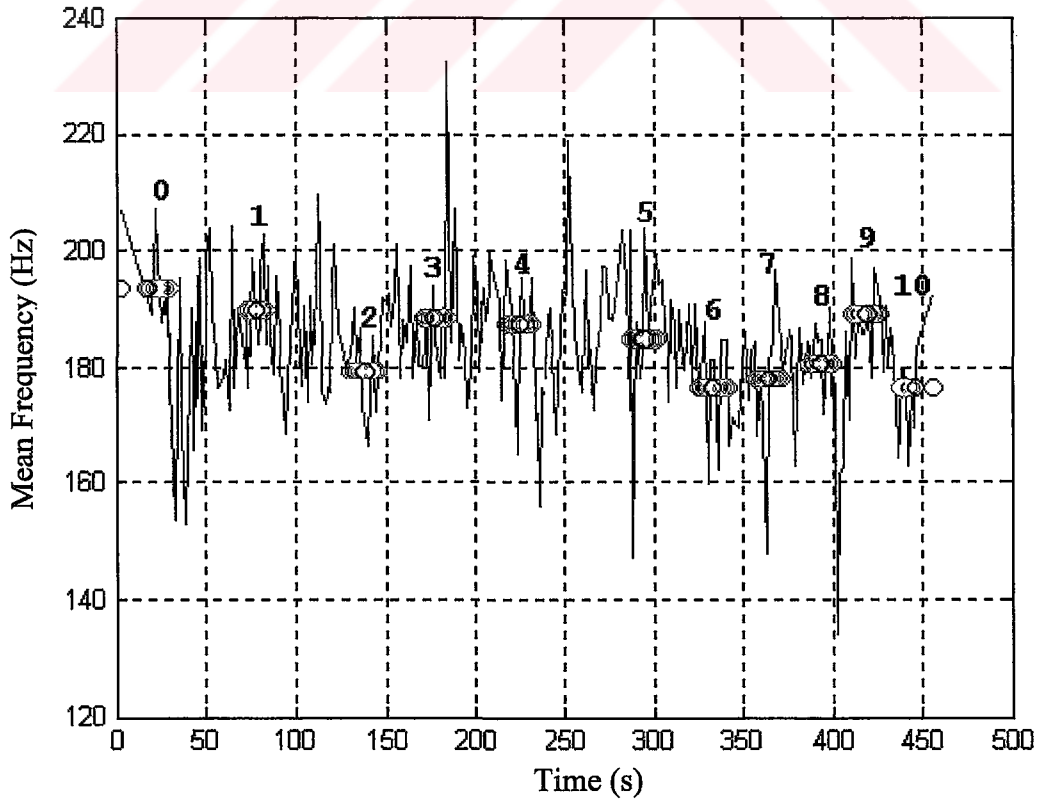

Figure 6.4 MNF of subject Bur_2 for experiment II.

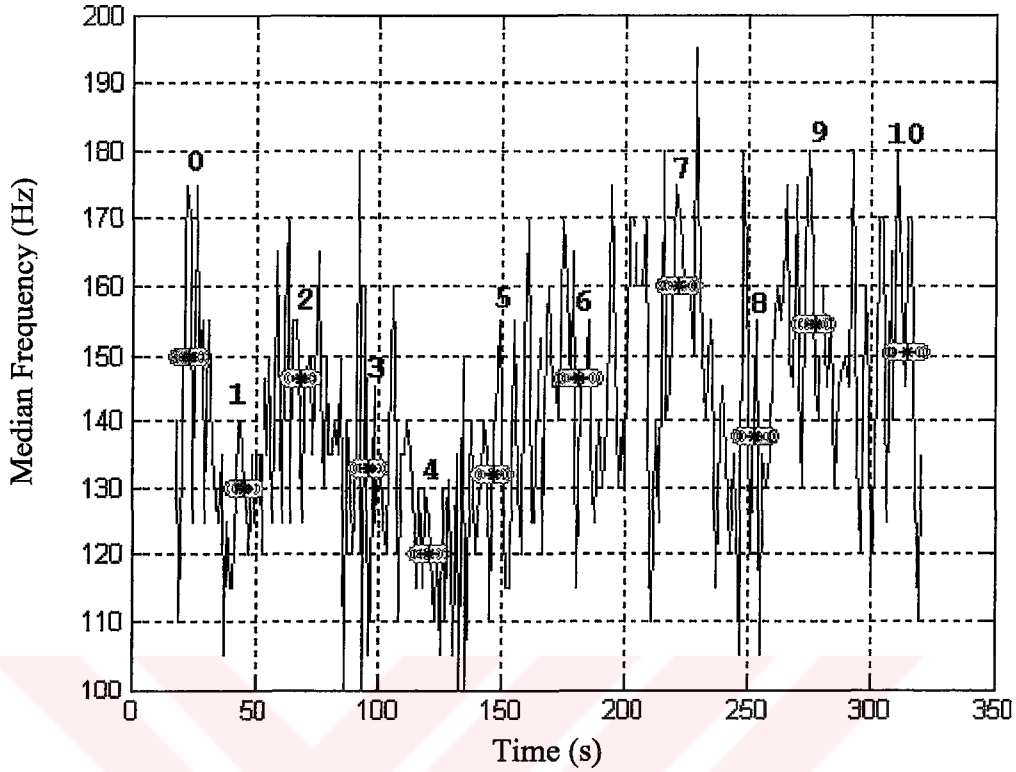

Figure 6.5 MDF of subject Cey_1 for experiment I.

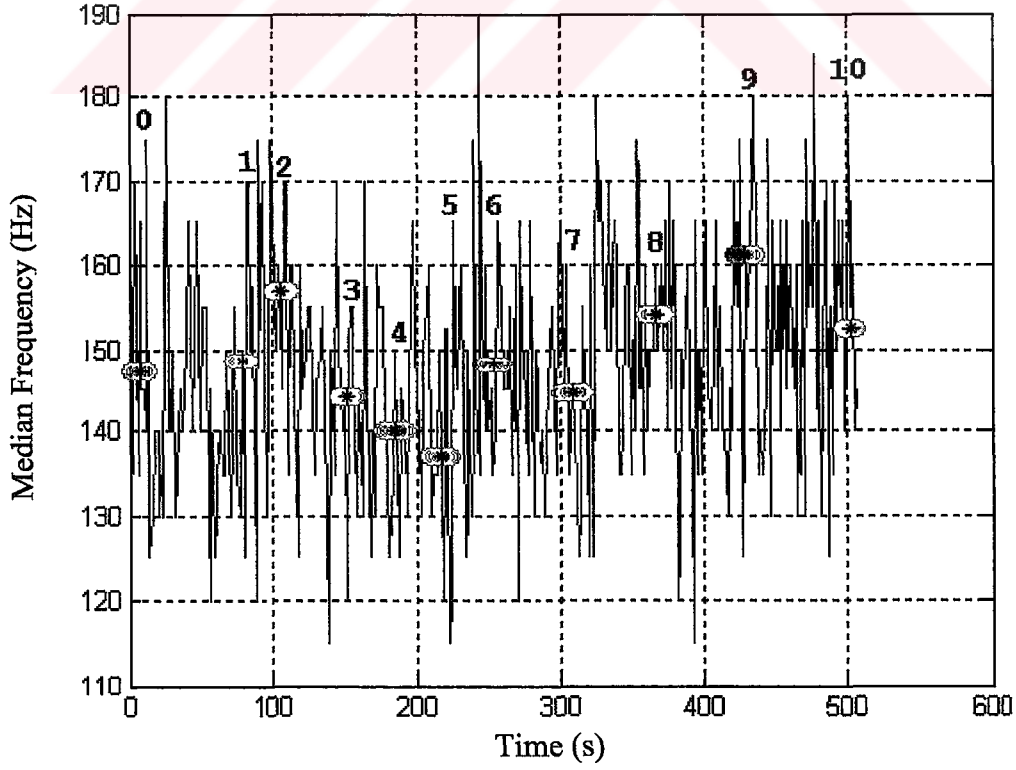

Figure 6.6 MDF of subject Cey_2 for experiment II.

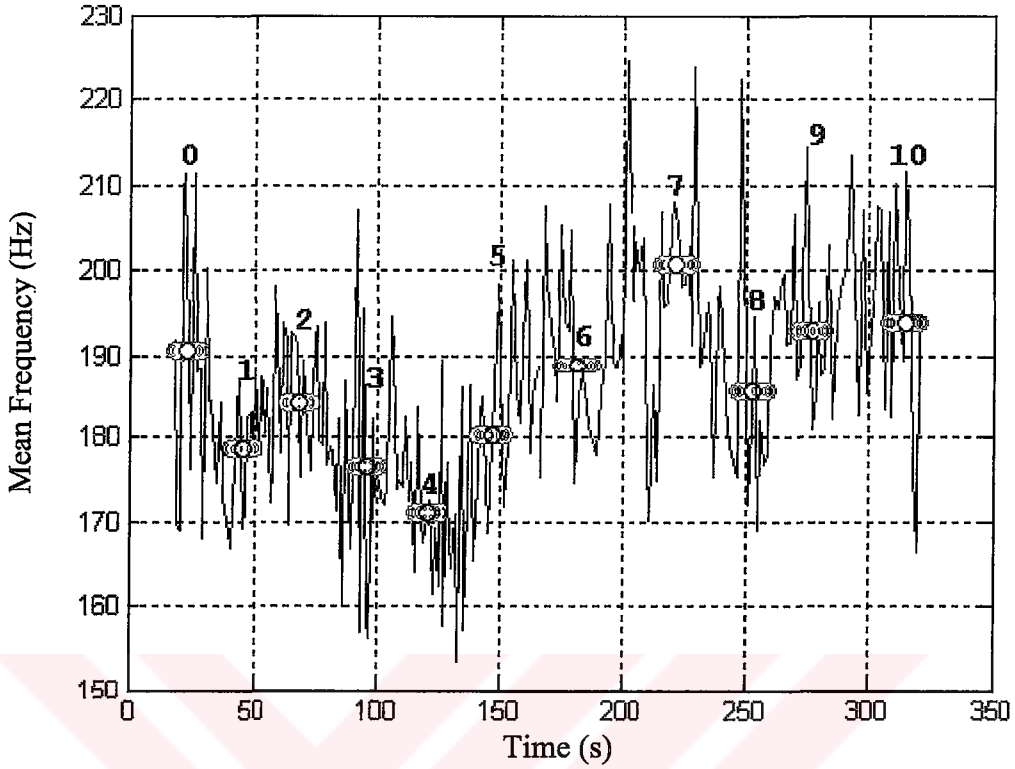

Figure 6.7 MNF of subject Cey_1 for experiment I.

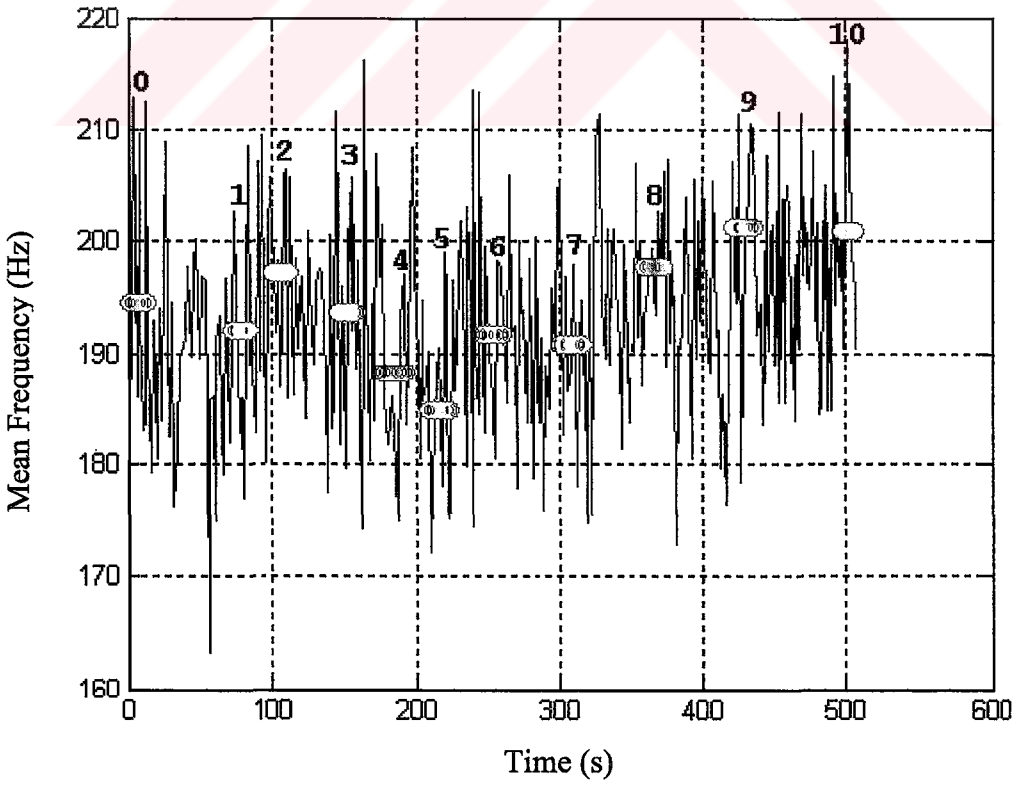

Figure 6.8 MNF of subject Cey_2 for experiment II.

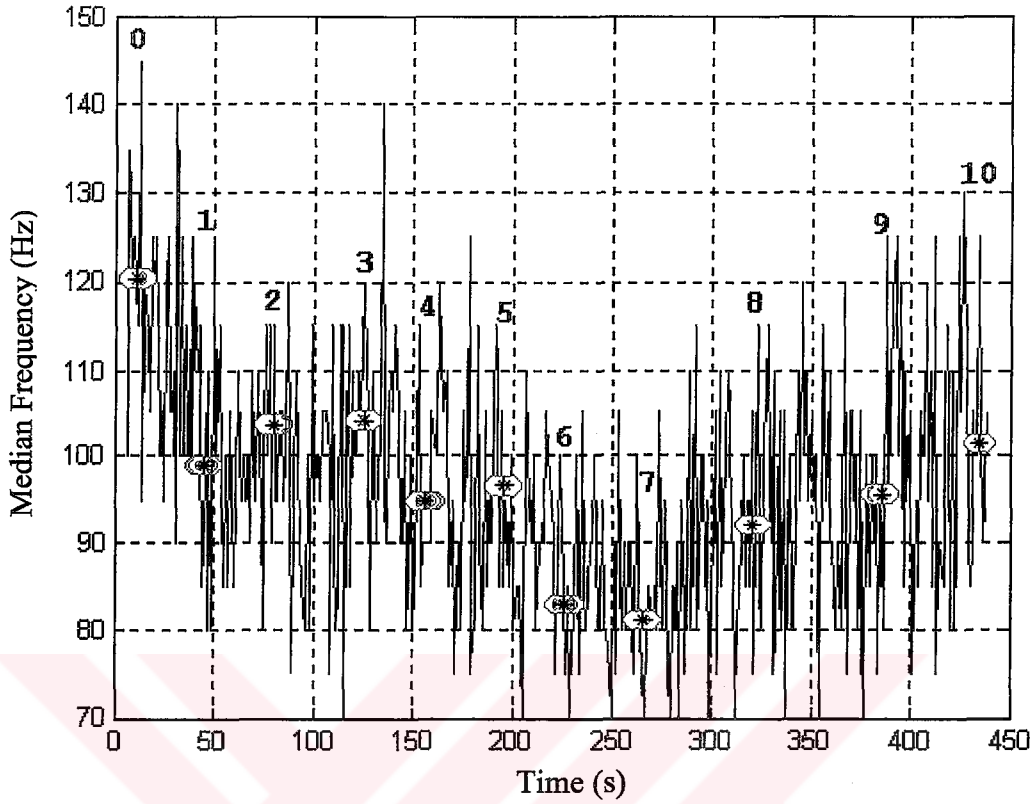

Figure 6.9 MDF of subject Ebr_1 for experiment I.

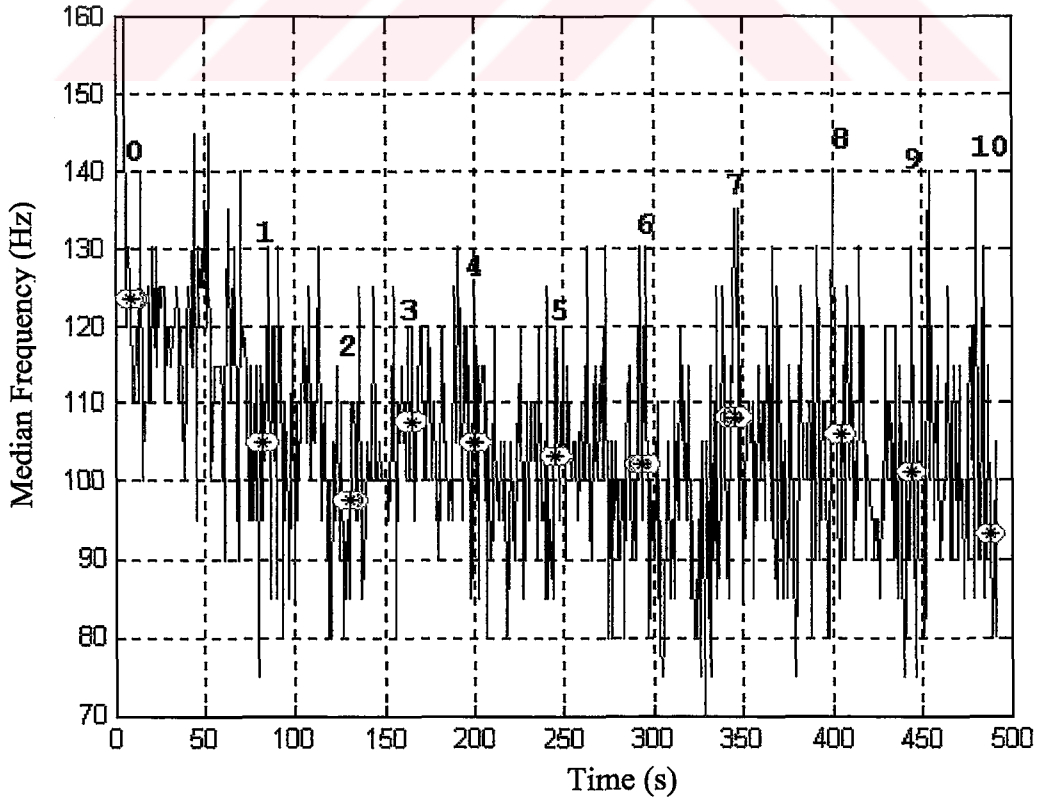

Figure 6.10 MDF of subject Ebr_2 for experiment II.

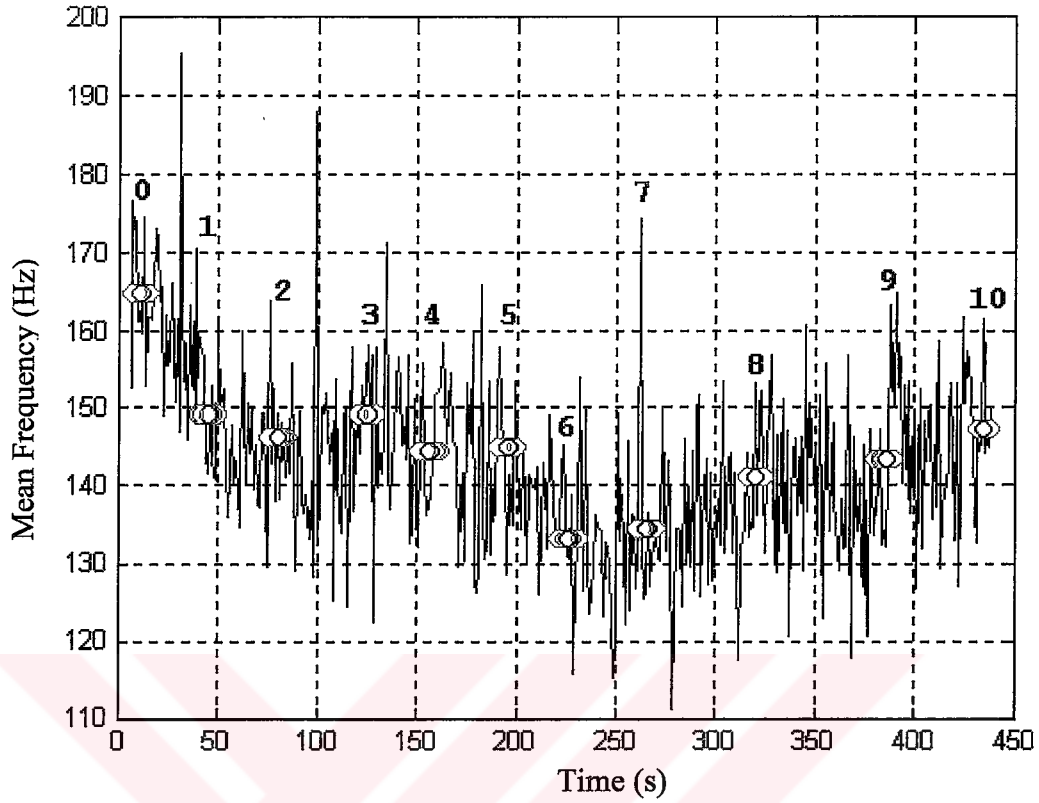

Figure 6.11 MNF of subject Ebr_1 for experiment I.

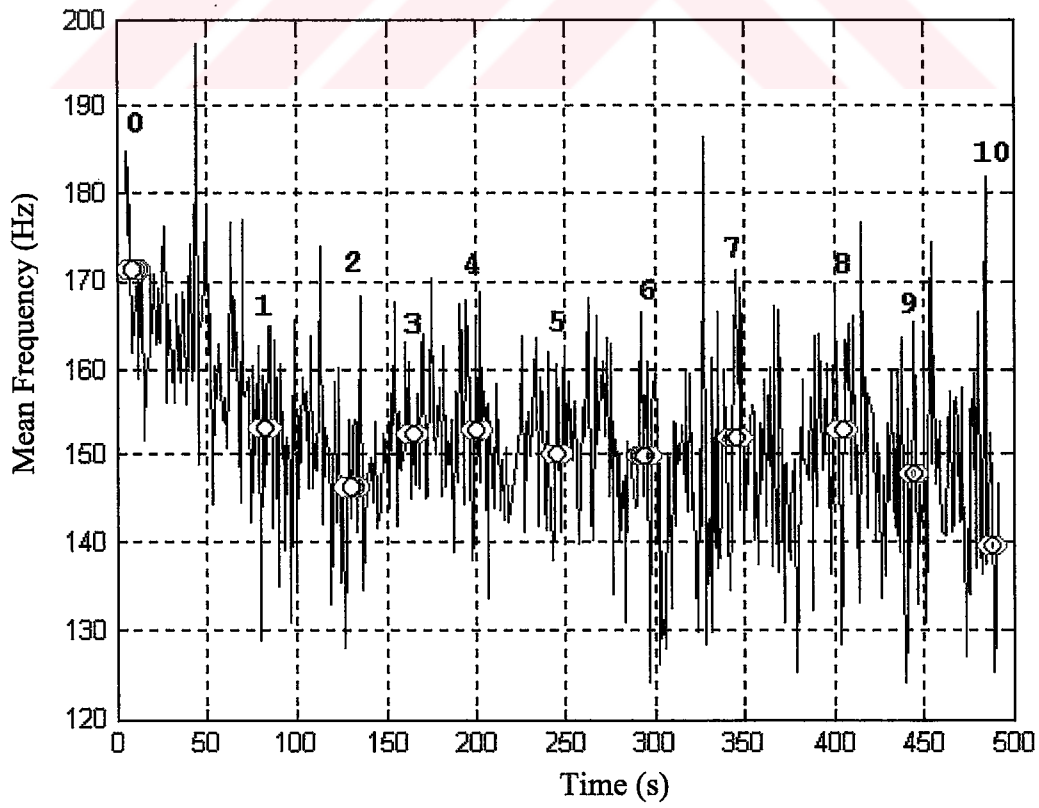

Figure 6.12 MNF of subject Ebr_2 for experiment II.

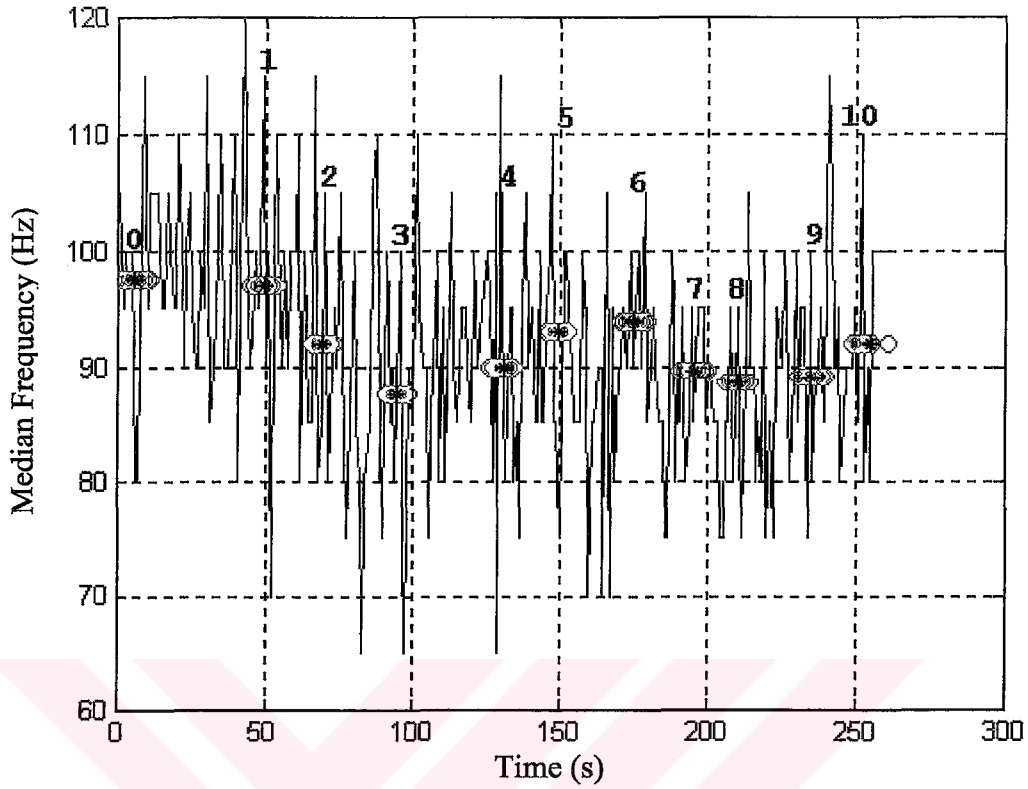

Figure 6.13 MDF of subject Fat_1 for experiment I.

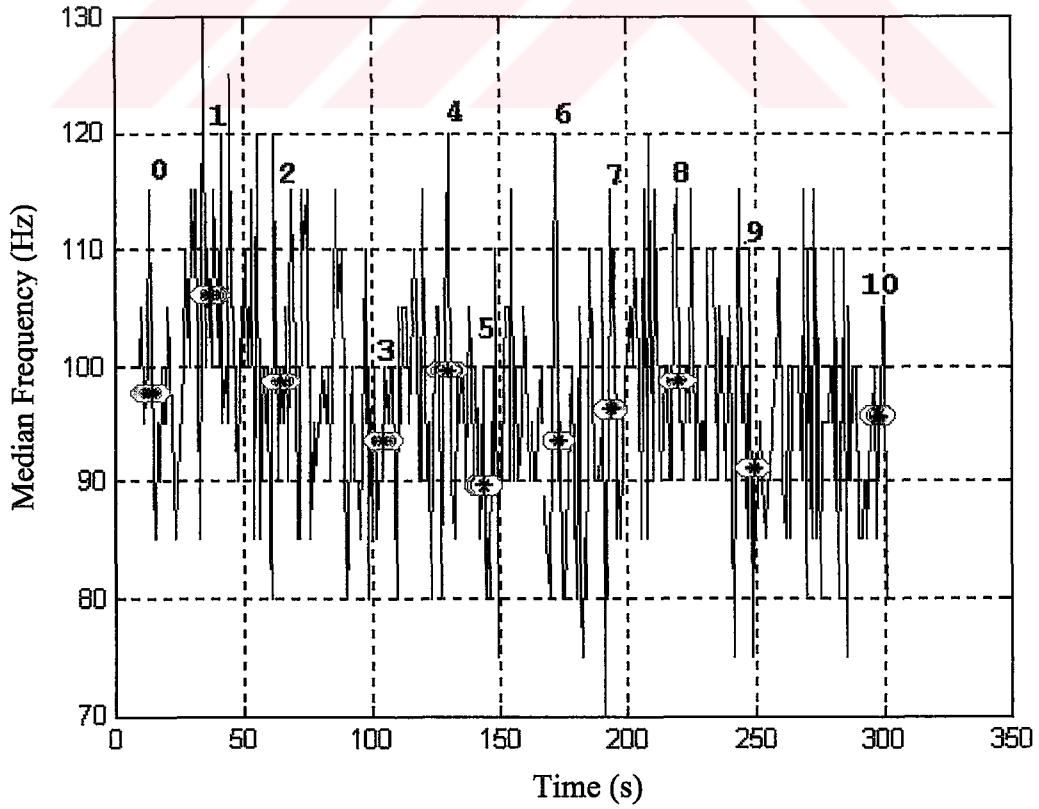

Figure 6.14 MDF of subject Fat_2 for experiment II.

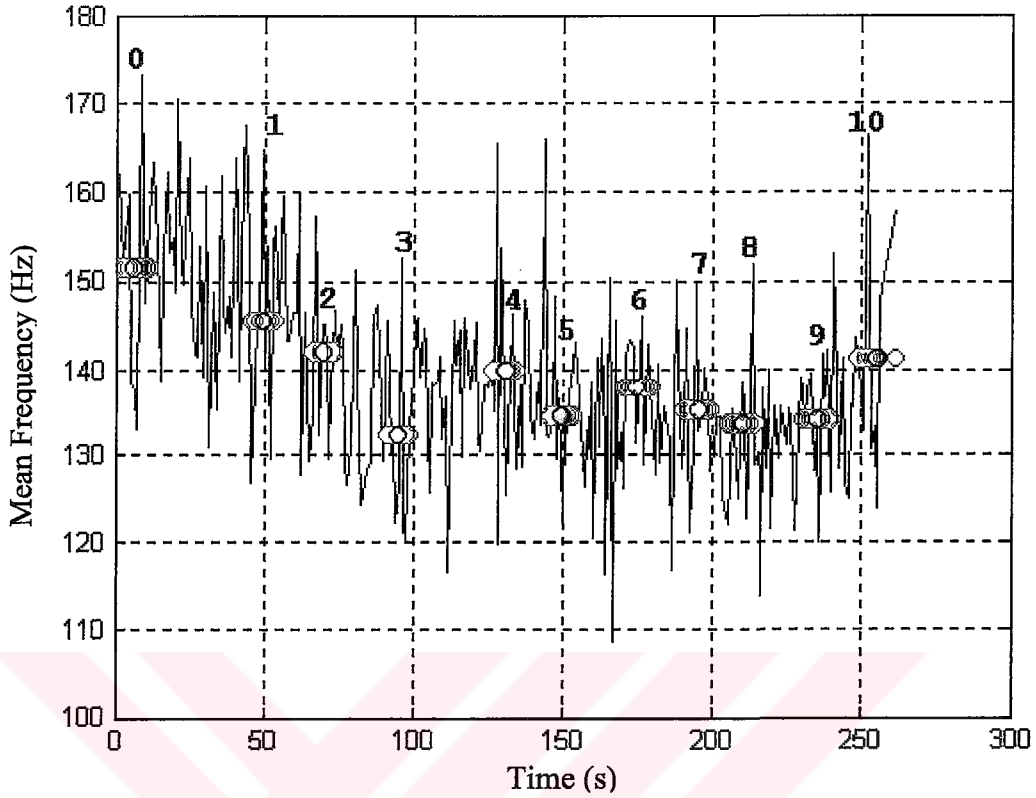

Figure 6.15 MNF of subject Fat_1 for experiment I.

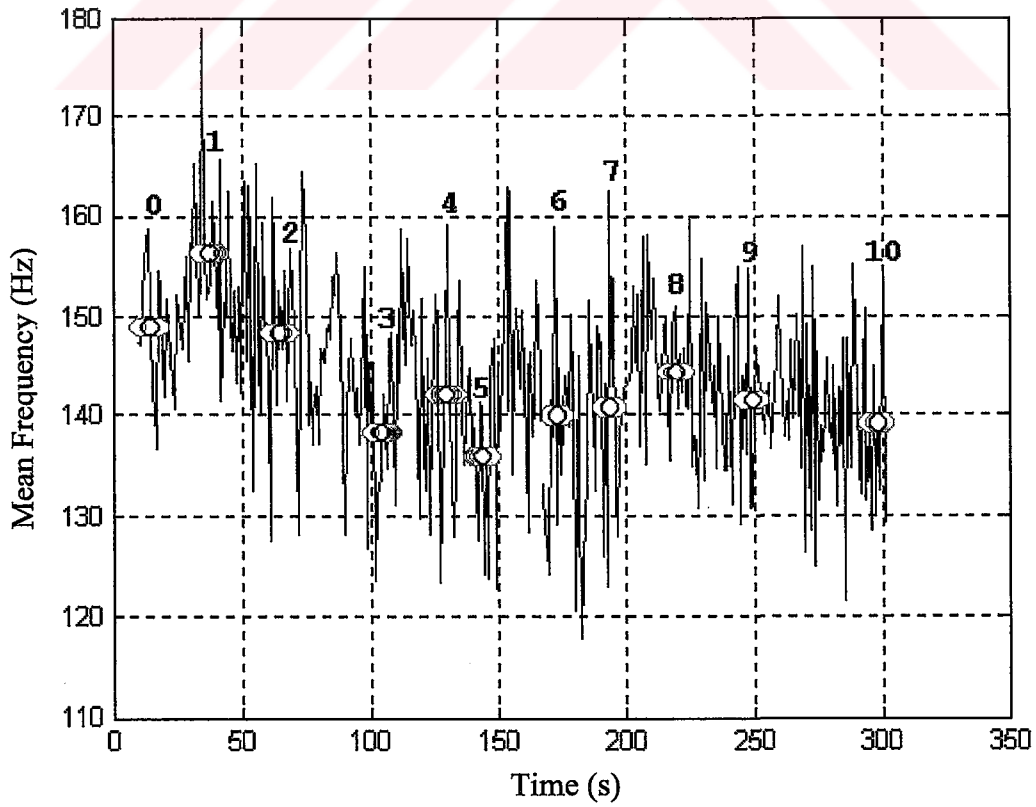

Figure 6.16 MNF of subject Fat_2 for experiment II.

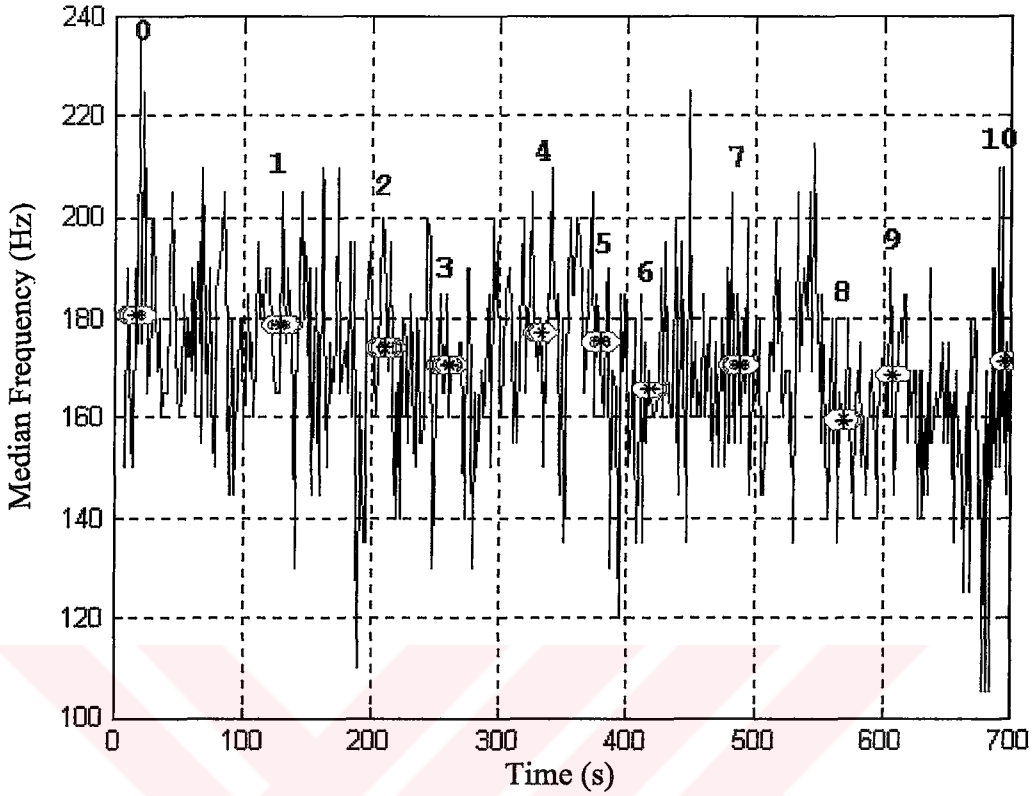

Figure 6.17 MDF of subject Hal_1 for experiment I

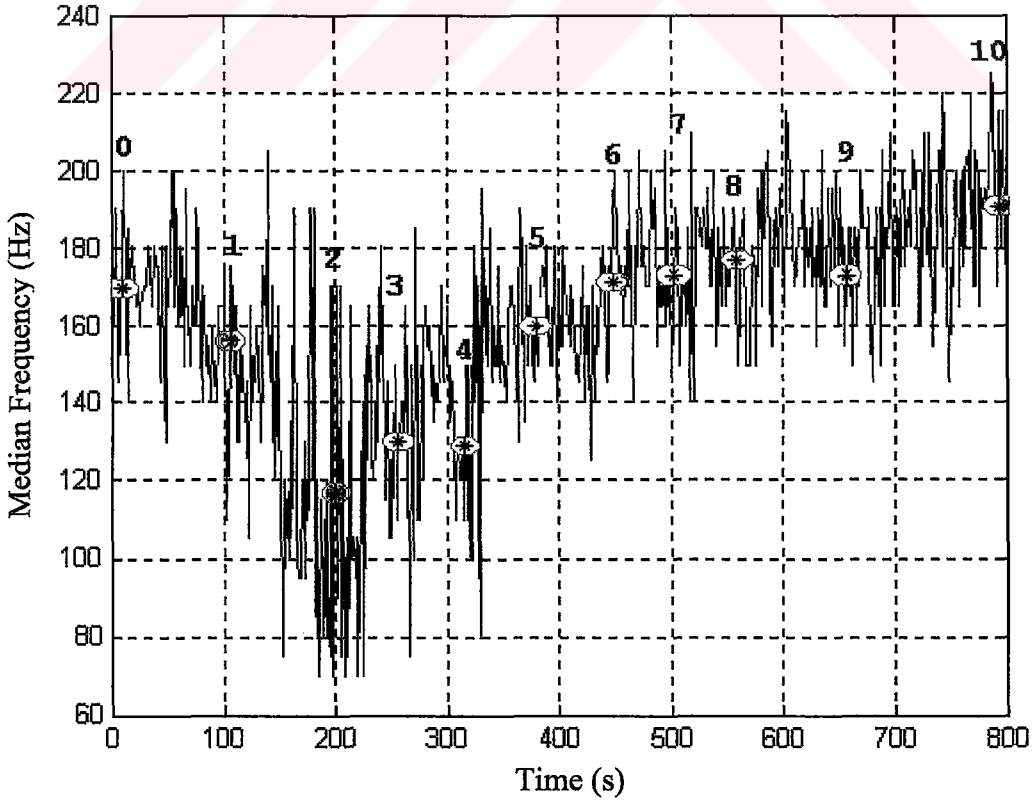

Figure 6.18 MDF of subject Hal_2 for experiment II.

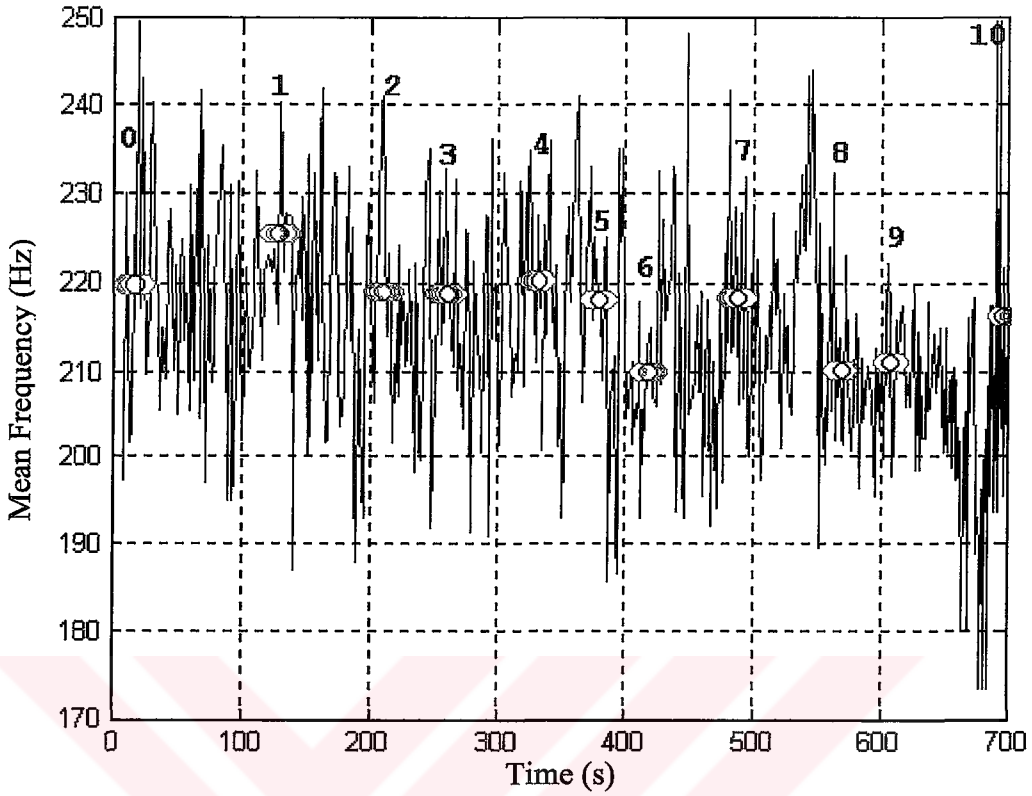

Figure 6.19 MNF of subject Hal_1 for experiment I.

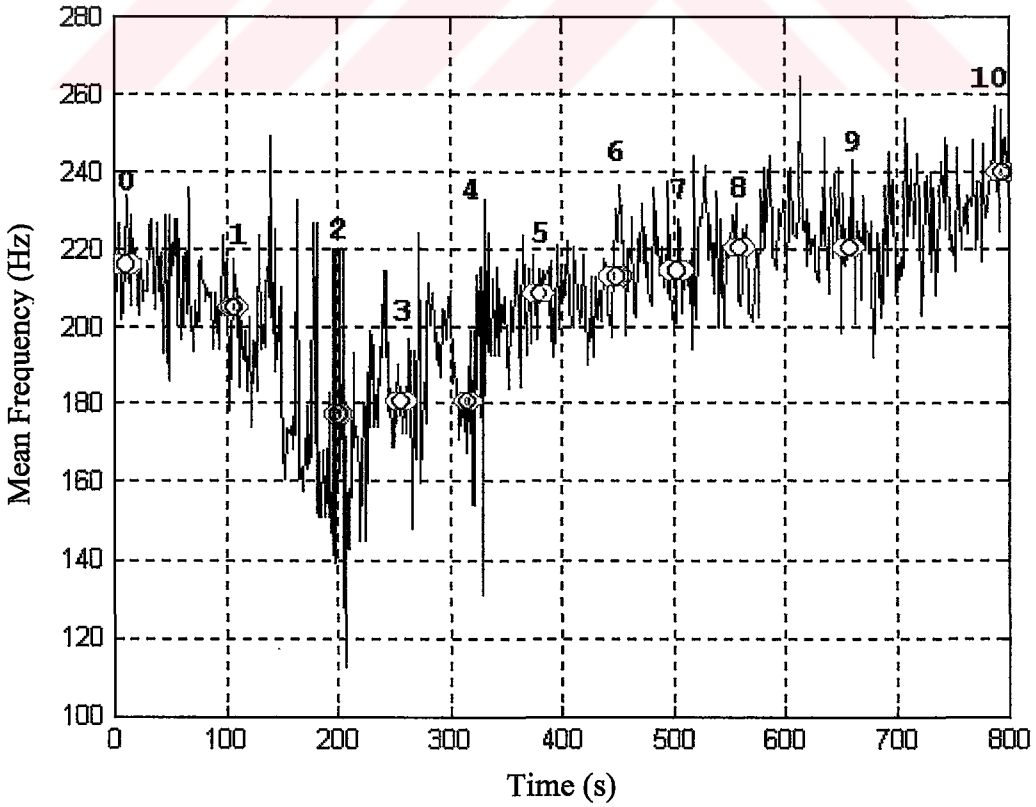

Figure 6.20 MNF of subject Hal_2 for experiment II.

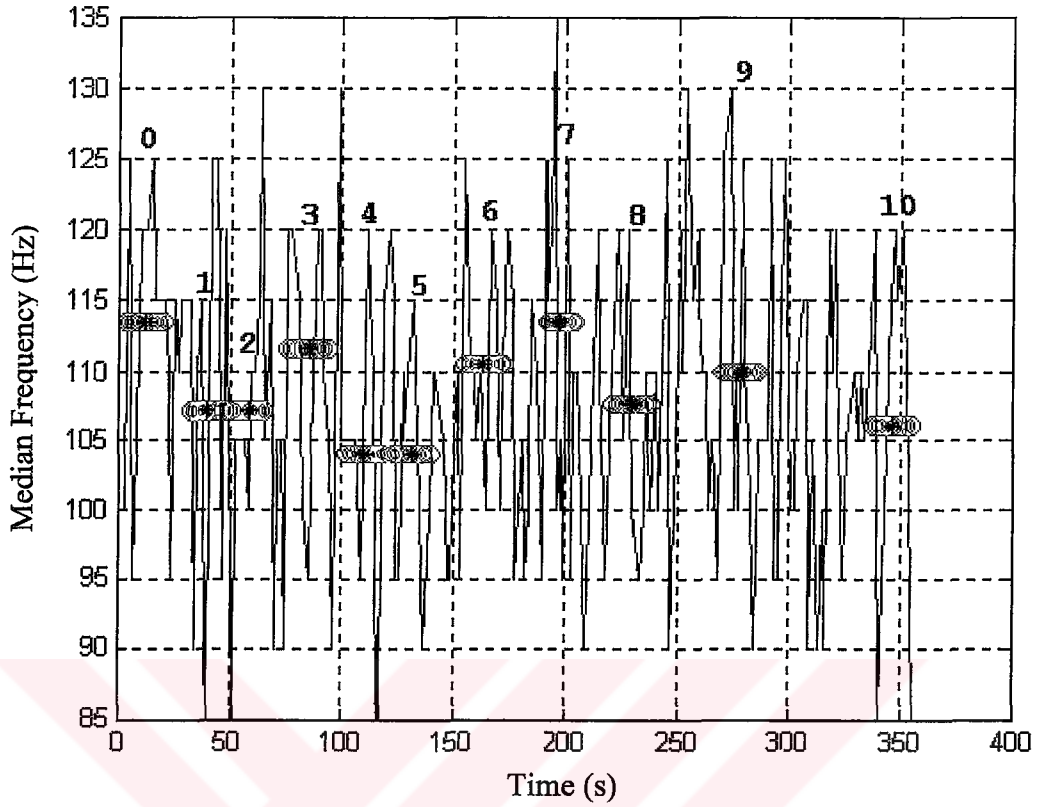

Figure 6.21 MDF of subject Hav_1 for experiment I.

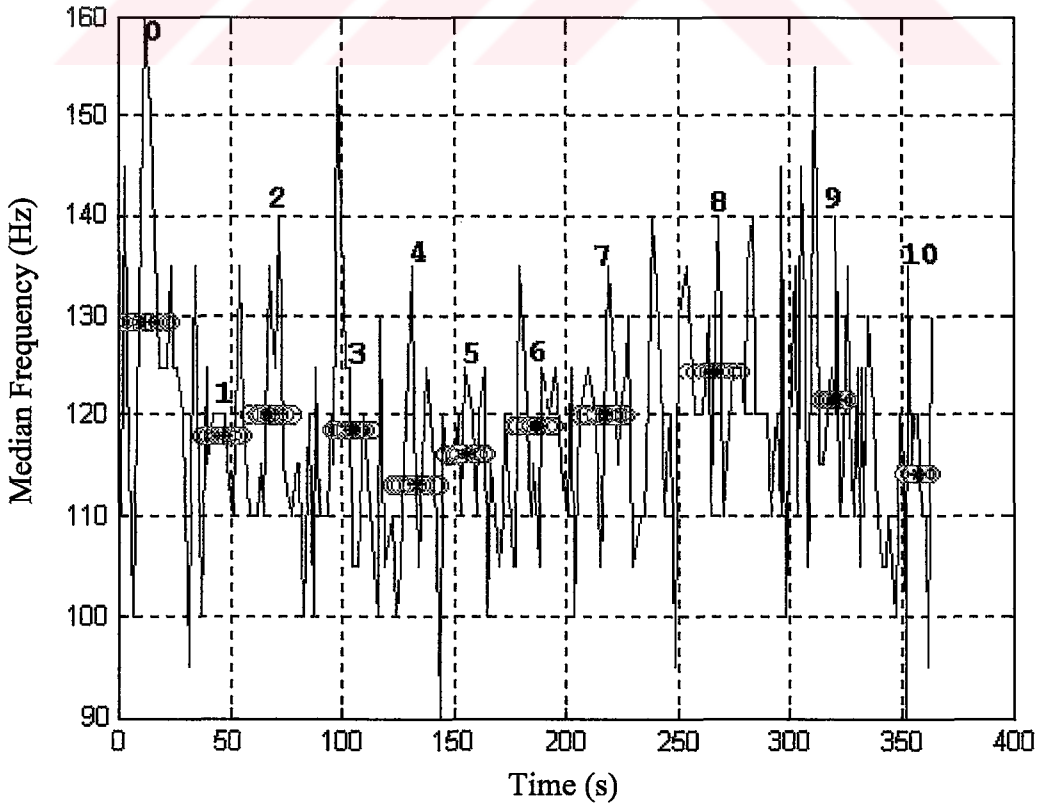

Figure 6.22 MDF of subject Hav_2 for experiment II.

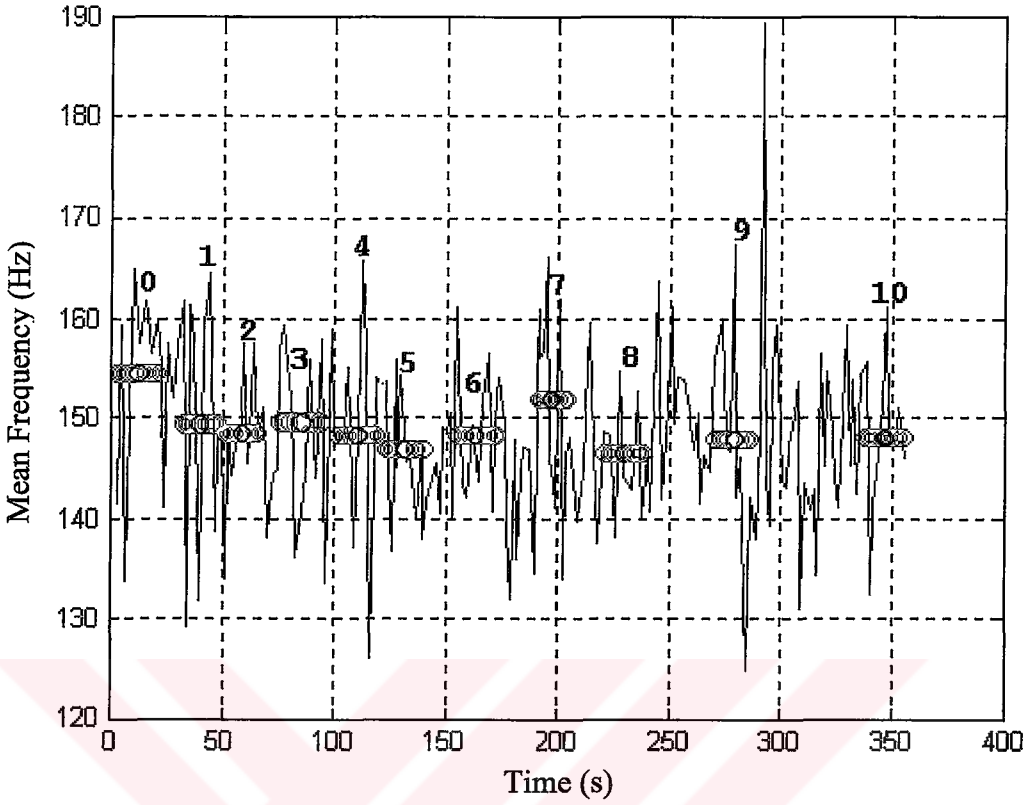

Figure 6.23 MNF of subject Hav_1 for experiment I.

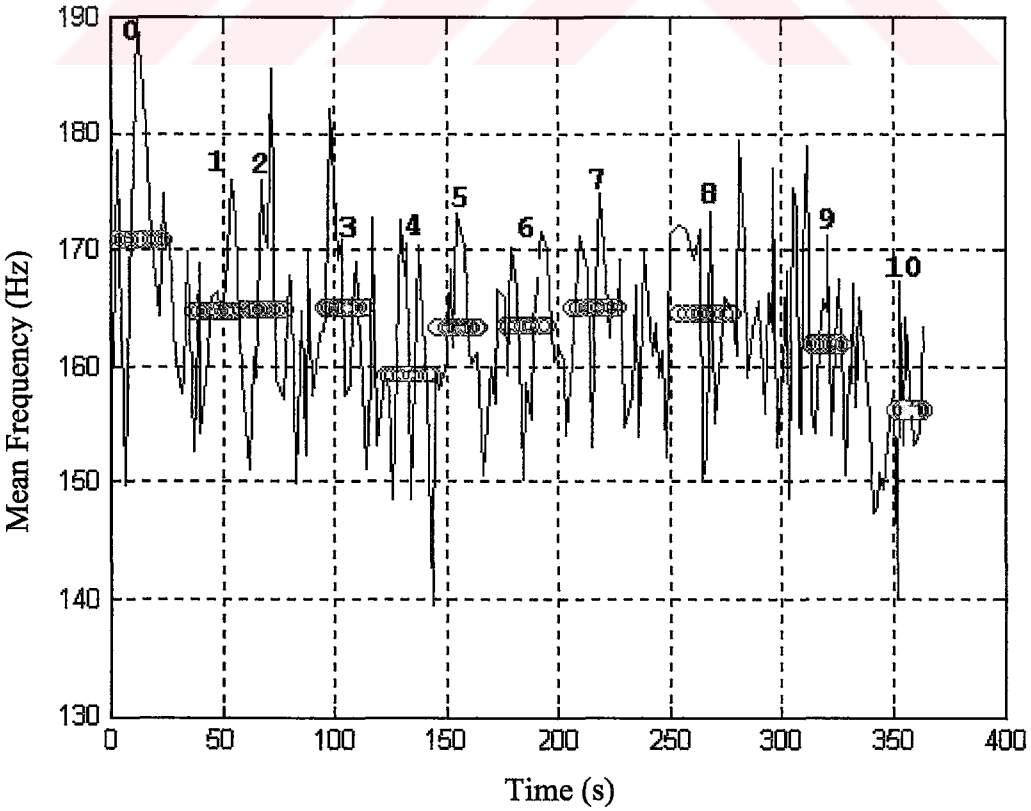

Figure 6.24 MNF of subject Hav_2 for experiment II.

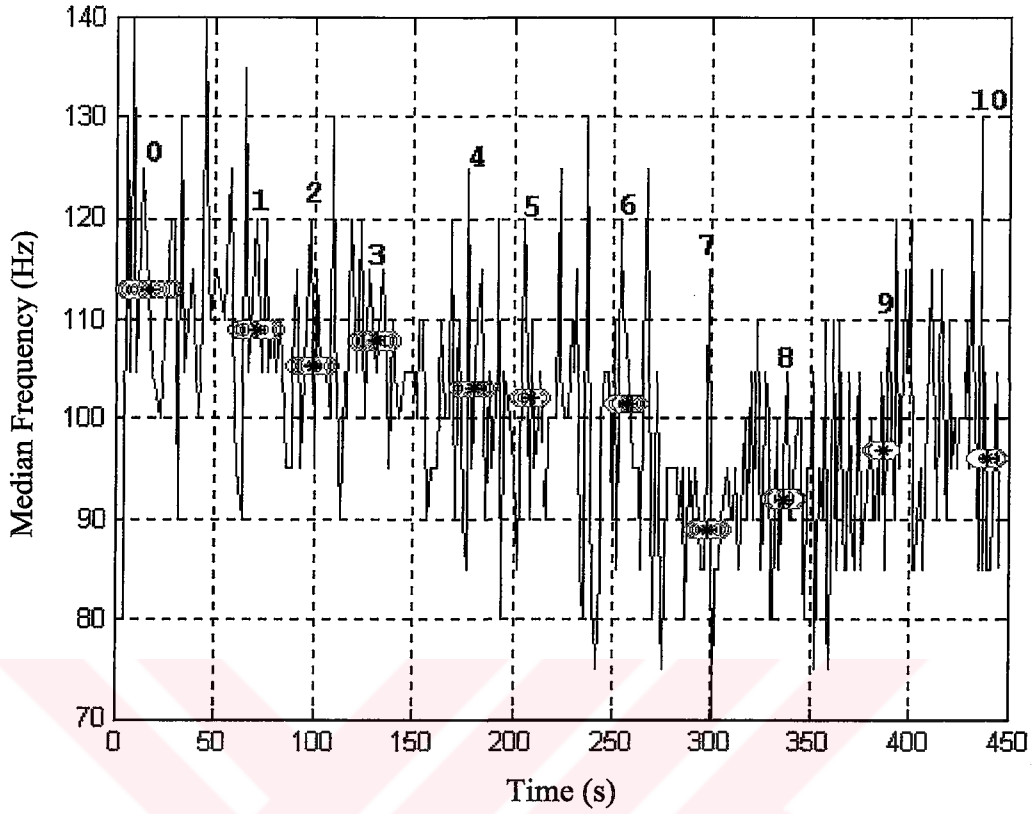

Figure 6.25 MDF of subject Ire_1 for experiment I.

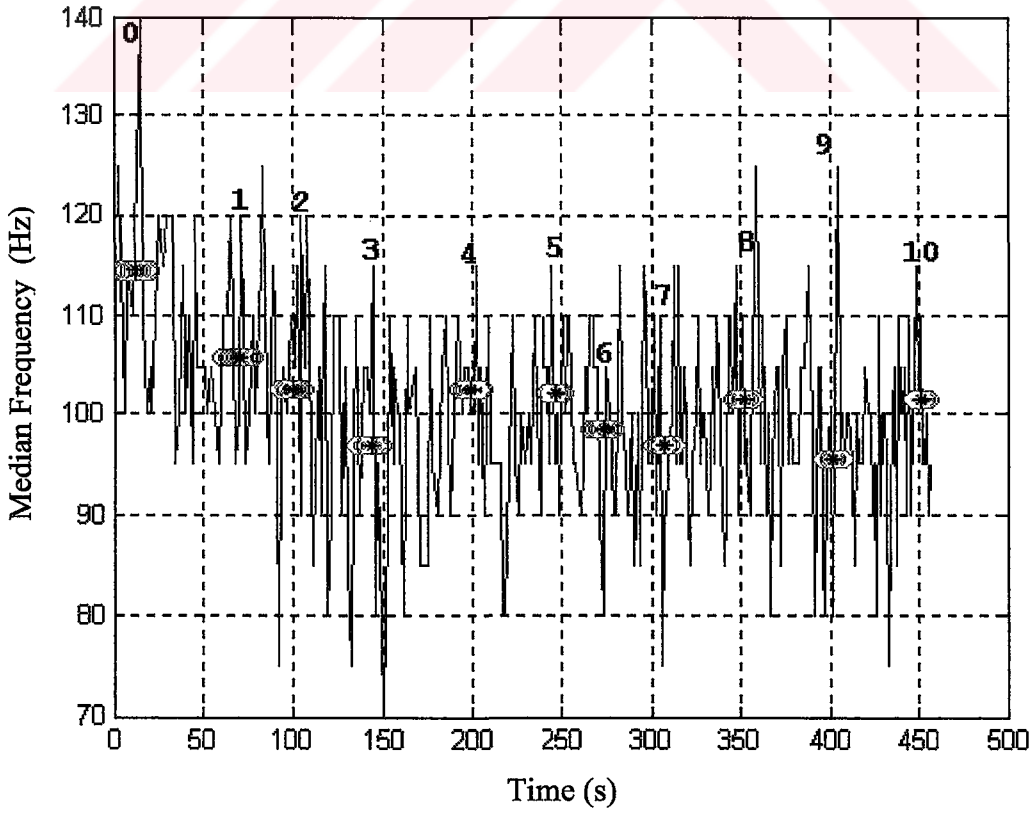

Figure 6.26 MDF of subject Ire_2 for experiment II.

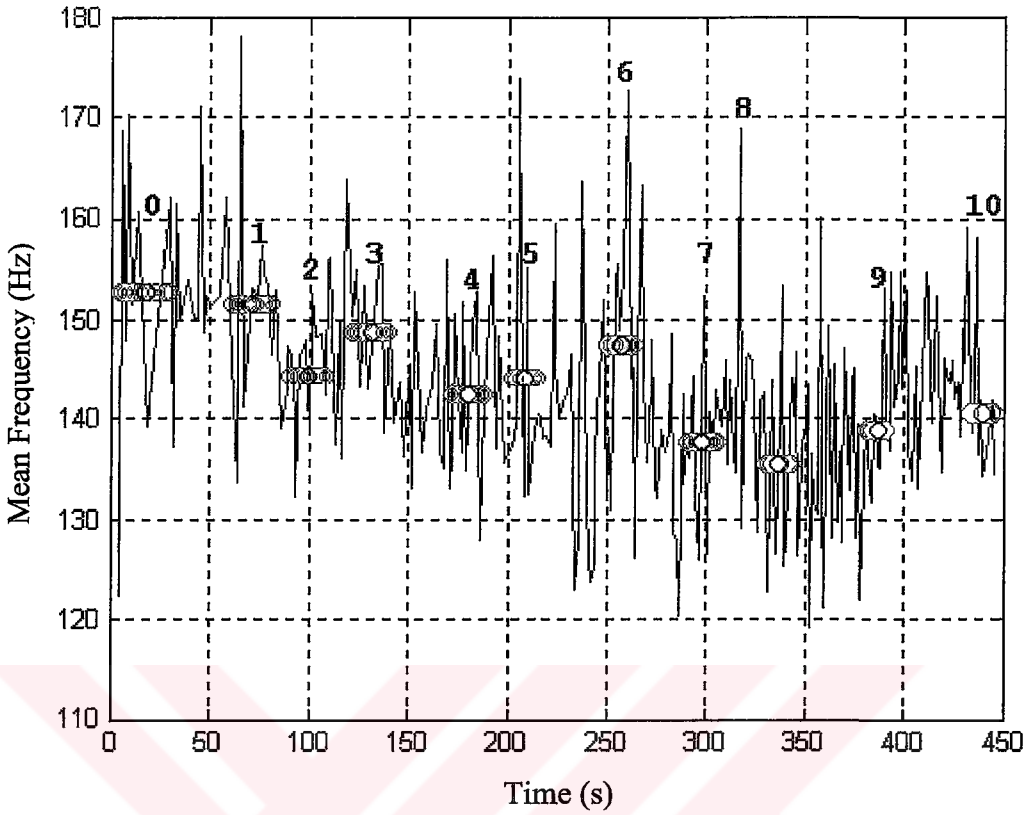

Figure 6.27 MNF of subject Ire_1 for experiment I.

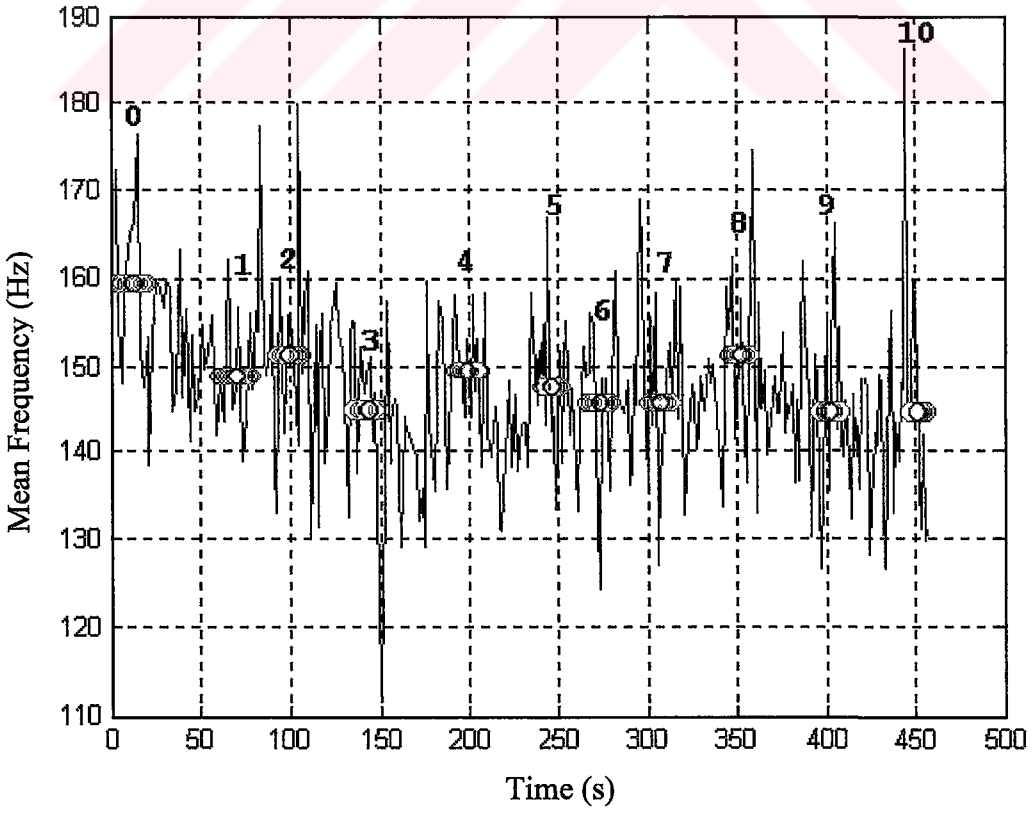

Figure 6.28 MNF of subject Ire_2 for experiment II.

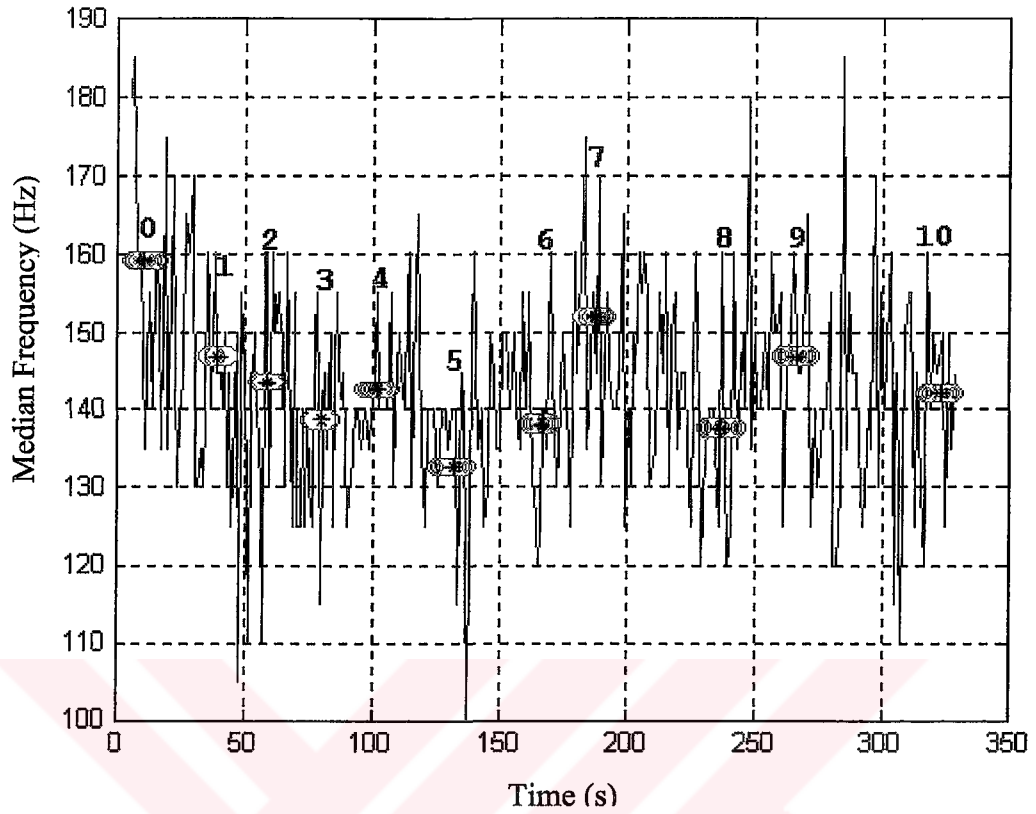

Figure 6.29 MDF of subject Mah_1 for experiment I.

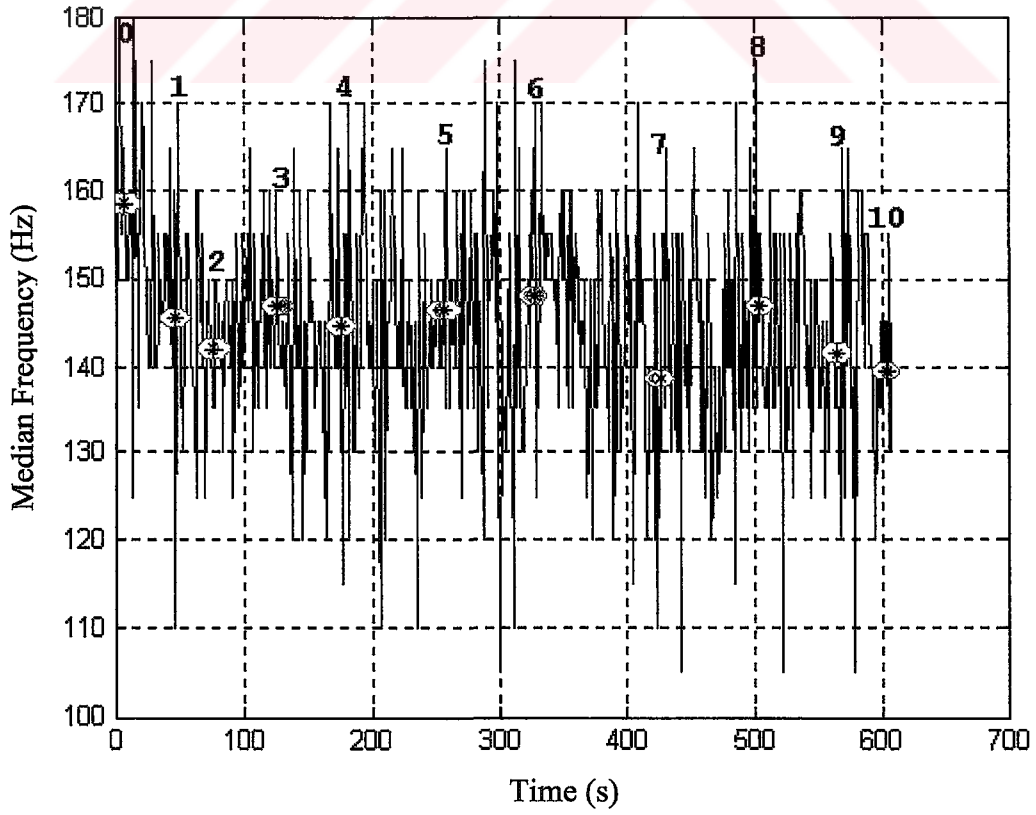

Figure 6.30 MDF of subject Mah_2 for experiment II.

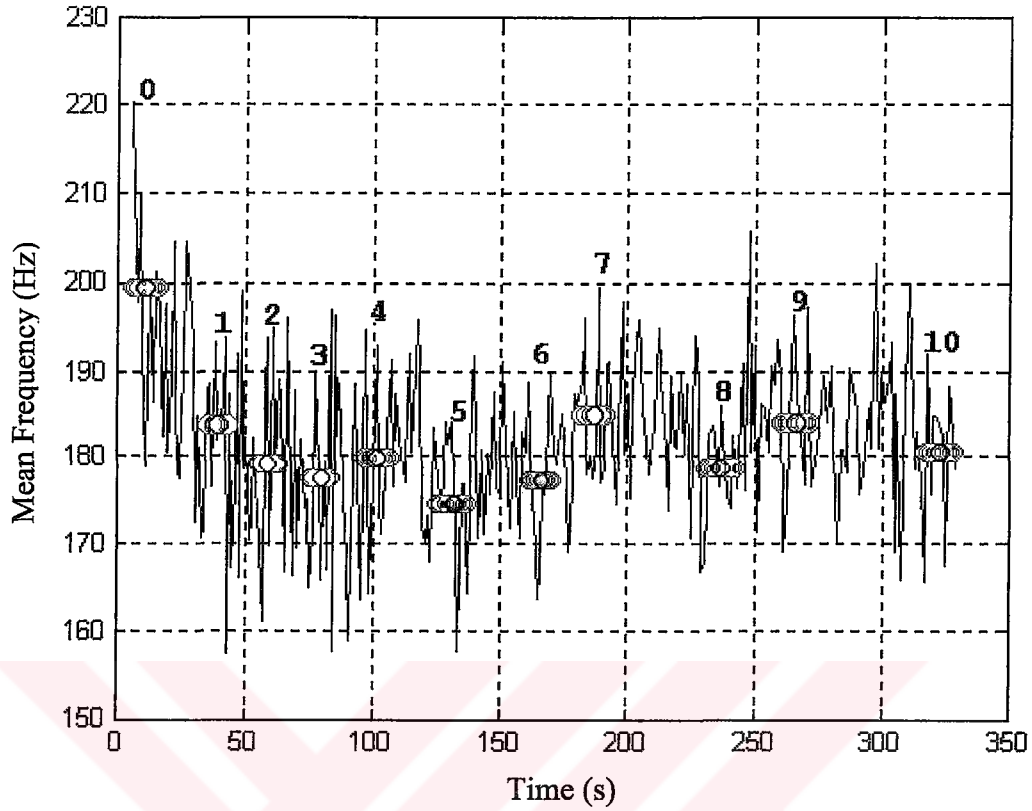

Figure 6.31 MNF of subject Mah_1 for experiment I.

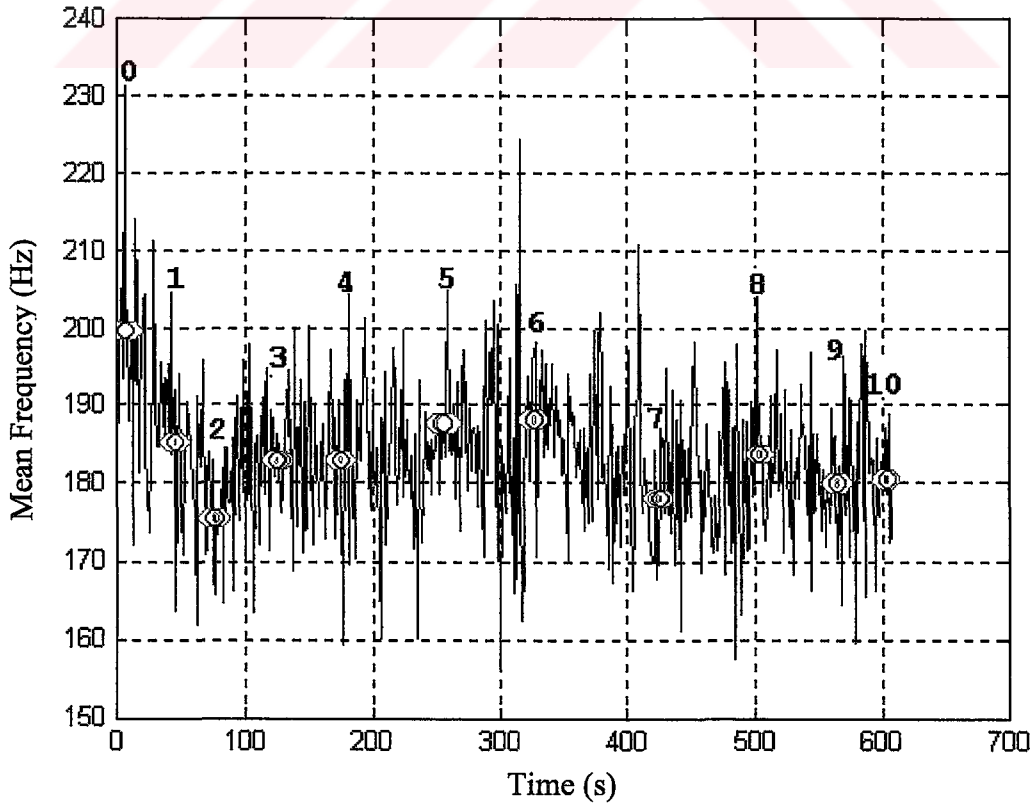

Figure 6.32 MNF of subject Mah_2 for experiment II.

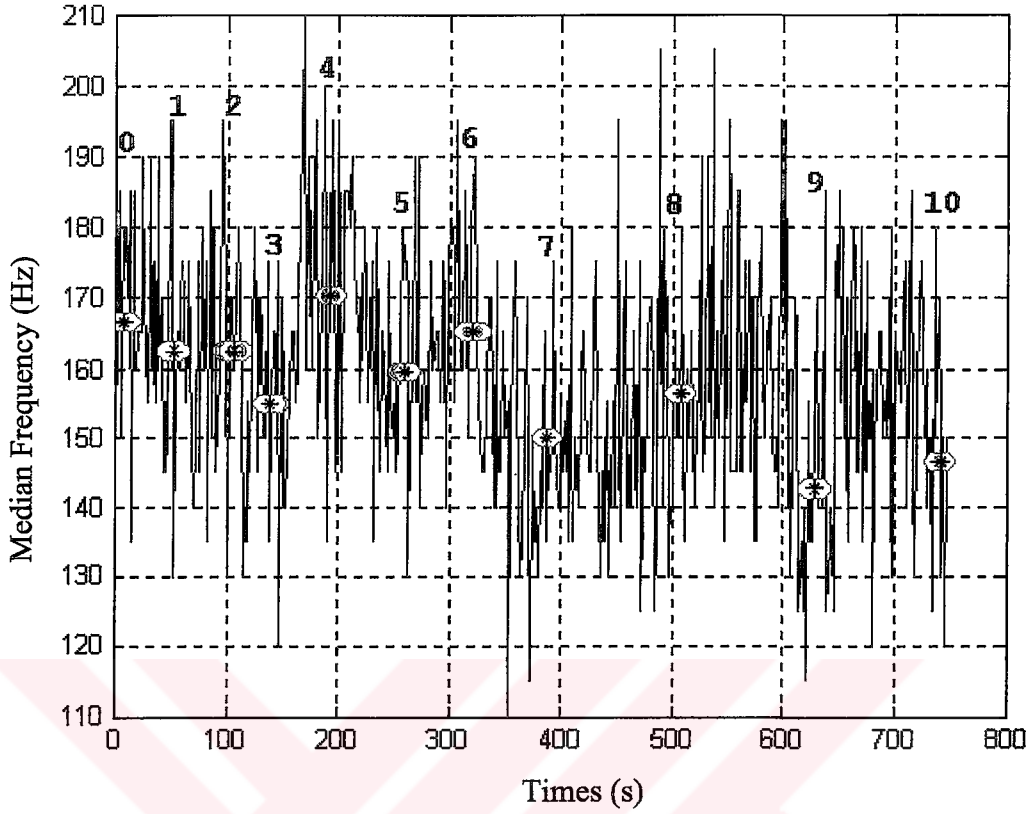

Figure 6.33 MDF of subject Pin_1 for experiment I.

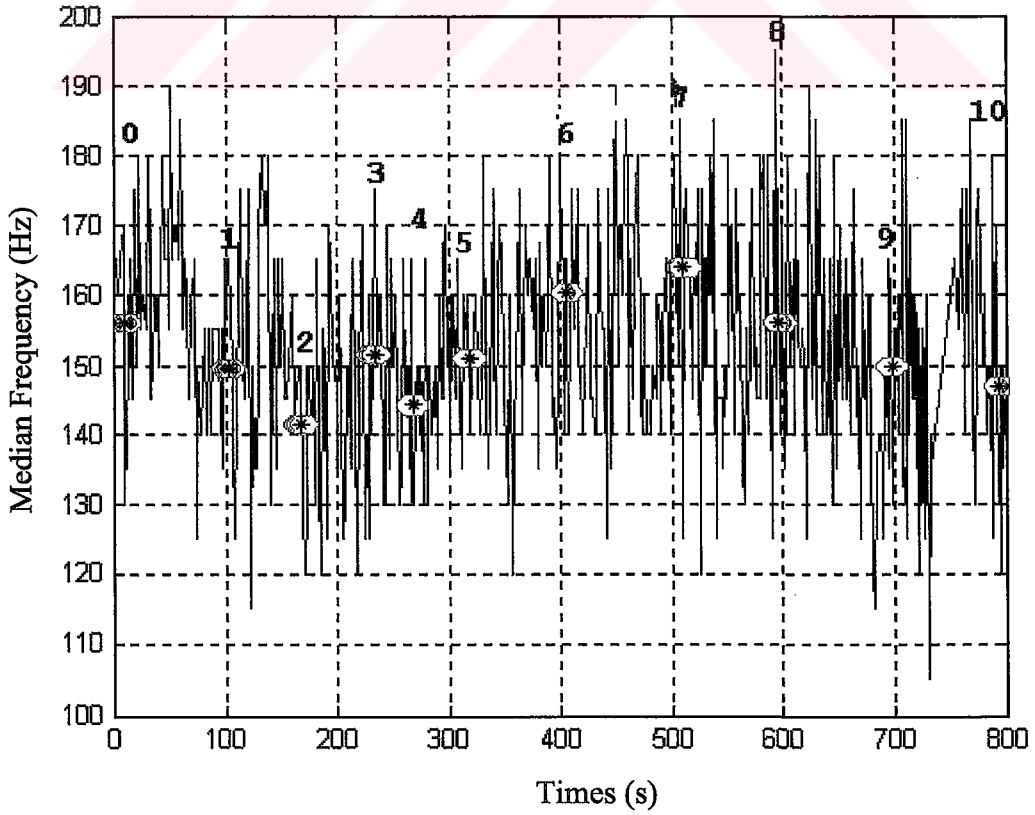

Figure 6.34 MDF of subject Pin_2 for experiment II.

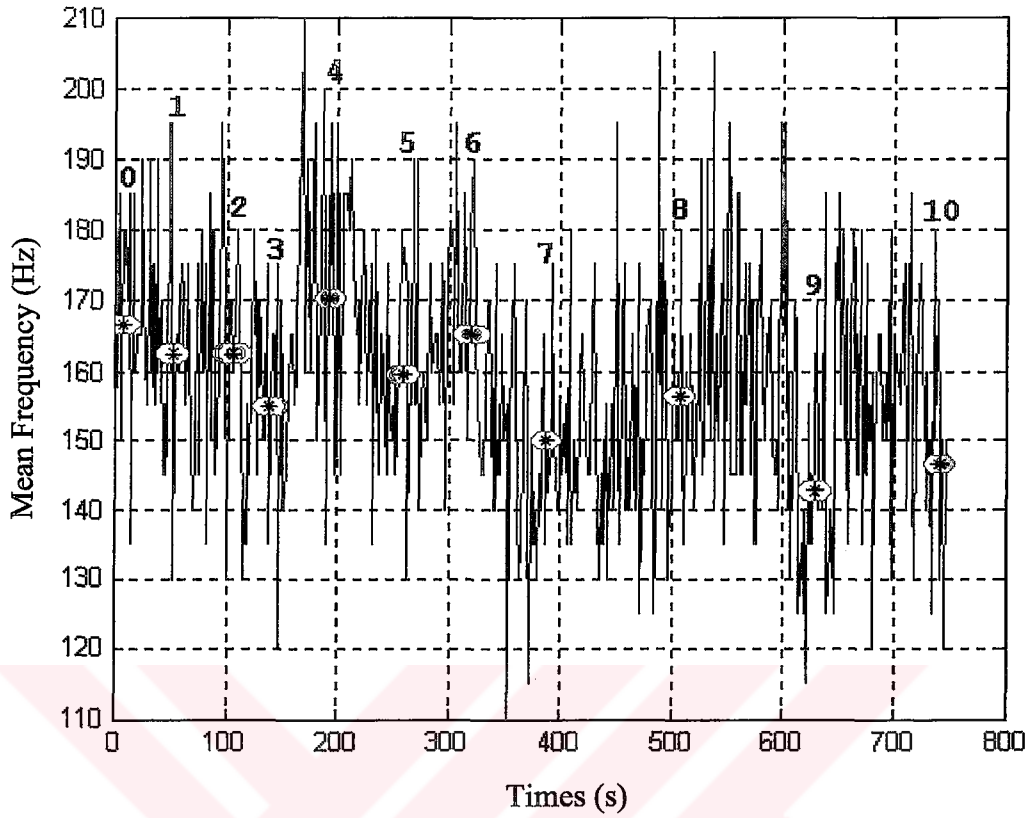

Figure 6.35 MNF of subject Pin_1 for experiment I.

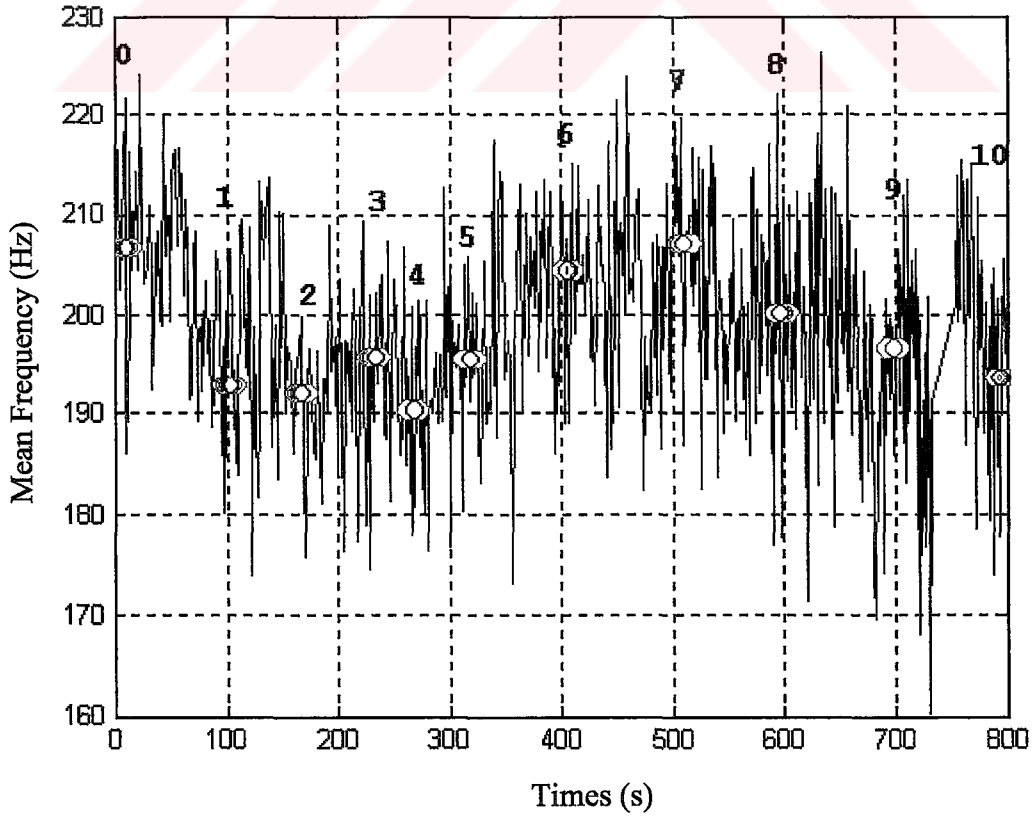

Figure 6.36 MNF of subject Pin_2 for experiment II.

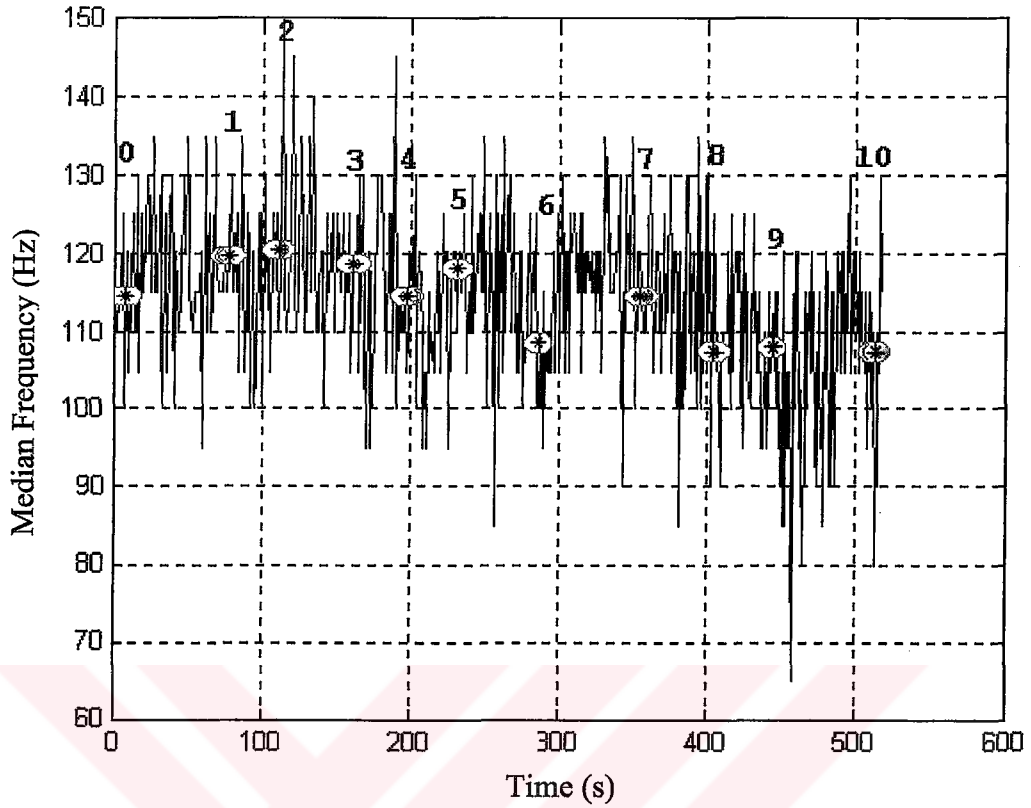

Figure 6.37 MDF of subject Zeh_1 for experiment I.

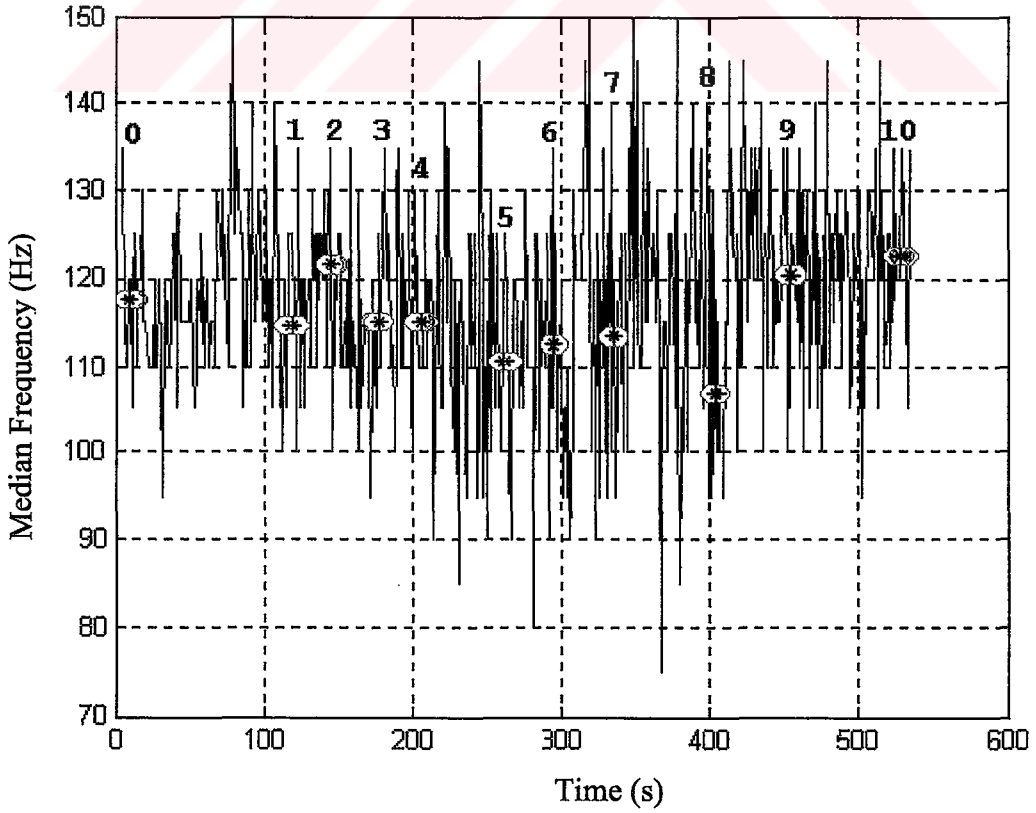

Figure 6.38 MDF of subject Zeh_2 for experiment II.

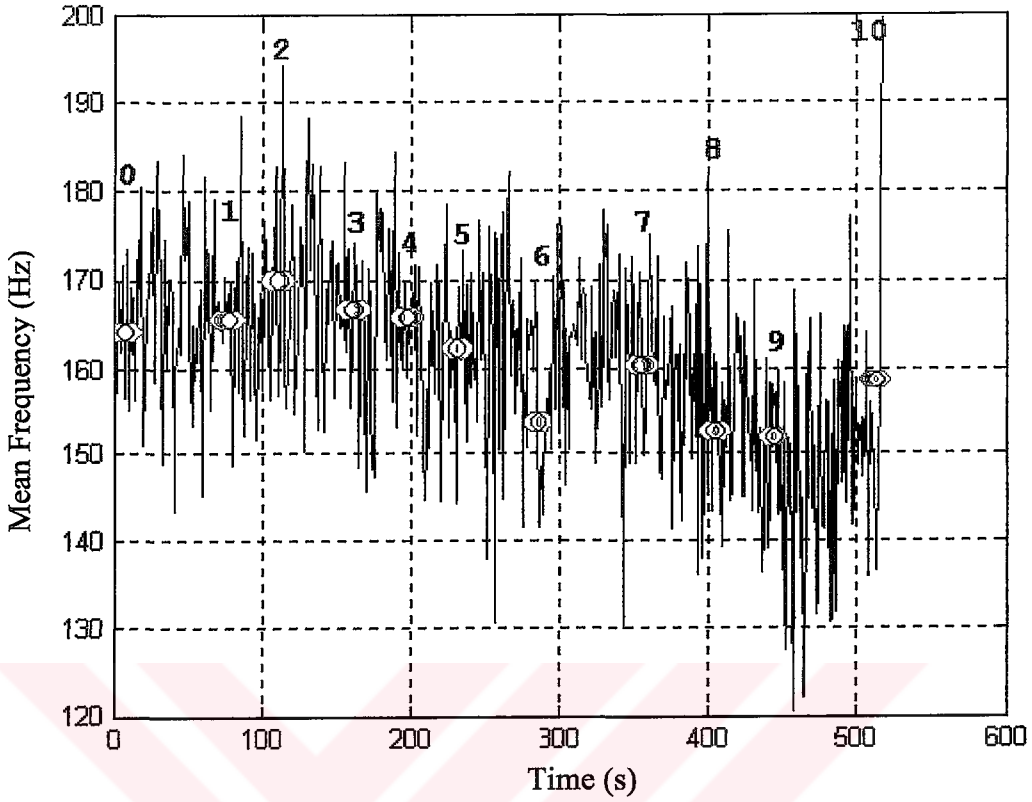

Figure 6.39 MNF of subject Zeh_1 for experiment I.

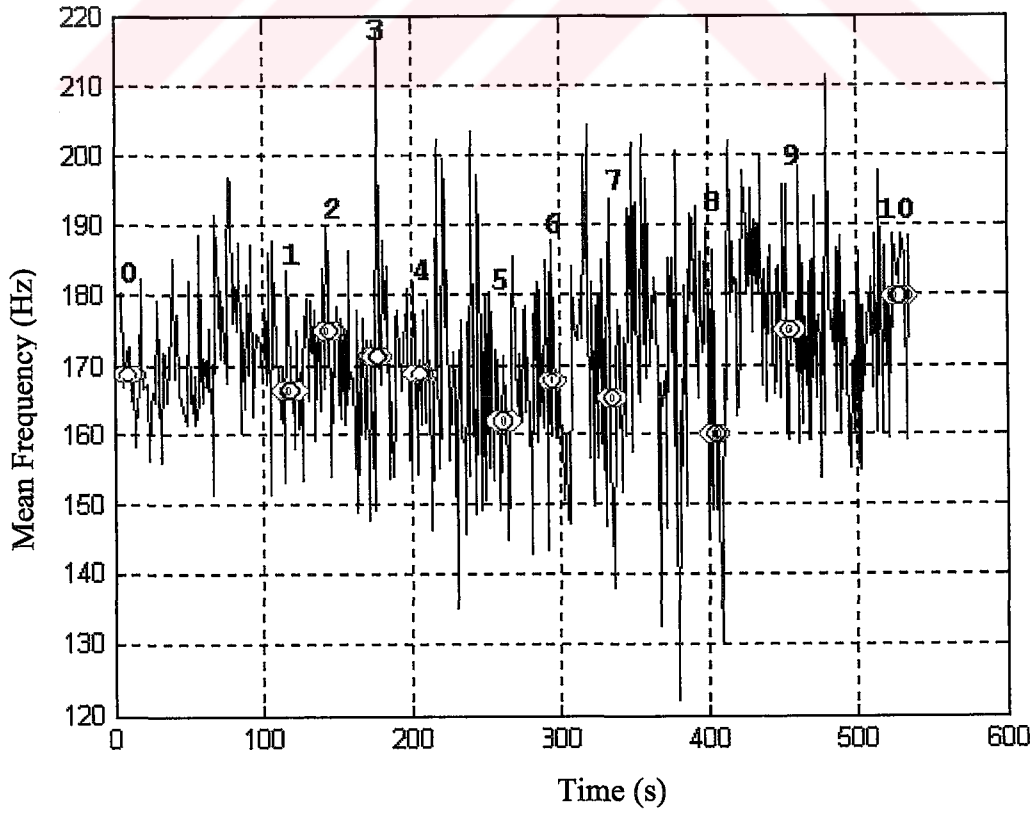

Figure 6.40 MNF of subject Zeh_2 for experiment II.

At Bur_1, the changes in MDF resemble a periodic sinusoidal curve. While the beginning value of MDF is ~175 Hz the biggest decrease in MDF (~147 Hz) is between 220 and 270 seconds and also in the last seconds (600s).

At $Burc_2$, the differences of MDF take the shape of sinusoidal curves, which follows each other consecutively. There is no difference of MDF (~148 Hz) in the first 100 seconds. The biggest decrease of the MDF (~121 Hz) is in the last 20 seconds.

In both Bur_1 and Bur_2, the sinusoidal curve of MNF and MDF seems similar for both tests.

At Cey_1, the MDF changes show remarkable periodic sinusoidal curves, which first decrease and then increase. The MDF has indicated a little increase in the last 100 seconds in comparison to the beginning.

MDF changes of Cey_2 are also periodic sinusoidal curves like those of Cey_1. However, the increase of MDF from ~147 Hz to ~153 Hz values of Cey_2 is greater than those of Cey_1 in the last 100 seconds.

The MNF values of Cey_1 and Cey_2 resemble sinusoidal like periodic curves similar to those of the MDF values. Moreover, for the second test (Cey_2 for MDF and MNF values), although the subject is fatigued, MDF and MNF values show a slight increase in the last 100 seconds.

At Ebr_1, the sinusoidal curve like periodic characteristic is more apparent. In the beginning of the test, while Median Frequency is around 120 Hz, it decreases to 90-100 Hz after the first 50 seconds. Although the subject could maintain the experiment 437 seconds, the smallest MDF values (80-95 Hz) are observed between 200-300 seconds. MDF continuously increases in the last 200 seconds and reaches 100-105 Hz.

At Ebr_2, there are smaller sinusoidal periodic curves than Ebr1. In addition, there is a definite decrease at the end of the experiment. At the beginning, while MDF is around 125 Hz, it continuously decreases to 95-100 Hz around 130 seconds. In the last 100

seconds, MDF decreases from ~105 to 93-97 Hz Furthermore, at Ebr_2, there is a considerable change towards lower frequencies during the first and last 100 seconds for MDF values.

At Ebr_1, the periodic sinusoidal curve of MNF is similar to MDF. In the first 50 seconds, there is an exponential decay.

At Ebr_2, MNF values show a decrease like the MDF values; an exponential decay is seen in the first 150 seconds. But, then there is no any important change up to 400 seconds. However, there is a remarkable decrease in comparison to the beginning in the last 90 seconds.

At Fat_1, there are sinusoidal like periodic curves for the MDF values. There is no difference for MDF values in the first 50 seconds ~ 97 Hz. Even though the experiment lasted 250 seconds, for MDF values the biggest decrease ~ 87 Hz is observed between 90-100 seconds.

At Fat_2, MDF values increase from 97 Hz to 110 Hz in the first 30 seconds; thereafter-periodic decreases and increases are more apparent during the test. While the highest MDF value is around 106 Hz, the smallest MDF value is around 88 Hz.

At Fat_1, MNF values show exponential decay in the fist 100 seconds (they decrease from 150 Hz to 130 Hz), later MNF remains at the same level for a while, and then there is small increase (~140 Hz) in the last seconds.

At Fat_2, there is a sinusoidal curve like periodic characteristics as for the MNF values. At first seconds, MNF values are between 150-157 Hz, the biggest decrease is to ~135 Hz in the first 140 seconds and then in the last seconds the values are around 140-145 Hz.

At Hal_1, the MDF values remains at the same level 160-180 Hz during 700 seconds. So there are no definite sinusoidal like periodic curves; only small decreases and increases are seen during the test.

At Hal_2, the graph of MDF values is very different compared to Hal_1. While MDF values are ~170 Hz at the beginning, they decrease markedly to 116 Hz until 200 seconds. Then, the MDF values increase towards higher frequencies ~190 Hz until the end of the experiment.

At Hal_1 and Hal_2, the changes in MNF are similar to the changes in MDF.

At Hav_1, the MDF changes show sinusoidal periodic characteristics.

At Hav_2, sinusoidal curve characteristics are more apparent for the MDF values. They decrease from 129 Hz to 115 Hz in the first 150 seconds.

At Hav_1, MNF shows little decrease from 154 Hz to 148 Hz in the first 50 seconds; thereafter MNF remains nearly at the same level during 350 seconds (140-150 Hz).

At Hav_2, MNF values decrease from 170 Hz to 164 Hz in the first 50 seconds then remains at the same level until 120 seconds. They decrease around 156 Hz in the last 30-40 seconds.

For Ire_1, at the beginning MDF changes in the direction of lower frequencies from 110-120 Hz to 85-90 Hz. However, in the last 150 seconds, an increase is observed in the MDF values from 85-90 Hz to 95-105 Hz. But the MDF values in the last seconds are lower than those at the beginning. The most impressive decrease at MDF (to about 85 Hz) is at 300 seconds.

At Ire_2, the MDF values decrease linearly down to the 150^{th} second from ~115 Hz to ~ 95 Hz, then MDF shows small increases and decreases between 95 and 105 Hz until the end of the test 2.

At Ire_1, there are no differences in MNF values ~152 Hz up to 90 seconds. Hen MDF values show sinusoidal periodic curves. After 300 seconds MNF values are between 135 Hz and 140 Hz.

At Ire_2, there is a decrease from ~159 to ~148 Hz in the first 100 seconds for the MNF. Then MNF values show small increases and decreases that follow each other consecutively.

At Mah_1, an exponential decay is seen in the MDF values from 160 Hz to ~135 Hz in the first 100 seconds. Afterwards, the changes of MDF values resemble sinusoidal periodic curves.

At Mah_2, an exponential decay is also seen in the MDF values from ~155-140 Hz to 140-145 Hz in the first 100 seconds. Then periodic increases and decreases in the MDF values are observed.

MNF values of Mah_1 and Mah_2 show sinusoidal periodic curves, too.

At Pin_1, MDF values exhibit an exponential decay in the first 150 seconds. There are also sinusoidal periodic increases and decreases for the MDF values. While these range between 160 Hz and 170 Hz in the first 100 seconds, in the last 150 seconds the fluctuation is between 140 Hz and 150 Hz.

At Pin_2, an exponential decay has been seen for the MDF in the first 200 seconds. Pin_2 maintained the test about 800 seconds. MNF ~165Hz shows an increase towards 500 seconds in comparison to the beginning ~155 Hz and the end ~145 Hz of the test.

At Pin_1 and Pin_2, the values of MNF are similar to those MDF.

At Zeh_1, in the first 100 seconds, a little increase is seen at MDF from ~115 Hz to ~120 Hz. After 400 seconds, MDF ~108 Hz values remain at the same levels up to the end of the test. In this subject there are no definite decreases and increases. Generally, in contrast to Zeh_1, the sinusoidal curves observed for the other test subjects, show decreases in the first seconds followed by increases.

At Zeh_2, there are small sinusoidal like periodic curves for the MDF. Interestingly, there is an increase from ~117 Hz to ~123 Hz for MDF in the last 100 seconds in comparison to the beginning.

At Zeh_1, at the beginning, there is a small increase in MNF values from ~164 Hz to ~170 Hz up to the 110^{th} second. Then they decrease gradually down to 152 Hz. At the last 50 seconds, MNF values go up to 158 Hz.

At Zeh_2, there are sinusoidal curves in MNF like MDF. There is an increase from ~168 Hz to ~180 Hz of MNF in the last 100 seconds in comparison to the beginning.

In summary, in the first experiment, when we examine MDF and MNF values, in 90 % of subjects (except Pin_1), MDF and MNF values show the biggest decrease at the beginning or at the middle of the test instead at the end of the test. All subjects have given up the test when they felt exhausted. Therefore, the lowest point of the MDF and MNF values do not show the time of maximum fatigue.

For 80 % of subjects, there is an increase in the MNF and MDF values. There is an increase of the MNF and MDF values in % 10 (Zeh_1) and no changes in 10 % (Hal_1) in the first ~100 seconds.

For 80% of the subjects, after a decrease in the first seconds of the MNF and MDF values, the frequency changes resemble sinusoidal periodic curves. For 10 % of the subjects (Hal_1), MDF and MNF values remain nearly the same during the test. However, for the other % 10 (Cey_1), there is a decrease at MDF and MNF values in the beginning followed by sinusoidal periodic curves; at the end of the test the frequency values increase.

In the second experiment, when we examine MDF and MNF values, in 70 % of subjects (except Ebr_2, Hav_2, Bur_2), MDF and MNF values show the biggest decrease at the beginning or at the middle of the test instead at the end of the test. All subjects have given up the test when they felt exhausted. Therefore, the lowest point of the MDF and MNF values do not indicate maximum fatigue. For % 30 of the subjects, the lowest values of MDF and MNF are observed at the end of the test.

Interestingly, in the second experiment, when we compare the beginning and end of the test, for % 30 of the subject's obvious increases are observed at the end (Cey_2, Hal_2, Zeh_2).

In the first seconds, there is a decrease of MNF and MDF values in 60 % of the subjects, an increase in % 20 of the subjects and no significant difference in the rest 20 %. Thereafter, the frequency changes resemble sinusoidal periodic curves.

The most interesting result is found for Hal_2; while the MDF value is ~170 Hz at the beginning; it shows a marked decrease to 116 Hz until 200 seconds. Then, the MDF values increase towards higher frequency ~190 Hz until the end of the experiment. Whereas at Hal_1, there is no meaningful difference for MDF and MNF values during the test. Furthermore, this subject can maintain the test 700 s in the first experiment and 800 s. in the second one. This subject has won rewards at national rowing races.

7. DISSCUSSION AND CONCLUSION

The major findings of this study demonstrate that the inter-individual fatigue profiles differ in both MDF and MNF graphics. Differences are also noted in the first and the second experiments applied to the individuals in terms of the frequency power spectral shift. However, the appearance of the spectral values in the MDF and MNF graphics of both experiments are similar. What is common for all the subjects is that there are decreases and increases in the shape of sinusoidal curves in their MDF and MNF values during the experiments. These sinusoidal curves appear in a sequence in most subjects. This finding may be special to elite rowers.

In most studies till present, it has been well documented that the power spectrum shifts to lower frequency bands during development of muscle fatigue in the sustained sub-maximal contractions [7,48,54,56,58,59,69]. The subjects in the majority of these studies are either sedentary volunteers or university students exercising in a recreational level. Yet, we focus on the elite rowers who have been practicing training sessions for at least three years. The difference in the results between earlier studies and our study may stem from the fact that the subjects are elite female rowers. Rowing needs very intensive and long lasting training program developed to increase power, endurance and velocity, which basically aim to improve performance to win the race. This intensive training program may have caused a difference in the muscle morphology of the rowers.

In the literature, there are different cases regarding the effect of muscle force, on the Power Spectrum of EMG signal.

Firstly, in the previous studies [11,17,54], the power spectrum of the EMG signal was found to shift toward the lower band during prolonged muscle contraction in the dynamic exercises. Although a spectral shift with fatigue is generally attributed to a decrease in muscle fiber conduction velocity over the duration of sustained contraction, there are many possible causes of this shift. These causes may include changes in the duration of the motor unit action potential, recruitment and deactivation of motor units, synchronous discharge of motor units, alteration in activity between synergistic muscles, changes in tissue impedance, changes in diameter of muscle fibers, accumulation of

metabolic by products, water and electrolyte concentration shifts, changes intra-muscular pressure and possible isocheimal, and decreased sarcolemmal excitability.

Studies demonstrated distinct neuromuscular fatigue profiles for the different types of muscle contraction (isometric, isokinetic, eccentric and concentric actions) [9,11], for example, in the study of Masuda at all [11], the effect of contraction types of MFCV, MDF, and mean amplitude of surface electromyography was examined in the vastus lateralis of 19 healthy male adults. The subjects performed knee extension both statically and dynamically until they were exhausted. The static contraction was a sustained isometric extension of the knee at joint angle of 90 degree with 50% of the MVC load. The dynamic contraction was a repetitive isotonic extension of the knee between the angles of 90 and 180 degree with the same 50% MVC load frequency of 10 times per minute. While during the static contraction significantly decreased, MFVC during the dynamic contraction did not significantly change throughout the exercise. MDF decreased and AMP increased during both types of contraction [9]. Sakamato and Mito explained that the increase of accumulation of lactic acid was also one of the reasons the MFCV decreased sustain isometric contraction. The second reason, the reduction MFCV is due to a fall in the velocity for the active group of motor units or a fall in the recruitment of motor units with faster velocity The recruitment of motor units with faster velocity denotes that the motor units with both high conduction velocities and large twitch tension are more resistant to fatigue, and they are predominant in the EMG signal obtained when fatigue processes. The predominance of slow motor unit tends to decrease the MFCV during sustain contraction [61].

In addition to this, altered fatigue profiles were shown over the different muscle on the literature, for example, Masuda et al., CV measured with multi-channel surface electrodes during sustained isometric contraction for 14s. The target force was set at four levels from 30% to 90% of MVC. They studied three typical muscles in even healthy male. In the vastus lateralis, CV increased with contraction force in many cases. In the biceps brachii, CV decreased rapidly with time before the contraction force reached the target levels of 70% or 90% MVC. CV in the biceps consequently showed no apparent dependence on the contraction force. The tibialis anterior showed intermediate change in CV between the vastus lateralis and biceps brachii [6]. This varied results stem from those

different muscles, which have different muscle fiber composition and distribution, and different tissue filter effects both of which can produce different spectral change with force.

Secondly, an increase in muscular force is not only accompanied by an increase in the EMG amplitude but also MDF and MNF that reflects a spectral shift to higher frequencies. Investigators [12,57,89] hypothesize that the change in the power spectrum resulted from the recruitment of larger motor units as the contraction level increased, which caused an increase in the action potential conduction velocity and suggest that additional motor units were progressively recruited to compensate for the loss of contractility due to some degree of impairment of fatigued motor units.

Solomonov and et al. investigated the motor unit recruitment and firing rate variations to the MDF of the electromyogram's power density spectrum with orderly stimulation of the cat gastrocnemius motor units via nerve electrodes. They found that firstly, orderly recruitment of motor units gives rise to an increase in the MDF. Secondly, as a statistical recruitment pattern conforming to the size principal progresses linearly over time, it causes a linear increase in the MDF. Thirdly, changes in the firing rate of active motor units have very little effect, if any, on the EMG MDF as long as the muscle does not develop fatigue [81].

It has been shown that a change-firing rate may not influence the power spectrum or will influence the power spectrum only to a minor extent since a fourfold increase in firing rate will only increase the MNF and MDF by approximately 5 %. Rather changes in shape and duration of active motor units influence the power spectrum [70]. Enoka and Fuglevand also stated, the graduation of force during the shortening contraction was achieved by recruiting additional motor units rather than increasing discharge rate [71]. Researchers found that a comparison among subjects using concentric needle electrodes at a contraction level of 10% MVC has shown that MPF was higher in subjects with a high firing rate than in subjects with a low firing rate. An explanation could be that a subjects with a high firing rate at a given force uses fewer motor units than a subject with a low firing rate, which perhaps may result in a summation of a lower number of action

potentials and may therefore cause an increase in high frequencies of the power spectrum [70].

Most of the skeletal muscle the myoelectric power spectrum MDF increases with increasing force output, possibly reflecting the greater size and conduction velocity of the later recruited (fast twitch) fibers. Whereas, the Erector Spinae, in which fast twitch fibers are smaller than slow twitch, may display an atypical relationship between force output and MDF. Therefore, Mannion and Dolan investigated that ten healthy men held forces ranging from 20-80 % MVC of the back extensors for 4-6s, at muscle lengths corresponding to 30, 60, 90 % of lumbar spinae. MDF was determined from thorasic and lumbar regions of the ES. They found that the muscle length effect affect on MDF might reflect a reduction in conduction velocity of the stretched and narrowed muscle fibers. Force output had a significant effect on MDF although the shape of relationship differed between the two levels of the Erector Spinae. In the thorasic region MDF increased with force up to 40-50% MVC and then leveled off, whereas in the lumbar region MDF was relatively stable up to 30-40%MVC and then declined with increasing force. Their results suggest that the mean fiber size of the later recruited motor units is, in the thorasic region, larger, and in the lumbar region, smaller, than that of he earlier-recruited motor units [12].

In the literature studies have noted contradictory results in both the power spectrum median frequency and muscle fiber conduction velocity (MFCV) with increasing contraction level. In the study of Lowery and colleagues, the Spectral Compression Estimate (SCE) is compared with MDF of EMG power spectrum, the MDF of the EMG amplitude spectrum and MFCV measured during sustained isometric, fatiguing, contractions of the brachioradialis (BR) muscle at 30, 50, and 80 % MVC. Their study shows significant increases in BR. This was not associated with any significant change in MFCV [7]. There are similar increases in the previous studies in the same type sub-maximal exercises [62,67,68,81]. It has been suggested this due to the progressive recruitment of larger motor units having higher MFCV. Rainoldi et al. [8] reported differences in the behavior of MFCV and the EMG power spectrum with increasing force in the biceps brachii. They found small decrease in the mean frequency (MNF) of power spectrum 10, 30, 50, and 70 % MVC without any significant change in MFVC. Zedka et al. [55] examined that ten subjects performed 5 s isometric contractions of erector spinae (ES) at 20, 40, 60, 80, and 100 % MVC by pulling upward on a handle bar attached to the floor

with ten minutes of recovery period of the task They also found that MDF decreased with increasing force. According to their explanation it is a different histological composition of the paraspinal muscles. In the ES the Type I muscle fibers have smaller diameters than the slow twitch Type I fibers. Therefore, the motor units recruited later at higher force level fire at lower frequency.

Thirdly, some researchers found that the characteristics frequencies are unaffected by changes in muscle force and contraction types [14,52].

Most of the studies concerning force and spectral parameters, which is from the literature, have been performed using men sedentary male as subject. Yet, the muscle structure of male and female are different between each other in terms of muscle morphology and the proportion of muscle fiber type is changed with exercises type, intensity and duration between individuals. The subjects in our study who are younger female rowers and are training at elite level can be shown as a reason of the sinusoidal curve in the MDF and MNF values. Age, genetic, sex and trainings cause changes in fiber type, which is demonstrated by investigations. However, how fiber type changes happen cannot be explained exactly. Moreover, the influence of the fiber-type composition and fiber-type areas is not clear. Glenmarc and Hedberg [27] showed that the relative proportion of the different skeletal muscle fiber types change between individuals in relation to sex and training.

Hakkinen examined effects of fatiguing heavy resistance loading on voluntary neural activation and force production ten male and nine female athletes loaded their leg extensor muscles by performing 10 sets in the squat –lift exercise. They found that in males' athletes neuromuscular fatigue may be greater and recovery from fatigue slower than in females' athletes [16]. This finding could partly explain the present results, because some female rowers can maintain doing our experiments without feeling tired for 800s such as Pin, Hal.

Moreover, the influence of the fiber-type composition and fiber-type areas is not clear. Most of the studies show that men have greater type II fiber areas than type I fiber areas whereas the type I areas are greater than type II fibers in women. According to

orderly recruitment of motor units the type II fibers (e.g. motor units) will be recruited after the type I fibers with increasing force. Yet, the type I fibers (motor units) will first be recruited followed by type II A and at highest output level type IIB. In addition to this the type II motor units are associated higher MDF and MNF values [61,62]. The vastus lateralis muscle of females, they found an increase in the MNF value an increasing force level [61]. In similar way, Biledeau et al. [67], demonstrated that an increase MDF and MNF value for anceneous, triceps brachii and biceps brachii muscle.

One of the hypotheses can be confirmed knowing that the recruitment of large, type II muscle fibers, with a higher muscle action potential conduction velocity, is associated with an increase in MDF or MNF values of power spectrum of surface EMG. That both MDF and MNF values are reported that classically to be affected by the MU potential shape and MU firing frequency can be considered as indicators of MU recruitment strategies [66].

Roy et al. [74] found that the rate of change of MDF was not affected by electrode location. Estimates of conduction velocity were most stable in a region between the distal tendon and the adjacent innervation zone for tibialis anterior. Recently, researchers claimed that a very importance source of variation in MNF and MDF during dynamic contractions is the position of the electrodes relative to fiber innervation and termination zones, and the depth of subcutaneous tissue. Both effects are here referred to as changes in the muscle geometry. As the muscle extends and shrinks, the electrode position relative to the innervation / termination zones changes producing time - varying end effects in the signal [57,90]. The vastus lateralis has short muscle fibers and small propagation distance. This anatomical causes the electrode position to be further sensitive to muscle movement. The distance between the innervation zones and the fiber ends were not long enough for the MFCV measurements in some subjects. [13]. Furthermore, in the distal region of vastus lateralis, the size of the stable zone reduces when the contraction level increases, on both the tendon end and of the innervation area. This can be seen as an effect of the mechanical deformation of muscle on the electrical parameters. Moreover, morphological and anatomical differences between subjects make individual comparisons difficult [79]. However, in our study, according to our experiment results, in all of the subjects the shift

of MDF and MNF are like sinusoidal curves. These results that difference between literature and our results do not stem from electros replacement.

The results of the study of Mc Lean [91] and colleagues are shown similarity to our findings. In their experiment, EMG data was collected from the cervical paraspinal extensors, the lumbar erector spinae, the upper trapezius, and the forearm extensors while participants performed their usual computer work activities. No significant slope for either amplitude or mean frequency was determined in either the break or no break trials over an eighty-min recording period. Instead, most data sets revealed a cyclic trend in terms of frequency and amplitude parameters. They explained that, this cyclic trend is a potential indicator of the cyclic recruitment of motor units during sustained postural contractions. In their research, MNF values were registered during 80 minutes with %10 MVC. Normally, a shift towards lower frequency is expected in MNF values during this long time.

In the previous studies, measurements of muscle fatigue have been tested in short time about 50-100 s for both isometric and dynamic contractions. On the other hand, in our study, athletes continued with auxotonic contractions up to the point where they couldn't keep going on the tests due to exhaustion. There were subjects who could carry on the test about 800s (~13 min) with 80 % MVC. If we have looked only at the changes of MNF and MDF in the first 100s, in most of our subjects, a shift to lower frequencies would have been demonstrated in MDF and MNF values in the first 50-100s.

Consequently, in our study what is common for all the subjects is that there are decreases and increases in the shape of sinusoidal curves in their MDF and MNF values during the experiments. These sinusoidal like periodic curves appear in a sequence in most subjects. This results conflict with most of the literature of sustained sub-maximal dynamic contractions. There could be many reasons for this contradiction. Rowing could have resulted in some changes of the fiber type of the female athletes. Moreover, after prolonged training, athletes achieve the ability to sustain high power output although the muscle is working under anaerobic conditions. The decreases, which come after increases in the MNF and MNF values, could have two reasons according to literature results. The first may be the recruitment of larger motor units, which caused an increase in the action potential conduction velocity; additional motor units could have been progressively

recruited to compensate for the loss of contractility due to some degree of impairment of fatigued motor units. The second one may be the cyclic recruitment of motor units during sustained auxotonic contractions.

Above all, there are only few studies on muscle fatigue and training over the elite athlete using spectral analyses of EMG. Therefore, there should be further research on various sport branches to make a fair evaluation of muscle fatigue in the athletes for different contraction types and in different muscles.

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