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ABSTRACT

STUDY OF EMG
FREQUENCY BEHAVIOR

by
Mark Steven Fiedorowicz

It has previously been determined that the power spectral density of an electromyogram shifts towards lower frequencies over time during an isometric contraction. In this study the power spectral density curve was examined to see if changes would occur over a period of time as a subject walked on a treadmill at various speeds. The shapes of the power spectral densities recorded from the soleus shifted to the lower frequencies over time. The parameters associated with the curves showed trends. One of the parameters, zero crossing, demonstrated adaptation and fatigue in all four patients, for the first portion of the study. The average frequency, median frequency, quarter area frequency and three quarter area frequency dropped when calculated over the entire frequency range of 0 to 500 Hz, thus confirming the fatiguing of fast twitch fibers and recruitment of slow twitch fibers to compensate. It was found that there were similarities for four of the subjects, in the shapes of the plots for area under the curve, such as a nadir after 175 seconds of walking and an acme at 250 seconds of walking. The variance another parameter also demonstrated fatigue.

STUDY OF EMG FREQUENCY BEHAVIOR

by
Mark Steven Fiedorowicz
Advisor: Dr. Stanley Reisman

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

Biomedical Engineering Committee

May 1993

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This thesis is dedicated to Anthony and Natalie Fiedorowicz.

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CHAPTER 1

INTRODUCTION

1.1 Purpose

The electromyogram first used to test electrical potentials of muscles during the 1910s has become an extremely useful tool in the 1990s. The computers of today can handle large quantities of data taken at high sampling rates. These can be stored and analyzed and with the new technological advances many more concepts of neuromuscular control will be comprehended. The purpose of this study is to determine if fatigue, adaptation and motor unit recruitment can be observed in a person walking on a treadmill. Most fatigue studies have been done using an applied force on a muscle. In this study factors of gait and recruitment become involved and will affect various parameters of the power spectral density. Even with these additional factors, it was predicted that changes would be detected.

1.2 Muscle Physiology

1.2.1 Functions

The two primary functions of muscles are motion and support. Out of the three types of muscle, cardiac, skeletal, and smooth, the present study focuses on the observation of skeletal muscle. The soleus and lateral gastrocnemius were the two skeletal muscles that were examined. The soleus is

located directly in back of the tibia, shin bone. The main function of this muscle is to flex the foot so the toes point downward. The soleus is attached with tendon to the back of the head of the fibula, a slender bone situated along the outside of the tibia. The other attachment is to the Achilles tendon which is shared also by the gastrocnemius muscles. The lateral gastrocnemius is situated along the back outer side of the tibia. The other attachment of this muscle is to the outer condyle of the femur right behind the knee. Its main purpose is to flex the knee and also point the toes downward. Both the soleus and the gastrocnemius muscles are extensively used in walking [1].

1.2.2 Muscle Structure

Each muscle is made of many cells called muscle fibers. A muscle fiber wears its name well. Its size ranges anywhere from 10 to 100 micrometers in diameter and can extend up to 20 centimeters in length. These fibers are connected to tendons which are attached to the bone. In muscles where the fibers do not span the length of the muscle the fibers are attached to connective tissue [2].

Looking through a microscope, we can see that each muscle fiber is made up of smaller myofibrils. Repetitive light and dark bands can be seen surrounding the myofibrils. A light band dark band unit is known as a sarcomere. Each sarcomere contains actin and myosin filaments which slide

along each other. It is this sliding mechanism that shortens or lengthens the sarcomere. The summation of all the sarcomeres reacting is responsible for muscle contraction and relaxation [2].

1.2.3 Muscle Control

Each skeletal muscle fiber is under neuromuscular control. Motor neurons are nerve cells which originate at either the brain or spinal cord and terminate at the muscle cells. A motor neuron controls more than one muscle fiber's contractions, but note that each muscle fiber is controlled solely by one motor neuron unless the fiber is extremely long. The nerve cell ends in an expanse called the motor end plate. It is this location where the contraction begins. The fibers each neuron controls are not conglomerated but are dispersed throughout a muscle. The motor neuron and the muscle fibers it controls are termed motor unit [3]. Also note that the soleus and later gastrocnemius do not have the fine control that muscles such as the eyelids have. This is because there are more fibers per motor unit in the legs than in the eyelids. A motor unit in the soleus may be responsible for thousands of muscle fibers [2].

During a single muscle fiber contraction, the brain delivers a motor unit action potential through a motor unit. The motor unit action potential originating from the brain propagates unhindered by effects of distortion to the muscle

facing 4

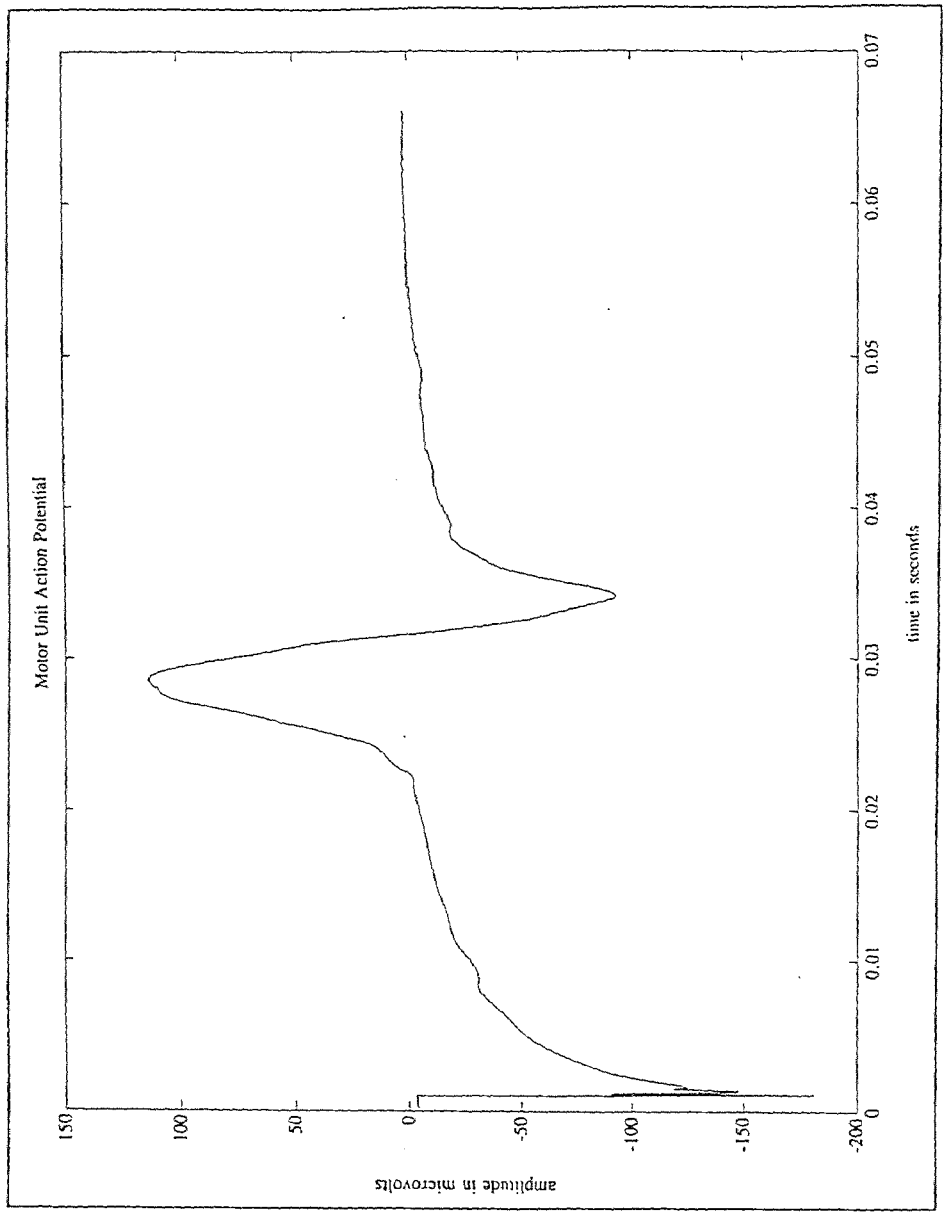

Figure 1 A Sample of a Motor Unit Action Potential

fibers. A nerve's physiology works in such a way that an impulse in one portion of a nerve will affect the adjacent portion to cause the same pulse there. That adjacent portion will do the same to the next adjacent portion and so on. An analogy, in a mechanical sense, is to hold a long rope in one hand and tie the other end to a pole. With a quick flick of the wrist, you can start a wave propagating to the end of the pole.

The action potential is a very complex process. To put it in simpler terms there is an exchange of positively charged sodium and potassium ions across the cell membrane. This transfer of ions produces a change in voltage across the cell membrane. It happens very rapidly, within a few milliseconds. The shape of voltage detected by a single motor unit action potential response is shown in (figure 1). Voltage sensitive channels within cells open and close governed by the concentration of the ions. Thus this characteristic shape is produced with each evocation from the brain. An electromyograph waveform detected by an electromyograph machine can record a summation of all the action potential responses of the muscle fibers in the vicinity of the electrodes [2].

To cause a voluntary contraction one must first think of doing the desired movement. Emotions, memory and other high thought processes are involved. For instance, a person begins to walk but realizes the floor is slippery because it

is wet. He then remembers the time when he walked very fast on a hot summer day by a pool side and he fell down and scraped his knee. He cogitates to walk slowly and carefully.

To start a contraction the brain must have information about how far the muscle is stretched to begin with; Is there a shoe at the end of the leg that will require a greater attraction? These and other sensory factors are sent to the brain for processing before the onset of motion. The part of the brain associated with motor activity in the legs is located on the top of the brain in the cerebral cortex [1], [2].

Once the brain processes all the information needed, only then does the muscle voluntarily move. The brain; however, programs itself to do certain motor actions. Infants need to learn how to walk; whereas, adults do the task effortlessly.

1.2.4 Muscle Fatigue

When a person lifts an object, it is not lifted by a mere motor action potential. Many muscle fibers are induced to cause tension in order to move the object. In walking and standing the same principle applies. Both actions will tire a person out if he does them for a prolonged period of time. This is because muscle fatigue has set in. As a muscle fatigues it looses its ability to contract [2], [4].

Weight lifters become fatigued because of lactic acid build up in the muscle when energy is expended. This decreases the ability of actin and myosin to bind to each other thus decreasing the ability for muscle contraction. Long distance runners suffer fatigue because their glycogen, the muscles energy source, has become depleted. Psychological fatigue is a completely different type of fatigue which occurs in the brain. The brain decides that the muscles cannot continue to contract and therefore contraction ceases [2], [4].

Each muscle contains a mixture of two fiber types. Fast twitch fibers have a fast contraction rate. Slow twitch fibers have a slow rate [5]. The soleus and the gastrocnemius muscles contain a greater amount of slow twitch fibers than most other muscles. These muscles are essentially non-fatigable compared to the other muscles of the body. A person no matter how strong cannot walk on his or her hands all day but certainly they can walk on his or her feet. Fast twitch fibers on the other hand are more prone to fatigue than the slow twitch [5].

The amount of slow and fast twitch fibers that each muscle contains is based upon a genetic code. Each muscle can be trained for endurance or strength so that certain fibers will perform better than others, but training will not change a slow twitch fiber to a fast twitch fiber or vice versa.

Some scientists have studied EMG responses of single motor units and found that responses in the fast twitch fibers decreased and slow twitch fibers increased as fatigue set in [6]. Taking this to a macroscopic view, this would cause changes in the electromyogram over time because slow twitch fibers will show lower on a frequency plot in relation to fast twitch.

1.2.5 Recruitment

Recruitment is the process of additional motor units firing to compensate for a greater change in force. Additional motor units may also fire in the case of maintaining the same force level to compensate the failure to do so by the fatiguing muscle fibers. This is due to the fact that fatigued muscle fibers will not contract with the same efficiency as they did at the commencement of the contraction [2].

Large motor neurons are usually called upon first to begin contraction. In general, the initial voltage needed for the motor neuron to fire is proportional to its size. The slow twitch fibers are associated with small motor unit size. If a greater contraction is needed the large neurons will ensue firing of the fast twitch fibers. Once all of the fibers in the muscle are being utilized, the muscle is said to be at maximum voluntary contraction [5].

1.2.6 Adaptation

Articles regarding muscle adaptation usually contain discussions of increase in capillaries around slow or fast twitch fibers, increase in fiber diameter, and contractile activity. [2], [4], [5], [7]. The present study is not concerned with this type of adaptation but is concerned with mental adaptation. If a behavior such as walking at a constant high speed has not been learned then it will take a certain amount of time to do so to obtain a minimal energy expenditure. This behavior should be reflected in the response of the electromyogram. With a basic view of how the muscular system works now we turn to some of the aspects of frequency analysis needed to accomplish this study.

1.3 Frequency Analysis

1.3.1 Fast Fourier Transforms

Frequency analysis has proven to be an excellent technique for the extraction of information from biopotentials. The motor unit action potential train is a summation of many motor unit action potentials and to an untrained eye looks like noise. By taking a power spectral density, we can determine some characteristics which will differ between normal people and people with pathological disorders that cannot be detected just by examining a time plot.

The power spectral density is simply an encompassment of a series of sine waves which when added together will produce the discrete time waveform x(n) [8].

$$x(n) = \frac{1}{N} \sum_{k=0}^{N-1} X(k) e^{jkw_o n} \quad 0 \leq k \leq N - 1 \qquad \textit{(Eq. 1-1)}$$

In the equation, N is the number of data points and is an integer. k and n are integer values in between 0 and N-1. j is the square root of -1. w_o is the fundamental frequency which is equal to $2\pi/N$. Note that time signals will be represented in lowercase letters and the frequency signals will be represented in uppercase. Also, as a reminder, x(1), the first point in the temporal waveform, doesn't solely rely on the value of X(1). It relies on the integration of all the frequencies. X(k) is the discrete frequency function.

(Eq.1-1) has a sister or Fourier transform pair.

$$X(k) = \sum_{n=0}^{N-1} x(n)\, e^{-jkw_o n} \quad 0 \leq k \leq N - 1 \qquad \textit{(Eq. 1-2)}$$

This equation, the discrete Fourier transform, allows the data to be transformed into a frequency response. A fast Fourier transform (FFT) is the method which the computer used in the experiment to obtain the frequency response. The FFT has a reduced number of multiplications but an increased number of additions when compared to the standard Fourier Transform. The FFT takes 524288 multiplications to complete a 2^{16} point transform. This is down considerably from 4.3

billion calculations needed to calculate the discrete Furrier transform. The approach is to break the discrete Furrier transform into 2 smaller (N/2) point transforms. Then break down the two (N/2) point transforms into 2 smaller transforms, giving 4 (N/4) transforms and so on [8], [9].

A fast Fourier transform of the time based signal can be multiplied by its complex conjugate to obtain a power spectral density. The power spectral density curve holds an array of amplitudes which correspond to sine waves of various frequencies. If each amplitude of a power spectral density was multiplied by its respective frequency and all the terms were added together it is possible to obtain the original time function.

1.3.2 Other Methods

Another way of doing frequency analysis is the bandpass filter technique which can be done in real time. The signal is input into the band pass filters. The output of each of these filters is put through its own full wave rectifier. The average is then obtained by putting this signal into a low pass filter which extracts the DC component [10]. It would be beneficial to examine the power spectral density in real time. However, the spectrum of an EMG recording of walking is very sporadic. The amplitudes of each frequency vary tremendously from second to second [5]. For a single

voluntary contraction five seconds is a sufficient amount of sampling time for data extraction. In the case of analyzing electromyograms of the calf muscles while walking, longer periods of time are needed. This calls for large data storage which is handled more readily by a computer than the bandpass filter technique.

1.4 Frequency Parameters

Eight measures were computed from the Fourier Transform. These will be used to characterize the experimental data. Definitions for the frequency parameters will now be presented first.

1.4.1 Area Under the Curve

The first thing that was done to the power spectral density curves was a calculation of the area underneath them. This is an indication of how hard the muscle is working. The greater the area the greater the number of motor units are firing.

$$\text{area} = \sum_{k=0}^{N/2-1} X(k) \cdot (f(k+1)-f(k)) \qquad \textit{(Eq. 1-3)}$$

1.4.2 Mean Frequency

The mean frequency depends upon the frequency of gait, the frequency of muscle fiber contraction, and motor unit recruitment.

$$\text{mean frequency} = \sum_{k=0}^{N/2-1} (X(k) \cdot f(k)) / \text{area} \qquad (Eq.\ 1\text{-}4)$$

1.4.3 Variance

The variance relates to the confinement of the curve about the mean frequency. The second moment is first calculated as follows [11], [12].

$$\text{2nd order moment} = \sum_{k=0}^{N/2-1} (X(k) \cdot f(k)^2) / \text{area} \qquad (Eq.\ 1\text{-}5)$$

The variance is then equal to this second order moment subtracted by the square of the mean frequency.

$$\text{variance} = \text{2nd order moment} - (\text{mean frequency})^2 \qquad (Eq.\ 1\text{-}6)$$

The variance will display information on increases in the high and low frequencies about the mean. Gait contains lower frequencies. Muscle fiber contraction provides a high frequency response.

1.4.4 Skew

The skew indicates how the shape of the curve is offset from the average frequency. It is derived from the mean frequency, the variance and the third order moment.

$$\text{3rd order moment} = \sum_{k=0}^{N/2-1} (X(k) \cdot f(k)^3) / \text{area} \qquad (Eq.\ 1\text{-}7)$$

The skew is then given by the equation [13].

$$\text{skew} = \text{3rd order moment} - 3 \cdot (\text{mean frequency}) \cdot (\text{variance})^2 - (\text{mean frequency})^3 \qquad (Eq.\ 1\text{-}8)$$

1.4.5 Median Frequency

The next parameter determined was the median frequency. This is the point where the area to the left of this frequency is equal to the area to the right. The median frequency can be calculated by equation 1-9 utilizing equation 1-3.

$$.5 = \frac{\sum_{k=0}^{(N/2)-1} X(k) \cdot (f(k+1)-f(k))}{\sum_{k=0}^{(Z/2)-1} X(k) \cdot (f(k+1)-f(k))} \qquad \textit{(Eq. 1-9)}$$

(N/2)-1, as before, is the number of points of the power spectral density. (Z/2)-1 is the value which makes the equation equal to a 0.5. f(Z) is the median frequency.

1.4.6 Pth fractiles

Other analysis parameters are the quarter frequency and three-quarter frequency [14]. These have been labelled as 'pth fractiles'. The quarter frequency is the frequency in which the area to the left of this frequency, under the spectral curve, is one quarter of the total area. Calculated the same way, the three quarter frequency is the frequency where the area under the curve to the left of this frequency is three quarters of the total area. The equations for these parameters are the same as for the median frequency except that 0.5 is replaced by .25 or .75 in equation (1-9).

1.4.7 Zero Crossings

Zero crossings were calculated for each window. This is an examination of how many times the temporal waveform crosses the zero line or zero voltage. The computer program utilized examined the sign of the function. A for loop which counted from 1 to N/2 - 2 was applied. Each discrete amplitude was compared with the following amplitude. If there was a change of sign between the two values a counter was incremented.

1.4.8 Peak Frequency

The peak frequency is the frequency with the highest amplitude. It was calculated to see how gait affected the treadmill study. Walking is a periodic motion and the frequency of stepping might overpower the rest of the EMG signal. As we will see, this effect was not major.

1.5 Previous Studies

1.5.1 Power Spectra Shifts

The present study used frequency analysis because it is known that the power spectral density changes over time due to factors of fatigue, adaptation and motor recruitment. Studies have been done showing that contraction level, length of the muscle, and the side of the body the muscle is located can be related to changing patterns in EMG power spectra [15]. One experiment also concluded that the muscles studied had a power spectrum that could be reproduced [5].

When a muscle was contracted for five seconds and allowed to rest and contracted for five seconds again, the two power spectra attained showed that the inflection points of the power spectral curves and their respective amplitudes were within five percent. It was also concluded that just from the shape of the power spectral densities, it could be identified correctly as being from a certain muscle. Many researchers have found that EMG amplitude increases with time and have detected a shift in the frequency response curve [4], [16], [17]. [5] examined EMG of 10 different muscles groups. Tension was placed perpendicular to the limb involved. An increase in the lower frequencies and a depression of the higher frequencies was found over time [5]. It was noted that if the peak of the frequency curve was located between 50 to 70 Hz it had shifted to 35 to 45 Hz at the end of contraction. This was explained as a decrease in discharge frequency of individual motor units. It was also noted that the total power or the integration of the frequency response increased over time. This could be explained by the recruitment of new motor units as fatigue arises.

1.5.2 Recruitment

Recruitment can be defined as the firing of additional motor units as time progresses during a sustained contraction [18]. In a particular study during a three second time

window, it was found that the stimulation of the gastrocnemius motor neurons caused a rise in median frequency from the evoked muscle fibers. A surface electrode which encompasses a greater amount of neurons showed a constant median frequency. Therefore, we cannot say the results were contradictory to most other studies which claim that the median frequency shifts to the lower end of the spectrum [2], [4], [7], [8], [17].

1.5.3 Median and Mean Frequency Shifts

It was found that the non - dominant hand's muscles fatigued faster than the dominant side [15]. This was reflected not only in EMG but amount of force that could be maintained. A slower decline in the mean frequency on the right hand for right handed patients was also found. The group also claimed that there was no notable fatigue within the first minute and a half.

A study was done on how muscle fiber length relates to fatigue [8]. In this case the muscle was electrically stimulated in order to produce fatigue. The mean power frequency was calculated as the ratio of the first order moment to the zero order moment, as was mentioned before. The studies showed a decrease in the mean power frequency over time. It was also found that the greater the muscle was stretched the greater the muscle had become fatigued at the

end of each study. The maximum peak of the power spectrum of the soleus was found to be around 10 Hz.

An interesting study was performed by two biomedical engineers [19]. Since gait is a periodic function, it can be broken down into envelopes of certain time intervals, depending on the time from heel strike of the right leg to the next heel strike of the right leg. They were able to match peaks from one envelope with the peaks of another. This experiment showed that if a correlation like this could be made in the time domain then the nine parameters which were used in the present study contain valuable information about motor recruitment, fatigue and adaptation to be retrieved from the power spectrum of the signal. However, they admitted that they could not determine from the profile whether the patient was diseased just from envelope examination. This shows the need for frequency analysis.

Another group studied the mean frequency; median frequency; the slow wave ratio, the area under the power spectral density curve above 40 Hz over the area below 40 Hz; and the difference in power spectra from onset of contraction until relinquishment [17]. They looked at acute fatigue and accumulative fatigue. Acute fatigue was considered to be a contraction of a 1 kg or 5 kg weight for a six minute period. It was decided that the time of contraction had to be longer than thirty seconds to show detectable signs of fatigue. The results showed that the

mean frequency dropped an average of 3 Hz for the subjects holding a 1 kg weight for six minutes and an 11 Hz drop for the subjects holding the 5 kg weight. The accumulative fatigue study was performed by having the patients type for three hours. They could not find any interesting results from this part of the study.

A team of kinesiologists examined the differences in EMG of walking on a treadmill and normal walking [20]. The treadmill gait was found to be longer in length. The EMG revealed that a person utilizes the treadmill to bring the leg backward, thus less energy is expended and muscles are utilized much differently than in normal walking. Other kinesiologists examined the minimum muscle energy by a correlation of the EMGs for ten different muscles and calculated minimal forces that each muscle produced [21]. They proved, with the addition of moments taken into consideration, that myoelectric signals could not depict the force that the muscle had exerted and that more physiological factors were needed to complete the study.

A study on errors in EMG power spectra was performed by [14]. The median frequency, zero-crossing frequency, the mean frequency and pth fractile frequencies where 'p' was 0.10, 0.25, 0.50, 0.75, 0.90 were examined. All methods were used in the present study except for the 0.10 and 0.90 pth fractile frequencies. They found that to do any spectral analysis of EMG one must look at successive periods of a

finite duration. Although the study tried avoiding fatigue effects, information was found that was pertinent to this thesis. The median was claimed to be less affected by the addition of white noise as compared to the mean and zero-crossing frequency. The median might be the best calculation to look for alterations caused by fatigue. Therefore, pth fractiles, mentioned above, were utilized in the present study because of their similarity to the median.

The mean and median frequencies were examined in another study [16]. Ratios of certain characteristics were examined, for example, the ratio of the area below 25 Hz to the area above 25 Hz of the power spectrum. It was concluded that the median frequency could be more useful in conduction velocity estimation than the mean.

1.6 Summary

With all these studies in mind, the conjecture was that walking on a treadmill would provide useful information about fatigue, adaptation and motor recruitment. The same parameters mentioned in the previous studies could be obtained from the electromyogram of a person walking on a treadmill. The fatigue studies that have been mentioned used an applied force on a muscle. In the present study data was acquired while the muscle was in motion. Fatigue, adaptation and motor unit recruitment can be observed in a person walking on a treadmill regardless of the motion.

CHAPTER 2

METHODS AND MATERIALS

Equipment used during the experiment were the following: Quinton treadmill (R); DANTEC COUNTERPOINT (R) which is a 4 channel electromyograph; computer with a Metrabyte Das-16 data acquisition board, Matlab data analysis package, and a 486 clone.

2.1 Treadmill

The treadmill had the capability to rise to an incline of 25 percent and advance to a speed of 10.4 mph. The machine was much more durable than the ones in the department store, which have 'give' when you walk on them. This was important to the study because it was important to have a stiff surface. On a flexible surface muscles will fatigue at a slower rate. Both the speed and incline had a digital display and the ability to change the speed and incline within seconds was desirable for the study.

2.2 DANTEC COUNTERPOINT

The DANTEC COUNTERPOINT, the electromyography machine used, had many features most of which will not be discussed. The electromyograph had 64 different preset programs to be utilized. The motor unit action potential trains could be observed on its color monitor capable of displaying four

channels of EMG simultaneously. The machine possessed an output port for connection to a computer which allowed the four channels to be read. However, one channel was read due to the limited space on the hard disk. This is why only one channel was selected in recording the data. Gain and sweep speed were controlled by two joysticks. Upper and lower frequency bandwidths for the filters could be altered. The one thing it could not do is show a power spectral density for a twenty-five second interval. The DANTEC did the following amplifications with the electromyogram (Table 1).

Table 1 Amplification of the Electromyogram as Received from the Output for Various Voltage Per Division Settings

Volts Per Division	Amplification
10mV/D	100 X
5mV/D	200 X
2mV/D	500 X
1mV/D	1000 X
500uV/D	2000 X
200uV/D	5000 X
100uV/D	10000 X
50uV/D	20000 X
20uV/D	50000 X
10uV/D	100000 X
5uV/D	200000 X
2uV/D	500000 X
1uV/D	1000000 X
.5uV/D	2000000 X

These amplifications were measured prior to the experiment with a known sinusoidal input.

2.3 Surface Electrodes

Two surface electrodes made of aluminum and copper were used along with the electrode cables which came with the EMG kit. The electromyography studies that began in the early 1910s, have evolved into two methods of retrieving the potentials. In the beginning the clinicians were non-invasive putting the electrodes on the outer surfaces of the skin in order to detect EMG activity. Data were collected but it could not be determined what would happen on the microscopic level. Needle electrodes were introduced which could show a single motor unit action potential.

These are inserted under the skin and are touching the muscle fiber. Most are secured by a spring mechanism making them hard to move. The needle electrodes eliminate the low pass filtering effects of the skin and in some instances are much more preferable to use than the surface electrodes [22]. Needle electrodes were not used in the study because they would inflict pain on the subjects, irritating their muscle. Hence, in the present study surface electrodes were used because of this and desire to see the overall effect of the muscle.

2.4 Data Acquisition

The Metrabyte DAS-16 board was previously installed in the personal computer used for data acquisition. Because the computer was shared with others, data was transferred to a

486 clone for analysis. The board was set to bipolar ± 5 volts. This was sufficient to retrieve any signal that the electromyography machine produced. The signal was clipped in some instances of very high motion artifact. This however, happened infrequently and it was more important to have an accurate signal most of the time than to have a signal with little definition but not clipped.

2.5 STREAMER

The STREAMER software package was used to acquire the data. The STREAMER program had a maximum sampling rate of 50 KHZ for 1 channel, or 3.125 KHZ for 16 channels. Data files were saved in packed files which had to be unpacked to ASCII code. For more about STREAMER commands please see Appendix A.

2.6 MATLAB

MATLAB was used for data analysis. The MATLAB software is excellent for doing Fourier analysis and other calculations. It is very user friendly. Specific programs can be written to create functions, print out graphs, etc. as well as use functions all ready written to perform different tasks. Therefore, the professional version was acquired for use on the 486. This version can be used simultaneously with windows which cuts down the time of analysis tremendously. It took one minute thirty seconds to calculate the nine

parameters for one 25 second time window which entailed taking an FFT. On an PC-XT it would take well over an hour. MATLAB files could be edited and packed files could be unpacked all from the same computer.

CHAPTER 3

PROCEDURE

3.1 Set Up

The first portion of the study entailed having the patient walk on the treadmill. Two surface electrodes were used along with a ground strap. The site of electrode placement was cleaned with an alcohol pad and an electrolytic gel was placed on the electrodes. The active electrode was placed underneath and betwixt the two gastrocnemius muscles. The reference electrode was placed 1.5 cm below the active. The ground strap was placed just above the ankle. There is little muscle activity in this section of the leg. The electrode wires were put through the belt loop of the pants or taped to the oblique to avoid having the patient trip.

3.2 Protocol

The protocol used was one that was similar to another study of heart rate variability so that data may be compared with it in the future.

Table 2 Protocol for the First Part of the Study

Walk for four minutes at 1 mph
Walk for four minutes at 2 mph
Sit for four minutes
Walk for four minutes at 1.5 mph
Walk for four minutes at 2.5 mph
Sit for four minutes
Walk for four minutes at 3 mph
Walk for two minutes at 3.5 mph

The total procedure lasted about 40 minutes for each subject. The second part of the study entailed a nine minute walk on an incline of 20 percent. The speed of the treadmill was set at 3.5 mph. Four subjects which will be numbered from 1 to 4 partook in the first part of the study. Four subjects which will be numbered from 5 to 8 partook in the second part of the study. The soleus muscle was examined in these eight subjects. Subject #9 also partook in the first part of the study; however the lateral gastrocnemius was examined.

3.3 Filtering

The filtering range used in [18] was 10 to 500 Hz and the data were sampled at 2048 samples per second. [14] used a frequency range of 30 to 600 Hz. It was decided to use a bandwidth of 2 to 1000 Hz for the present experiment. The low cutoff frequency would eliminate the effects of gait on the signal and the high cutoff frequency would allow examination up to 500 Hz of the frequency spectrum. It is certain that the 2 Hz corner frequency had cutoff some frequencies which were resultants from recruitment but the concession had to be made. A change in frequency parameters should be detected over time regardless of the bandwidth.

3.4 Voltage Sensitivity

For the first study the voltage sensitivity was set to 200 microvolts per division. The EMG signal was then amplified 5000 times by the DANTEC and sent to the analog output. The DANTEC allowed a maximum of ± 5 volts without clipping. When the speed of the treadmill increased to above 2.5 mph the amplitude of the electromyogram increased to the point where the voltage sensitivity had to be changed to 500 uV/div. In this case the amplitude of the signal was magnified 2000 times.

3.5 Sampling

Data was acquired in various formats. As a precursor to the study a patient's electromyogram was sampled at 10 KHZ. It was found that there was minimal activity above 500 Hz, so the sampling rate was lowered to 1000 Hz for the study. The sampling rate must be at least twice the highest frequency in the signal.

Table 3 Sampling for First Part of the Study

speed	Subject #	1	2	3	4
1 mph		4 min	4 min	4 min	4 min
2 mph			2 min	2 min	4 min
1.5 mph		4 min	4 min	4 min	4 min
2.5 mph		4 min	2 min	2 min	4 min
3 mph			4 min	4 min	4 min
3.5 mph			2 min	2 min	2 min

Since there was limited space on the computer hard drive data had to be transferred onto floppy disks. This is the reason why data was not taken for the entire period for subjects #1, #2 and #3. Data file size was specifically set to 1.1 megabytes in order to fit on 5'1/2", double sided, double density disks. This allowed a recording time of nine minutes and twenty-three seconds for a 1 KHz sampling rate, assuming 2 bytes per data point.

3.6 Error Analysis

The retrieved data, after being unpacked, was in ASCII code with values in the range of ±2048, where +2048 corresponding with 5 volts, and -2048 with -5 volts. This gives an optimal accuracy of within 4.88 microvolts for each of the data points with the DANTEC machine set at 200 microvolts per division and within 12.2 microvolts for each of the data points with the machine set a 500 microvolts per division, (table 1).

$$\frac{5 \text{ volts}}{2048} * 200 \text{ uV/div} * 10 \text{ div} = 12.2 \text{ uV} \qquad \textit{(Eq. 3-1)}$$

The data acquisition board had an internal offset of 4.4 millivolts on the 5 volt scale. This was eliminated by detrending the data. However, what could not be remedied was noise. With the DANTEC attached to the board but no output from the DANTEC the value fluctuated from the offset up to

facing 29

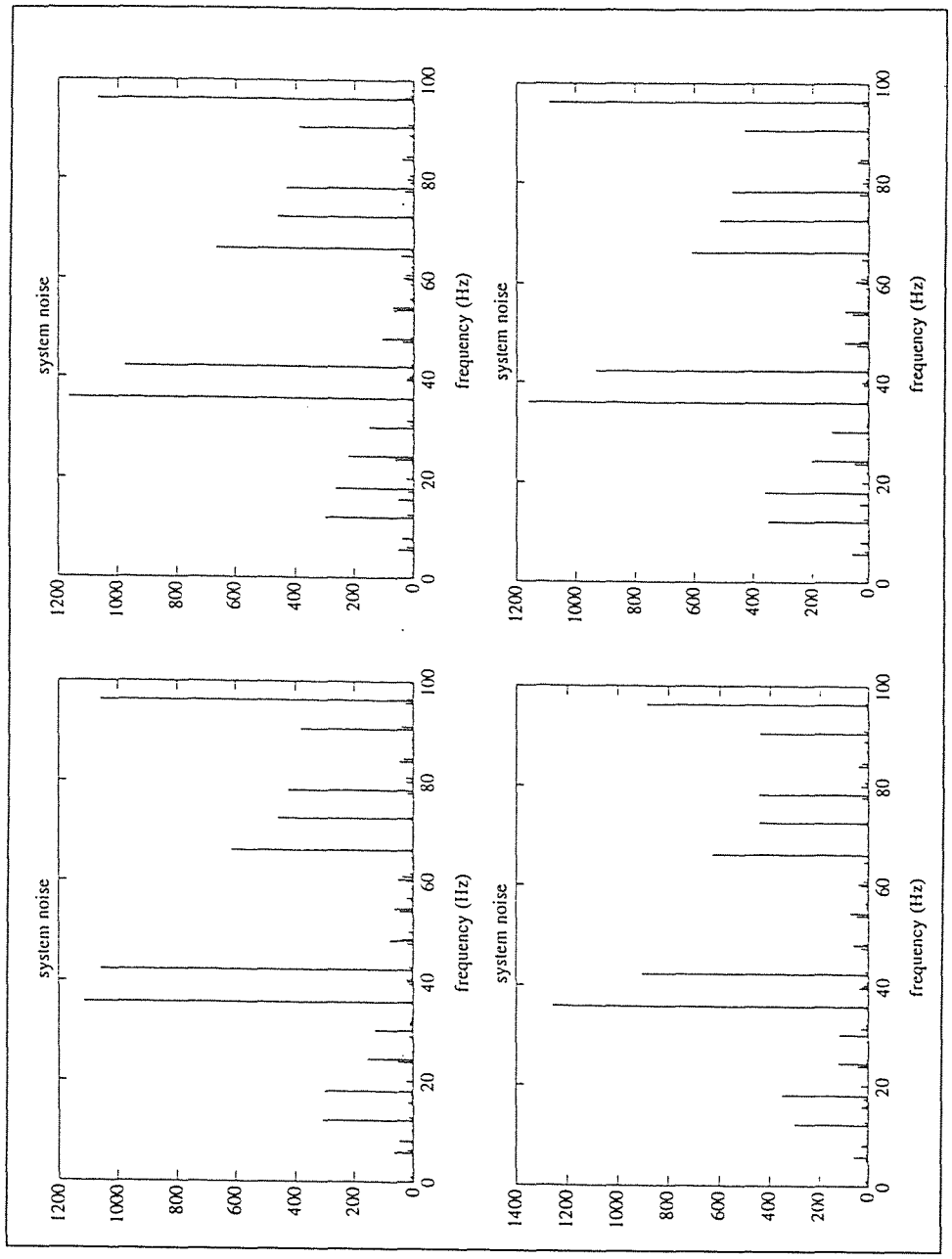

Figure 2 The Power Spectral Density of the Noise from the A/D board

2.4 millivolts on the 5 volt scale. Therefore, the actual certainty of a value was within 24.4 microvolts.

$$\frac{2.44\ mV}{5\ V} * 200uv/div * 10\ div = 24.4\ uV \qquad (Eq.\ 3\text{-}2)$$

The maximum value that could be obtained at the 200 microvolts/division setting was 2 millivolts. So there was approximately a one percent difference at the maximum.

Nevertheless, the noise was small compared to the EMG signal which was seen when a power spectral density was taken. (Figure 2) shows the noise retrieved from the DANTEC. The assumption is made that this noise will not change over a period of time. On the facing page are the power spectral densities taken of the board noise from four 25 second consecutive time windows. Notice that the values of frequency for the peaks with amplitudes above 200 remain within 20% of the initial value during the four plots. There are also no frequency shifts from plot to plot. Since the maximum value of the noise power spectrum is approximately 1200 and the power spectral plots obtained from the electromyogram had amplitude axes of 50000 or greater, then nearly all changes in the power spectral analysis could be attributed to a change in the frequency of the EMG signal and not a change in the noise from the board.

3.6 MATLAB Programming

Once an FFT is calculated by MATLAB, it is in a complex form. When it is multiplied by its complex conjugate it becomes real. The numbers calculated are the amplitudes of the power spectral density (PSD). The frequencies above N/2 are redundant and are simply a mirror image of the frequencies below N/2, so these are discarded. The power spectral density was in the frequency range of 0 to 500 Hz. This is a sufficient frequency range to capture EMG from surface electrodes. It was necessary to sample with the data acquisition board at twice the highest frequency of the signal to avoid aliasing effects. Therefore, the data was read by the data acquisition board at 1 KHz.

The value N, for a FFT, could be any multiple of two. However, for the best resolution a FFT should be taken with at least the number of points in the time signal. The present study looked at time windows of 25 seconds. At 1 KHz sampling, 25000 points were obtained per window. The FFT was taken to 2^{16} or 65536 points. The last half of the points were discarded which left 32768 points remaining. Therefore the frequency resolution is 500 / 32768 or .0153 Hz. A power spectral density is plotted as a frequency versus amplitude plot. The y axis, the amplitude, has units of volts squared per Hz.

MATLAB programming also allowed polynomial fits. Polynomial fits are curves calculated to best fit data

points rather than drawing a straight line point to point. A first order polynomial fit is the best straight line which can be drawn to give the minimal deviation from the actual points of the curve. The second order polynomial fit is the best parabola that would fit the points. The higher the order the better the polynomial fit. Polynomial curves can be used in predicting what point might be plotted next [23]. Program 7 in the appendix calculates a first order polynomial fit for curves with less than 7 data points; a second order polynomial fit for curves with less than 15 data points; and a third order polynomial fit for curves with less than 25 data points.

3.7 Data Analysis

Data were unpacked in blocks of 25000 points. Power spectral densities of these data blocks were then obtained. Most data files were multiples of 25000 in length, but, some data at the ends of the packed files were not 25000 data points long. These files weren't used in calculations. For the first part of the study, files were recorded for four minutes. This gave nine power spectral densities to be analyzed. Files recorded for two minutes gave four power spectral densities to be analyzed. For the second part of the study, data was acquired for nine minutes and twenty-three seconds. This allowed examination of the characteristics of twenty- two power spectral densities.

The frequency parameters were calculated by MATLAB Programming. In Appendix B the source code for all of the calculations are found. Comments are made on lines beginning with a percent sign. They are in italics. Program code is written in bold. The time taken by the 486 computer to calculate the power spectral density and the nine parameters was about a minute and a half for each window. This is extremely fast considering the number of equations that need to be solved per window. The speed was necessary because there were over 250 windows to be examined in the study.

3.8 Methods of Examination

Besides examining the frequency spectra in their entirety, the frequency spectra were examined in sections. The spectra from 0 to 35 Hz were examined as were the spectra from 35 Hz to 250 Hz. The idea was based on the work of [16] who examined the ratio of the root mean square of low frequency components to the root mean square of the high frequency components. An increase in ratio was found related to a decrease in conduction velocity. Therefore, valuable information might be gained by computing the same nine parameters for the higher and lower portions of the density.

Plotting of frequency spectra was first done by a screen dump from a Sun (R) work station to a Hewlett Packard Laser Jet (R). This was done to examine alterations in the shape of the frequency response over time. For speed

of plotting and ease of transfer the FFT was shortened to 2^13 points. A spectra of the FFT taken with 2^13 points does not have the definition as one taken with 2^16 points, but if one shows changes in shape then the other will also.

Chapter 4

Results

4.1 Subject Reactions to the Study

The subjects had several pertinent comments during the study that need be mentioned. Subject #1 said he felt tired at the end. Subjects #2 through #4 said that they felt no signs of fatigue. Subject #5 felt fatigued after five minutes but continued on for two more minutes until she asked to stop. This is why her data ends earlier than Subjects #6 to #8. Subject #6 mentioned she skied cross country and felt no different from the beginning of the exam. Subjects #7 and #8 said they were slightly tired at the terminus. However, signs of fatigue were found in all subjects regardless of what they claimed.

4.2 Power Spectral Plots

The power spectral plots taken with 2^{13} points were first examined for some of the subjects. The shapes of these were compared. When frequency shifts were found, it was then decided to continue by scrutinizing the longer 2^{16} point FFTs. In this chapter are examples of how the curves were interpreted by the examiner. It is important to examine the changes within the power spectral density in its entirety. Fatigue cannot be determined just from the calculation of nine parameters. Certain changes must occur in the shape of

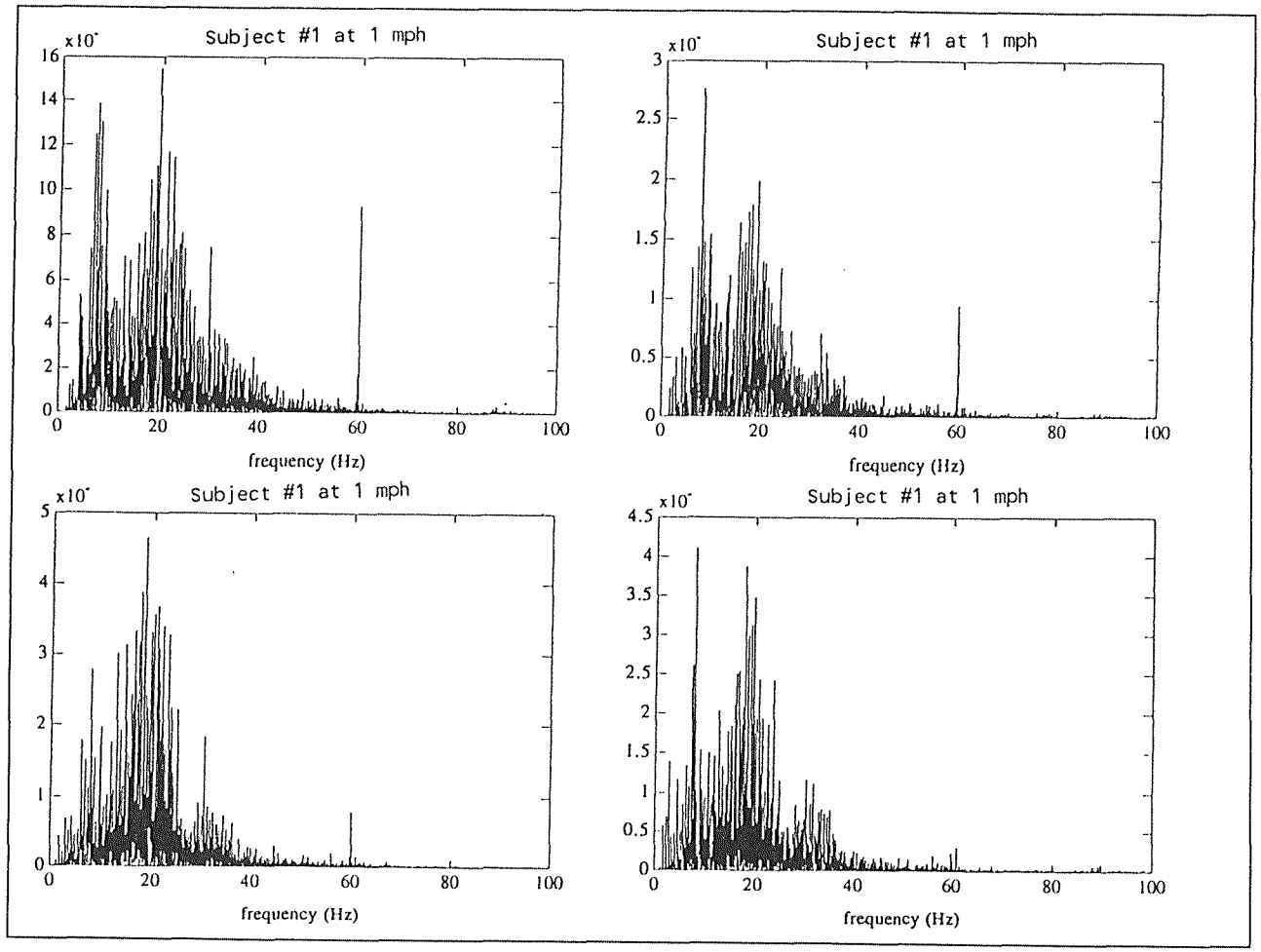

Figure 3 Power Spectra of 25 Second Time Windows for Intervals 1 to 4

the power spectral densities such as frequency shifts and not all of these changes can be detected in the nine parameters. For example, suppose there is one large peak at 20 Hz. After a few minutes, there are peaks of equal size at 18 Hz and 22 Hz and a nadir at 20 Hz. It is possible that the average frequency, median frequency, variance and skew have not changed. Four numbers cannot fully describe a plot with 32768 points. In subject #1 through #4, frequency shifts of the larger peaks to the lower end of the frequency spectrum were observed. In subject #5 through #8 trends couldn't be determined but changes were occurring in each subject over time.

(Figures 3, 4, 5) show the power spectral density plots for subject #1 at 1 mph. (Figure 3) is shown on the facing page. The rest of the power spectral density plots are in Appendix C. There are three major peaks of the curve. The first is situated around 8 Hz, the second around 20 Hz, and the third in the 33 Hz range. At the onset of the experiment, the amplitude of the peak around 20 Hz dominates the other two peaks, at least for the first 100 seconds. During the next four time windows, the 20 Hz peak is shifting to the left and it appears that the 8 Hz and 20 Hz peaks are merging together. A look at the last two time windows shows a larger concentration around 8 Hz as compared to the other two peaks. Also note that the 33 Hz peak has not increased. In the next four power spectral density plots

of subject #1 at 2 mph, (figures 6, 7, and 8), there is much less activity in the 33 Hz region. The curves at 2.5 mph, (figures 9, 10, 11), show the power spectral density to begin to take the shape of a single peak situated around 20 Hz, if the higher spikes in the 0 to 15 Hz range are neglected. neglect. It is evident in the last few intervals that the differences from 1 mph, (figures 3, 4 and 5), to 2.5 mph, (figures 9, 10, and 11), is dramatic. Since the peak at 33 Hz diminished in comparison to the peak at 8 Hz and 20 Hz, calculations of mean frequency should decrease over time.

Subject #2, (figures 12 and 13), had a greater ratio of activity above 35 Hz to below 35 Hz, than subject #1. This can be best seen by a comparison with (figures 1 and 2). Examine the last four intervals of walking at 1 mph, (figure 14). Note that, when the speed was changed to 2 mph, there is an obvious change in the shape of the curves, (figure 15). After the subject was allowed to rest for four minutes, the subject began walking at 1.5 mph, (figures 16 and 17). Notice the region above 35 Hz had more power than before the rest period when the subject was walking at 2 mph, (figure 15). When switching to 2.5 mph, a major decrease in the 0 to 10 Hz range can be observed in (figure 18), except for the very tall peaks. This is important because it may demonstrate adaptation. The power may be concentrating at some lower frequencies and diminishing at

other lower frequencies to produce more efficient contractions. After the second 4 minute interval, a division in the power spectral density was evident at 23 Hz. There was a peak from 2 to 20 Hz and one from 25 to 40 Hz. Both of these peaks occurred throughout 3 mph and 3.5 mph of walking, (figures 19, 20, 21).

Subject #3 had practically no activity past 20 Hz as compared with below 20 Hz at 1 mph, (figures 22, 23 and 24). His frequency response diminished until the 10th interval where the response had changed due to the altering of the speed to 2 mph, (figure 25). One minute after the speed had been changed to 2 mph, there was noticeable activity in the 20 to 60 Hz range. After the subject rested, the power spectral density showed great activity but then demonstrated a decline in activity over the following intervals at 1.5 mph in the 20 to 60 Hz range, (figures 26, 27 and 28). Data was lost due to a bad data file at 2.5 mph. Commencing at 3 mph activity ranging from 20 to 100 Hz is apparent, (figures 29, 30 and 31). At this time, there is a peak at 20 Hz. The peak which was at 10 Hz is smaller in comparison to the peak at 20 Hz. By the end of the 3 mph and on into the 3.5 mph, the 20 Hz peak is very prevalent but still a few frequencies from 0 to 10 Hz tower over the rest of the spectrum, (figure 32). Subject #3 has demonstrated that the curves spread out to the higher frequencies after the rest period but recessed back to the 0 to 20 Hz range at the end

of the walking period. Therefore, there is a shift in frequency to the lower end of the spectrum over time.

Subject #4 began the walk at 1 mph with a large peak in her power spectral density between 5 and 10 Hz (figures 33, 34, and 35). The subject had much more activity in the 20 to 100 Hz range than subject #3. However, this is not so, the scale of the axis of the power spectral densities of subject #3 is 100 times greater than #4. After the first four intervals a shift in the entire spectrum to lower frequencies is apparent. This should be reflected in the values for median frequency. At the end of 1 mph it is obvious that the power has increased, below 40 Hz. Throughout 2 mph of walking most of the curve, (figures 36 and 37), is situated in that lower frequency range, 0 to 40 Hz.

After a rest of 4 minutes, the subject began walking at 1.5 mph. The main peak is at 13 Hz, (figures 38, 39 and 40). The power spectral densities looked almost identical to each other except at the end of the four minutes. The switch to 2.5 mph destroys the definition of the peak, (figures 41 and 42). Large spikes in the 0 to 10 Hz range have increased in comparison to the rest of the curve. At 3 mph the peaks became extremely large, dominating over the rest of the curve, (figures 43, 44 and 45), and even more so in the four minutes at 3.5 mph, (figures 46 and 47). The domination of the high peaks demonstrates adaptation and motor

recruitment. Motor units fire at the same time in order to conserve energy. Also the shift to the lower frequencies represents fatigue.

Subject #5 was the subject who could not complete the study at 3.5 mph and 20% grade. The power spectral densities for this subject showed a peculiar ten fold drop in power from the first to the second intervals, (figure 48). Notice the scale changes. The only apparent difference between the later curves was a more gradual decrease in power from the 2nd interval until the 12th interval when the subject asked to stop, (figures 48, 49, 50).

The power spectral densities for subject #6 showed two peaks which were located in the proximity of 10 and 19 Hz, (figures 51, 52, 53, 54 and 55). The peak at 10 Hz dominated over the 20 Hz peak in some instances. In other instances, they were virtually the same value. There is no pattern of the fluctuations that can be noticed just by looking at the power spectral density. Subject #6, the cross country skier, said that she felt no fatigue.

Subject #7's power spectrum had three discernable peaks. These were not seen in the first four intervals, (figure 56), but by the 5th interval, (figure 57), there were peaks situated at 5, 16 and 24 Hz. The 5 Hz peak dominated the others until the 13th interval where the 16 Hz and 24 Hz peaks began to blend. The merger created a large peak situated around 20 Hz, (figures 58, 59 and 60).

The spectral plots for subject #8 show the signal situated from 0 to 100 Hz. Notice the activity in the 35 to 40 Hz range of the first one hundred seconds (figure 61). The next four plots show similar activity but the power around 20 Hz has started to overshadow it (figure 62). The last twelve intervals show that the 30 Hz to 40 Hz range is not as outstanding as it was at the onset of the walking (figures 63, 64, and 65).

Probably more evident than the great increase in the power from 0 to 20 Hz is the change in amplitude from 1 to 10 Hz. The first four plots of subject #8 demonstrate little activity in this range, (figure 61). The next four plots demonstrate more activity, (figure 62). In the next four plots, the increased amplitude is very apparent, (figure 63). A look at the next two plots shows the amplitude in this region to be at a maximum (figure 64). Then suddenly at six minutes fifteen seconds the activity in the area has ceased and does not increase for the remainder of the period, (figure 64 and 65).

Examination of the power spectrum of an EMG from a gastrocnemius, (figure 66), muscle reveals a liking resemblance to the spectra of the soleus, (figure 3). The main peaks are located at 20 Hz. The curve spreads to the higher frequencies with the same declination. One of the references, [5], had the same results. Just by inspection one could not tell the difference between the power spectra

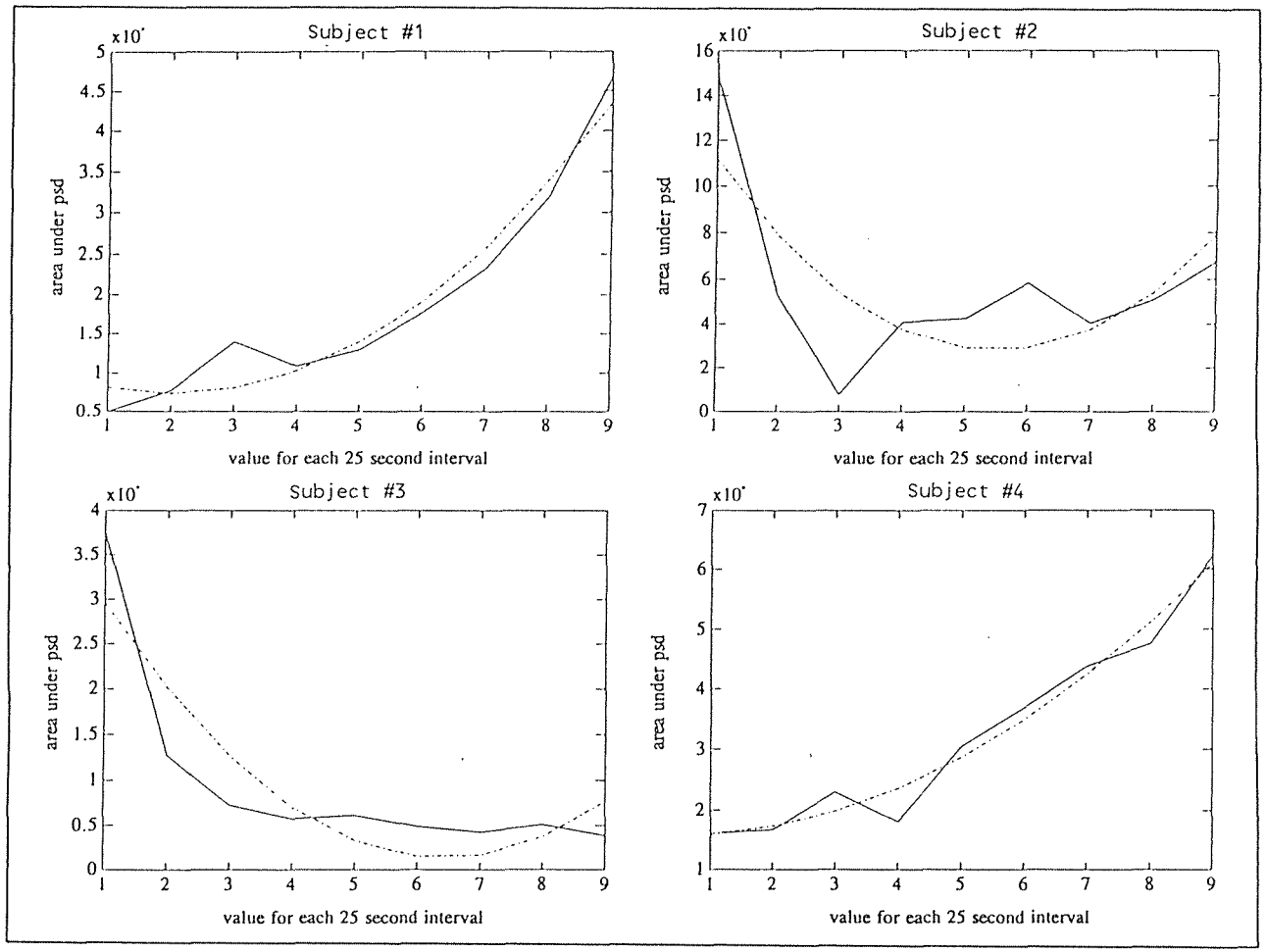

Figure 67 Changes in Area Under the Power Spectra (0 to 35 Hz) Over Time

of these two muscles. A power spectrum of the biceps or masseter muscle would reveal different shapes that would be distinguishable from the gastrocnemius and the soleus. The study could have been done on the lateral gastrocnemius as well.

4.3 Power Spectral Statistics

We will now examine the statistics of the power spectral densities. The area under the curve, the average frequency, the variance, the skew, the median frequency, the quarter area frequency and the three quarter area frequency were calculated for three different portions of the of the power spectral curve. These are the spectrum from 0 to 35 Hz, 0 to 500 Hz, and 35 to 250 Hz. Each gave important information to the study. Zero crossings and maximum peak were calculated for the entire spectrum. All of these nine parameters were defined in Chapter 1.

Data calculation of the parameters was first done from 0 to 35 Hz. The area under the spectrum for subjects walking at 1 mph showed contrasts between subjects. See (figure 67) located on the facing page. All other frequency parameter plots are located in Appendix D. Subject #1 has a large resemblance to subject #4 in shape of the curve and curve fit. Subject #2 has a dramatic drop in area under the curve but then it increases at interval three. For Subject #3 there was an extreme drop and a slow decrease.

At 3 mph and 20 percent grade there was a rise in area among subjects #6, #7, and #8 until the 5th, 25 second, interval (figure 68). All four subjects of the second study had a nadir at the 7th interval and an apex at the 10th. Subject #6 , #7 and #8 had a similar curve fit, with an apex at the 6th interval and a nadir at the 18th. Subject #5, who had fatigued prior to the end of the experiment, had an extreme drop in the beginning and a slow trend downward. The large drop distorted the characteristics of the curve and this is why the plot started at the 2nd interval instead of the first.

The average frequency plot revealed a drop over the first four minutes in subjects #1, #2, and #3, but in subject #4 there was an increase, (figure 69). Subjects #5 - #8 showed no notable trends or patterns, (figure 70). The median frequency followed the average to a great extent. The shapes of the polynomial fit curves were essentially the same, (figures 71 and 72). The quarter area frequency went down also in subjects #1, #2, and #3, but in subject #4 increased (figure 73). Subject #7 and #8 produced a decrease between the 5th and 10th intervals and an increase between the 15th and 20th intervals. These characteristics could not be seen in subjects #5 and #6, (figure 74).

The 3/4 frequency displayed a decrease in subjects #1 through #3 and no distinguishable trend in subject #4, (figure 75). In subjects #5 through #8 the fluctuation in

the values from interval to interval was so great that no information can be used as a comparison, (figure 76). Upon examination of the variance, the trend was downward toward the end for subjects #1 through #4, (figure 77). For subjects #5 through #8 every polynomial fit was completely different than the next, (figure 78).

The skew demonstrated an increase in subjects #1 through #3; however, a decrease in subject #4, (figure 79). Subject #8 had a negative skew which meant more power in the 17.5 to 35 Hz region than 0 to 17.5 Hz. Subject #6 through #8 had a common maximum at the 6th interval for the curve fit, (figure 80).

The maximum peak frequency showed no trend in all subjects, (figures 81 and 82). Zero crossing showed no trends from subjects #1 to subjects #4, (figure 83). However, the zero crossing plots did show in subjects #5 to subject #8, (figure 84), a sharp decrease followed by a gradual rise. Subject #8 had the largest rise in comparison with the other subjects of the second study.

The total frequency spectrum, 0 to 500 Hz, produced somewhat similar results to the 0 to 35 Hz range at one mile per hour for the area. This range is where most of the area under the curve was found. Compare (figure 67) with (figure 85) and (figure 68) with (figure 86). The exception is subject #4 who displays only a minor change in shape, to the naked eye, within the total spectrum and 0 to 35 Hz curves.

The total average frequency plot for subject #1 was similar to the curves from subject #4, but subject #2 and #3 had no comparison to subject #1 or #4 or to each other, (figure 87). Subject #5 had an average frequency that increased from 15.5 to 20.3 Hz. Subjects #6, #7 and #8 had similar curve fit shapes and all three demonstrated a high peak near the end of the testing, (figure 88). The variance showed no comparisons in subject #1 through #4, (figure 89); however, subjects #5 to #8 showed a low dip in the curve around the 10th interval and the curve fits showed an upward opening parabolic shape with an inflection downward at the end of the study, (figure 90). The skew did not show a trend for the 1 mph experiment, except subject #2 and subject #4 had similar shapes and curve fits, (figure 91). For subjects #5 through #7 there was a minimum inflection point about the 9th interval, (figure 92). Subject #8 had one earlier at the 5th interval. All curves of the second study had similar shapes.

The total median frequency revealed a negative slope for subjects #1 through #4, (figure 93). Subject #5's curve fit had a positive slope, (figure 94). Subject #6 had a curve fit that went down steeply and then gradually decreased. Subject #7 and #8 had polynomial fits that went down at the beginning and then increased. Subjects #6 to #8 all had a common high point around the 20th interval.

The quarter area frequency from 0 to 500 Hz showed the trend going downward for subjects #1 through #4 like the median frequency, (figure 95). The quarter area frequency showed similar results to the median for subjects #5 to #8, (figure 96). The three quarter frequency revealed a drop at the end of the study for the people walking at 1 mph, (figure 97) and for the people walking at 3.5 miles per hour showed the trend going upward, (figure 98).

The next portion of the spectral curve examined was from 35 to 250 Hz. Subject #1 had a constant rise in area under the curve in this region, (figure 99). Subject #2 and #3 had a high point at interval 1 and then the area under the power spectral density fell below 1×10^6 at interval 3. Subject #4 had a low of 4.3×10^6 at the start. It increased the next interval but dropped off at the fourth interval almost to the low. A positive slope was predicted at the 9th interval of the polynomial fit for all. In subject #5 the area abruptly dropped and continued to drop, (figure 100). In subjects #6 through #8 there was a low point at interval 16 and all three of the respective polynomial fits noted an inflection upward at approximately the 17th interval.

The average frequency plot from 35 to 250 Hz showed parabolas opening downward [24] for the polynomial fits for the 1st four subjects at 1 mph with their maximum points varying, (figure 101). For subject #6 through #8 the fitted

curves showed a drop until approximately the 8th interval and then a rise, (figure 102). Subject #5's fitted curve also showed a drop but did not begin to rise again until after the 9th interval.

The variance also demonstrated parabolas opening downward for subjects at 1 mph, (figure 103). In this case the maximum fell within the 5th to 6th interval. Subjects #5 through #8 had polynomial fits with similar curve shapes, (figure 104). The minimum inflection point lied around the 9th interval for subject #5, #6, and #7. Subject #8 had a low point at the 6th interval of the polynomial fit however its actual low point was at the 10th interval. The values for skew showed no trend in subjects #1 through #4, (figure 105). The skew for the 3.5 mph study only demonstrated a decrease in all cases from the first to the second interval, (figure 106). Nothing could be determined from this.

The median frequency increased in subject #1 through all nine intervals, (figure 107). In subjects #2 and #3 a downward opening parabola was calculated for the polynomial fit. Subject #4 showed a decrease downward in the median frequency. The median frequency gave different results for the 3.5 mph study, (figure 108). Parabolas opened upward in this case except for subject #3 which had a downward inflection at the 18th interval.

The quarter area frequency plot from 35 Hz to 250 Hz showed the characteristics, in the polynomial fits, as the

median for subjects #1 to #4, (figure 109). In subjects #5 through #8 there was much more variation between the quarter area frequency and the median frequency. The only fact from the graphs that could be meaningful was there was a switch in concavity around the 13th interval, (figure 110).

The three quarter area frequency demonstrated the parabolas opening downward for the polynomial fit, (figure 111). The inflection point was between the 6th and 7th intervals for subject #1 and #2; around the 5th interval for subject #3; and the 4th interval for subject #4. The three quarter area also showed the curve fits starting high, going lower and increasing and inflecting near the 20th interval for the subjects walking at 3.5 mph at a gradient, (figure 112).

CHAPTER 5

CONCLUSION

The goal of this work was to look for parameters from a power spectral density of an electromyogram that could signify fatigue, adaptation or recruitment. By examining the power spectral densities shapes, variations could be recognized over time. These variations have been seen by the others who have been referenced in the introduction. However, their papers did not examine these parameters while the subject walked on a treadmill.

5.1 Comparing the Spectra

The changes in the shapes of the power spectral curves of the electromyograms portray the changes that are occurring in the neuromuscular system. It is important to find similarities of change within normal people. From these similarities scientists can then determine what is abnormal and learn more about how to remedy the abnormalities.

All subjects' spectral plots demonstrated shifts to lower frequencies as time progressed. Subject #1 had three peaks. The two lower frequency peaks increased in comparison to the higher frequency. Subject #2 had great activity in the region above 35 Hz but this activity waned over time. Subject #2 had two peaks from 2 to 20 Hz and one from 25 to 40 Hz. Subject #3 had most activity in the region below 20

Hz. When speed was increased activity in the lower portion increased with respect to the upper portion. Subject #4 simply had an apparent shift to the lower frequencies as the study progressed.

Frequency shifts such as these can not be dependent on gait. As the speed was raised, the energy at the higher frequencies decreased with respect to the lower frequencies. Converting 3.5 mph to Hz gives

$$\frac{3.5\ miles}{hour} \cdot \frac{5280\ feet}{mile} \cdot \frac{hour}{3600\ seconds} \cdot \frac{1\ stride}{2\ feet} \cdot \frac{1}{2} = \frac{1.28}{sec} \qquad (Eq.\ 5.1)$$

Since only the right leg was recorded, we must divide by two which results in 1.28 Hz. In general the highest peaks were observed from 5 to 15 Hz in the power spectral densities. A statement that gait did not play a factor in the frequency parameters would be wrong. However, since the energy of the higher frequencies went down with respect to the lower frequencies while the rate of walking was increased, it can be assumed that something besides gait was causing the alterations in frequency.

One may argue that a person might lengthen his gait as he became tired, producing a decrease in frequency. The problem with this conjecture is again that the higher frequencies have diminished. The gait should have an effect on frequencies above 20 Hz because of harmonics. However a

longer stride causes a greater force during heel strike which can be explained through biomechanical analysis [25]. Higher harmonics should be transferred with greater force.

This logic can be also used on motion artifact. Motion artifact for this study can be defined as the following. When the heel strikes the treadmill, there is a high frequency spike produced. This high frequency spike's amplitude is in proportion to the force of the heel on the surface. When a person tires, the person will tend to hit the heel down with less force. A lesser force will produce lower frequencies. This might be the cause of the shift in frequency to the low end of the spectrum. This is not likely though because as the speed of the treadmill is increased a person will lengthen the stride. This will cause the person to strike down with the heel with greater force which again can be explained by biomechanical analysis [25]. The evidence of a frequency shift to the higher frequencies is not apparent when the speed changes occur.

It was important to rule out gait and motion artifact as not changing the frequency response before examining the parameters. Now, that these factors are ruled out. Frequency parameters that change over time can be attributed to fatigue, adaptation, recruitment or other factors of muscle physiology.

In subject #5 an extreme decrease in area of the power spectral density was detected over the first to second

intervals. Then she had a gradual decline. Subject #6 did not show patterns of change in her power spectral density. Subject #7 had three major peaks, two of which merged together at the end of the study. Subject #8 showed signs of a frequency shift to the lower end of the spectrum. A trend can not be demonstrated for the second part of the study just by examining the power spectral curves. However, frequency shifts to the lower frequencies might have occurred, undetectable by inspection, which might be detectable in calculations. Therefore, frequency parameters must be looked at for signs of fatigue, recruitment and adaptation.

5.2 Comparing the Frequency Parameters

The area under the power spectral density is one parameter that showed results for Subjects #5 through #8.
When examining these subjects, a distinctive pattern can be seen. In all cases there is a nadir at the 7th interval and an acme at the 10th interval. Less noticeable is a common rise at around the 17th interval in subject #6 through #8. This pattern may be a good indication of fatigue because it was seen in both the 0 to 35 Hz portion of the spectrum and the 35 to 250 Hz portion of the spectrum. The 7th interval begins at 150 seconds or 2 minutes 30 seconds. The muscle at this time might be depleted of ATP. The muscle sensing the depletion responds with an increase of this conversion [26].

Creatine phosphate + ADP ⟶ ATP + Creatine *(Eq. 5-2)*

Possibly this additional energy might correspond to the rise from intervals 7 to 10. From interval 10 on there is a drop in area until approximately interval 17. The switch to glycolysis might be happening at interval 17, where the area peaks again. This is after 7 minutes of vigorous walking.

Subjects #1 through #4 displayed no noticeable trends for the area under the power spectral density. This might be due to the fact that the speed was set too slow or too fast for people. If a person's normal walking speed is greater than 1 mph, the person's power spectral density might show completely different signs than a person whose normal walking speed is less than 1 mph. Subjects #1 and #4 were shorter than subjects #2 and #3. It is possible that they could be walking slower because of the length of their stride. Thus normal walking speed may play a factor in parameter fluctuations at 1 mph.

The zero crossing plots display a different characteristic in subjects #5 to #8. A large value for the first interval, then a drop, followed by a gradual increase could be detected. This may also reflect fatigue but it might link better to adaptation. The brain for the first 25 seconds does not know how to react at the body being forced to walk at 3.5 mph. Eventually, it learns how to become efficient in this task. The unnatural speed is analyzed by the mind for minimum energy expenditure and motor units are

evoked in a more rhythmic pattern. The most efficient rhythmic pattern is attained somewhere between the first few intervals. This rhythmic pattern however cannot be maintained indefinitely due to muscle fatigue. The brain has to constantly alter the firing patterns due to the changing contraction times of the fibers. Hence, a steady increase is observed in the zero crossings over time which can be attributed to the chaotic behavior of the fibers.

The polynomial fits for the average frequency of subjects #5 to #8 demonstrated a low at the 8th or 9th intervals from a frequency of 35 to 250 Hz. This might be an indication of fatigue. The latency period, looking back to the action potential in (figure 1), is the time from the onset of contraction to the end of contraction. This time is about 20 milliseconds. A sinusoidal waveform with period 20 milliseconds is 50 Hz and therefore, single motor units firing should be displayed in this range.

The variance showed trends in all subjects from 35 to 250 Hz. Recall that subject #1 through #4 had similar downward opening parabolas with their maximum at approximately the 6th interval. Subjects #5 through #7 all had a common low point around the 10th interval seen also in the calculations of the total power spectrum. This again might be a result of a loss of ATP and a switch to creatine phosphate conversion.

The median frequency and three quarter area frequency of the power spectral density from 35 to 250 Hz also showed signs of activity about the 10th interval for subjects #5 to #8. The curve fits were lowest near this interval and the lowest point on the curve was in this region in all the four subjects.

An overall drop in median frequency and quarter area was seen from 0 to 500 Hz in subjects #1 to #4. This might be linked with fatigue. Since fast twitch fibers have a faster rate of fatiguing than the slow twitch fibers, a drop in the median frequency over time would indicate that the fast twitch fibers have fatigued at a greater rate than the slow twitch fibers. Breaking the power spectral density in two sections from 0 to 35 Hz and 35 Hz to 250 Hz did not reveal any trends for Subject #1 through #4. This is because subject #4 had a median frequency that was much higher than the 35 Hz, where the spectral density was sectioned, and subject #1 had a median frequency which was much lower than 35 Hz. It might be wise to do sectioning not with respect to a certain value but with respect to the subject. Yet subjects #5 through #8 had variances which did not seem to show fatigue for the entire spectrum, 0 to 500 Hz, but demonstrated fatigue for the range of 35 Hz to 250 Hz. The curve fits showed parabolas opening upward in all cases.

Every parameter, except for maximum peak frequency and skew, revealed some characteristic which was common among

the 4 subjects in each study. The area under the curve and the zero crossings seemed to convey the most information. The average frequency, variance, median frequency, quarter area frequency, and three quarter area frequency basically show the same information, an inflection point in the vicinity of the 6th to 10th interval, depending upon the parameter. Therefore, it has been shown that an electromyogram of a person walking on a treadmill has useful information which can be extracted from it. The parameters calculated in this study can be linked to changes due to fatigue, adaptation and recruitment.

5.3 Further Studies

The presence of fatigue, adaptation and recruitment are expressed in the data collected. The times of consumption of ATP and creatine phosphates were not directly measured in the experiment. Some type of chemical analysis should be done to verify the times when the ATP and creatine phosphate supplies in the muscle are spent and when glycolysis becomes the major means of fueling the muscle. It is possible that these actions will happen at similar times for different subjects.

The peak frequencies of the power spectral densities of the electromyogram hold an enormous amount of information about motor recruitment. In a future study, it would be advisable to delve into an examination of the correlation

between the ten highest peaks of the spectrum. Along with neural network analysis, the peak locations might reveal information on how the brain selects which motor neurons will fire next. Weighting functions may be ascribed to different fiber types which fire at different frequencies. From this, individual firing patterns can be deduced.

APPENDIX A

USING STREAMER

To acquire the data using STREAMER the user must create a datafile in packed format by using the mkfile file which asks for the filename and size in kilobytes. The user must then type "STREAMER" and the data board type, in the presents case "DAS-16". This invokes the screen which the user can select the datafile to be recorded, the sampling rate, the channels utilized, unipolar or bipolar, and external or internal trigger.

The datafiles are not recorded in a readable form and therefore have to be unpacked. A file named "UNPACK" asks for the name of the datafile; a filename which to unpack the data to; the portion of the datafile to be unpacked; whether or not the datafile was recorded in bipolar or unipolar format; and the data acquisition board being utilized. Unpacked files are in ASCII format and are accessible by MATLAB and Lotus-123.

APPENDIX B

MATLAB PROGRAMMING

This appendix contains samples of the MATLAB programming that was used to obtain the plots and the frequency parameters. Comment lines begin with a '%' sign. They are displayed in italics for the reader's benefit but normally would be displayed in the regular font. The main lines are displayed in bold.

Unpacked data files were named specifically so that they would be easily recalled by a for loop. An example of a file name is 'MAR131.MAT'. 'MAR1' stands for March 1st. The '3' stands for 1.5 mph, the third, four minute interval of the test. The last '1' signifies the first 25 second interval of the four minute walk.

The programs are setup to read the file, do the necessary calculations, and increment the file to the next data file. The process is repeated until no more files are found. Program 1 was created to obtain the power spectral density of the data file. It then calls upon other programs which will obtain the various frequency parameters. It also shows various displays on the screen of the power spectral density.

Program 1: PSD.M

```
% this program is used to obtain power spectral
    % densities
```

```
if j<2;
     j=1;
end
% j is for array purposes

F=2^16;
% F is the number of points of the FFT you would like
          to take

N=1000;
% N is the sampling rate

file=input('file name to find PSD of?','s')
% input file name and press enter
% files when created had the month, day, and interval
%    incorporated in the title

rz=length(file);
% rz is the amount of points within the file

for v = 1:25
% set a loop to read the files
% files were numbered consecutively for this purpose

eval(['load c:\mark\',file,'.mat'])
% load the file into matlab

w = eval([file]);
% w is the contents of the file

% this next part is to detrend the data
q = mean(w);
% find the mean
for i=1:size(w)
w(i)=w(i)-q;
% subtract the mean
end


Y=fft(w,F);
% Y is the FFT of time signal w taken to F amount of
%    points

Pyy=Y.*conj(Y)/F;
% Pyy is the Power spectral density
spec = Pyy(1:F/2);
% spec is half of the power spectral density

f=N*(0:F/2-1)/F;
% f is an array of frequencies for the x axis

mdf
```

```
% call program to find the median, quarter area
%       and three quarter area frequencies

zcross
% call program to find the zero crossings

avf
% call program to find the average frequency, variance
and skew

subplot(211)
% allows four plots to simultaneously be plotted

semilogx(f,spec)
% plots a semilog plot of the power spectral density

plot(f,spec)
% creates a normal plot of the power spectral density

plot(f(1:2300),Pyy(1:2300))
% examines the power spectral density from 0 to 35 Hz

eval(['save a:\f',file,' spec /ascii'])
% save the file in ASCII code

eval(['save a:\f',file,' spec'])
% save the file in MATLAB format

% the next few lines contain the format for
%    incrementing numbers in ASCII
j=j+1
if j < 10 file(rz) = j + 48;
   end

if j > 9 file(rz) = 49;
   file(rz+1) = j + 38;
   end

if j > 19 file(rz) = 50;
   file(rz+1) = j + 28;
   end


setstr(file)
% convert incremented file name back to string format
end
```

Program 2 is summoned by program 1 to calculate the average frequency, the variance, the skew, and to find the

maximum peak frequency. It stores the values for parameters into arrays corresponding to the last number of the file name. The program determines the values for the range 0 to 35 Hz.

Program 2 : AVF.M

```
% a program for calculating mean frequencies
% (to be used after a power spectral density has been
%    taken)

g = f';
% invert array of frequencies for calculations

mul = 0;
tot = 0;
sq = 0;
stot = 0;
cube = 0;
ctot = 0;
% clear these parameters

sc = 230*10^4;
sp = 1*10^4;
% sc and sp correspond to the portion of the curve we
% wish to examine
% in this case
% sp corresponds to the lowest frequency close to zero
% sc corresponds to 35 Hz

for i=sp/N:sc/N
   tot = tot + Pyy(i);
   end


% compute the total area

for i=sp/N:sc/N
   mul = mul + Pyy(i) * g(i);
   end
% compute the sum of the amplitudes multiplied by the
% frequencies

ar(j) = tot * g(2);
% ar(j) is the area under the power spectral density

av(j) = mul/tot;
% av(j) is the average frequency
```

```
% compute the variance
for i=sp/N:sc/N
   sq = sq + Pyy(i) * g(i) ^ 2;
   end
va(j) =  sq / tot  - av(j)  ^ 2;
% va(j) is the variance

% compute the skew
for i=sp/N:sc/N
   cube = cube + Pyy(i) * g(i) ^ 3;
   end
sk(j) = cube/tot - 3 * av(j) * va(j) - av(j)^3;
% sk(j) is the skew

[y,i] = max(Pyy);
mx(j) = i * g(2);
% mx(j) is the maximum peak
```

A for loop ran and the amplitudes for each frequency of the power spectral density were summed consecutively in Program 3. When the half mark was reached, the loop was broken. The value of the counter was read which corresponded to the median frequency. The quarter area frequency was calculated similarly. When the quarter mark was reached, the loop was broken. The three quarter area frequency was calculated in the same manner.

Program 3 : MDF.M

```
% a program for calculating median frequencies and pth
%    fractiles
% (to be used after a power spectral density has been
%    taken)

g = f';
% invert the array of frequencies for calculations

mul = 0;
tot = 0;
hf = 0;
qt =0;
tq=0;
```

```
m=0;
k=0;
l=0;
md(j) = 0;
m4(j) = 0;
m7(j) = 0;
% clear these parameters

sc = 230*10^4;
sp = 1*10^4;
% sc and sp correspond to the portion of the curve we
%    wish
% to examine
% in this case
% sp corresponds to the lowest frequency close to zero
% sc corresponds to 35 Hz

for i=sp/N:sc/N,
   tot = tot + Pyy(i);
   end
% find the total area under the power spectral density

while hf < tot/2
   m = m+1;
   hf = hf + Pyy(m);
end
% find the frequency where the area is equal to half
%    the  total area

md(j) = g(m);
% md(j) is the median frequency

while qt < tot/4
   k = k+1;
   qt = qt + Pyy(k);
end
% find the frequency where the area is equal to one
%    quarter of the total area

m4(j) = g(k);
% m4(j) is the quarter area frequency

while tq < tot*3/4
   l = l+1;
   tq = tq + Pyy(l);
end
% find the frequency where the area is equal to three
%    quarters of the total area

m7(j) = g(l);
%m7(j) is the three quarter area frequency
```

Program 4 demonstrates the way the zero crossing parameter was calculated. A for loop increments a counter. Each element of the signal is compared to the following element. If there is a change in sign, a zero crossing counter is incremented.

Program 4 : ZCROSS.M

```
% a zero crossing program

z=0;
% clear parameter

for i=1:size(w)-1
        x=sign(w(i));
% find the sign of the time signal at instant i

        y=sign(w(i+1));
% find the sign of the time signal at instant i + 1

        if x~= y,
% if the signs are not the same then increment the
%    zero crossing counter by one
                z = z+1;
        end
end

zc(j)=z
%zc(j) is the zero crossing count
```

Program 5 was used to plot the montages of power spectral densities to the screen. The files were read in a similar way to program 1. The plots ran from 0 to 100 Hz. The most useful aspect of the program is that it reads multiple files and this allows plots to be printed unattended.

Program 5 : PLOTM.M

```
% a program for plotting the power spectral density to
%    a  printer

if j<2;
        j=1;
end

subplot(221)
% allows four plots to be displayed simultaneously

F=2^16;
N=1000;
file=input('file name to find PSD of?','s')
rz=length(file);
for v = 1:4,
eval(['load c:\mark\',file,'.mat'])
w = eval([file]);
q = mean(w);
for i=1:size(w)
        w(i)=w(i)-q;
end
Y=fft(w,F);
Pyy=Y.*conj(Y)/F;
spec = Pyy(1:F/2);
f=N*(0:F/2-1)/F;

plot(f(1:6550),Pyy(1:6550))
% allowed plotting of frequencies 0 to 100 Hz and their
%       respective amplitudes

j=j+1
if j < 10 file(rz) = j + 48;
        end

if j > 9 file(rz) = 49;
        file(rz+1) = j + 38;
end

if j > 19 file(rz) = 50;
   file(rz+1) = j + 28;
end
setstr(file)
end

print
% send graphics on  screen to the printer
```

Program 6 saves the parameters from the computations of Programs 1, 2, 3, and 4. Matrices had to be in column form to be saved. This is why they are converted. Files were stored in ascii code to save space on the hard disk and to allow other programs to import the data. Each filename saved by the program corresponds to the calculated parameter. For example the file ARMAR51 would correspond to the area under the power spectral density for the patient whose EMG was recorded on March 5th.

Program 6 : SVA.M

```
% program used to save all of the arrays

tav = av'
% invert the matrix to column format

eval(['save c:\mark\arr\av',file(1:6),' tav -ascii'])
% save the average frequency

tar = ar'
eval(['save c:\mark\arr\ar',file(1:6),' tar -ascii'])
% save the area under the power spectral density

tva = va'
eval(['save c:\mark\arr\va',file(1:6),' tva -ascii'])
% save the variance

tsk = sk'
eval(['save c:\mark\arr\sk',file(1:6),' tsk -ascii'])
% save the skew

tmx = mx'
eval(['save c:\mark\arr\mx',file(1:6),' tmx -ascii'])
% save the maximum peak frequency

tm7 = m7'
eval(['save c:\mark\arr\m7',file(1:6),' tm7 -ascii'])
% save the three quarter area frequency

tm4 = m4'
eval(['save c:\mark\arr\m4',file(1:6),' tm4 -ascii'])
% save the quarter area frequency
```

```
tmd = md'
eval(['save c:\mark\arr\md',file(1:6),' tmd -ascii'])
% save the median frequency

tzc = zc'
eval(['save c:\mark\arr\zc',file(1:6),' tzc -ascii'])
% save the zero crossing frequency
```

Plotting of the parameters was accomplished through the use of Program 7. The program asks for the names of four files to be plotted. It loads these files and computes polynomial fits of orders one to three, depending on the number of points of the plot. If the number of points is less than 7, a straight line curve fit is chosen. If the curve is comprised of 7 to 14 points it choses a parabolic curve fit. If the curve has 15 to 25 points a third order curve is chosen. The last point of each array was discarded because of possible erroneous data which may be resultant of the cessation of walking during recording.

Program 7 : PLGR.M

```
% a program to plot 4 graphs simultaneously

fil1=input('file name to find PSD of?','s')
% input file name of first file

eval(['load c:\mark\larr\',fil1,'.mat'])
% load the file

w1 = eval([fil1]);
% put contents  of file into array

rz1=length(w1);
% find the length of the array

% repeat the steps for three other files
fil2=input('file name to find PSD of?','s')
eval(['load c:\mark\larr\',fil2,'.mat'])
```

```
w2 = eval([fil2]);
rz2=length(w2);
fil3=input('file name to find PSD of?','s')
eval(['load c:\mark\larr\',fil3,'.mat'])
w3 = eval([fil3]);
rz3=length(w3);
fil4=input('file name to find PSD of?','s')
eval(['load c:\mark\larr\',fil4,'.mat'])
w4 = eval([fil4]);
rz4=length(w4);

a1=(1:rz1-1);
a2=(1:rz2-1);
a3=(1:rz3-1);
a4=(1:rz4-1);
% create an array of time interval numbers

if rz1 < 7
        pp1=1;
% do a first order polynomial fit
elseif rz1 < 15
        pp1=2;
% do a second order polynomial fit
elseif rz1 < 25
        pp1=3;
% do a third order polynomial fit
end

if rz2 < 7
       pp2=1;
elseif rz2 < 15
       pp2=2;
elseif rz2 < 25
       pp2=3;
end
if rz3 < 7
       pp3=1;
elseif rz3 < 15
       pp3=2;
elseif rz3 < 25
       pp3=3;
end
if rz4 < 7
       pp4=1;
elseif rz4 < 15
       pp4=2;
elseif rz4 < 25
       pp4=3;
end

y1=polyfit(a1,w1(1:rz1-1)',pp1);
y2=polyfit(a2,w2(1:rz2-1)',pp2);
```

```
y3=polyfit(a3,w3(1:rz3-1)',pp3);
y4=polyfit(a4,w4(1:rz4-1)',pp4);
% calculate the polynomial fit

r1  = polyval(y1,a1);
r2  = polyval(y2,a2);
r3  = polyval(y3,a3);
r4  = polyval(y4,a4);
% put polynomial fit into an array

clg
% clear the graph

subplot(221)
% set up to plot four graphs on one screen

plot(a1,w1(1:rz1-1),'w',a1,r1,'-.w')
% plot the actual curve and the polynomial fit

% determine which parameter is being plotted
if fil1(1:2) == 'ar'
        ylabel('area under PSD ')
        end
if fil1(1:2) == 'av'
        ylabel('average frequency ')
        end
if fil1(1:2) == 'md'
        ylabel('median frequency 35Hz ')
        end
if fil1(1:2) == 'm4'
        ylabel('quarter area frequency 35Hz')
        end
if fil1(1:2) == 'm7'
        ylabel('3/4 area frequency 35Hz')
        end
if fil1(1:2) == 'va'
        ylabel('variance 35Hz ')
        end
if fil1(1:2) == 'sk'
        ylabel('skew 35Hz ')
        end
if fil1(1:2) == 'mx'
        ylabel('maximum peak frequency vs. time')
        end
if fil1(1:2) == 'zc'
        ylabel('zcrossing vs. time')
        end
        xlabel('value for each 25 second interval')
        title('subject #1')
plot(a2,w2(1:rz2-1),'w',a2,r2,'-.w')
if fil2(1:2) == 'ar'
        ylabel('area under PSD ')
```

```
        end
if fil2(1:2) == 'av'
        ylabel('average frequency ')
        end
if fil2(1:2) == 'md'
        ylabel('median frequency 35Hz ')
        end
if fil2(1:2) == 'm4'
        ylabel('quarter area frequency 35Hz')
        end
if fil2(1:2) == 'm7'
        ylabel('3/4 area frequency 35Hz')
        end
if fil2(1:2) == 'va'
        ylabel('variance 35Hz ')
        end
if fil2(1:2) == 'sk'
        ylabel('skew 35Hz ')
        end
if fil2(1:2) == 'mx'
        ylabel('maximum peak frequency vs. time')
        end
if fil2(1:2) == 'zc'
        ylabel('zcrossing vs. time')
        end
        xlabel('value for each 25 second interval')
        title('subject #2')
plot(a3,w3(1:rz3-1),'w',a3,r3,'-.w')
if fil3(1:2) == 'ar'
        ylabel('area under PSD ')
        end
if fil3(1:2) == 'av'
        ylabel('average frequency ')
        end
if fil3(1:2) == 'md'
        ylabel('median frequency 35Hz ')
        end
if fil3(1:2) == 'm4'
        ylabel('quarter area frequency 35Hz')
        end
if fil3(1:2) == 'm7'
        ylabel('3/4 area frequency 35Hz')
        end
if fil3(1:2) == 'va'
        ylabel('variance 35Hz ')
        end
if fil3(1:2) == 'sk'
        ylabel('skew 35Hz ')
        end
if fil3(1:2) == 'mx'
        ylabel('maximum peak frequency vs. time')
        end
```

```
if fil3(1:2) == 'zc'
        ylabel('zcrossing vs. time')
        end
        xlabel('value for each 25 second interval')
        title('subject #3')
plot(a4,w4(1:rz4-1),'w',a4,r4,'-.w')
if fil4(1:2) == 'ar'
        ylabel('area under PSD ')
        end
if fil4(1:2) == 'av'
        ylabel('average frequency ')
        end
if fil4(1:2) == 'md'
        ylabel('median frequency 35Hz ')
        end
if fil4(1:2) == 'm4'
        ylabel('quarter area frequency 35Hz')
        end
if fil4(1:2) == 'm7'
        ylabel('3/4 area frequency 35Hz')
        end
if fil4(1:2) == 'va'
        ylabel('variance 35Hz ')
        end
if fil4(1:2) == 'sk'
        ylabel('skew 35Hz ')
        end
if fil4(1:2) == 'mx'
        ylabel('maximum peak frequency vs. time')
        end
if fil4(1:2) == 'zc'
        ylabel('zcrossing vs. time')
        end
        xlabel('value for each 25 second interval')
        title('subject #4')
```

APPENDIX C

POWER SPECTRAL DENSITY PLOTS

The power spectral density plots produced using Program 5 are located in this appendix. The plots for each patient are arranged in chronological order, starting from interval 1, 0 to 25 seconds. The plots allow a better understanding of how fatigue, adaptation and recruitment effects the frequency response of the EMG signal.

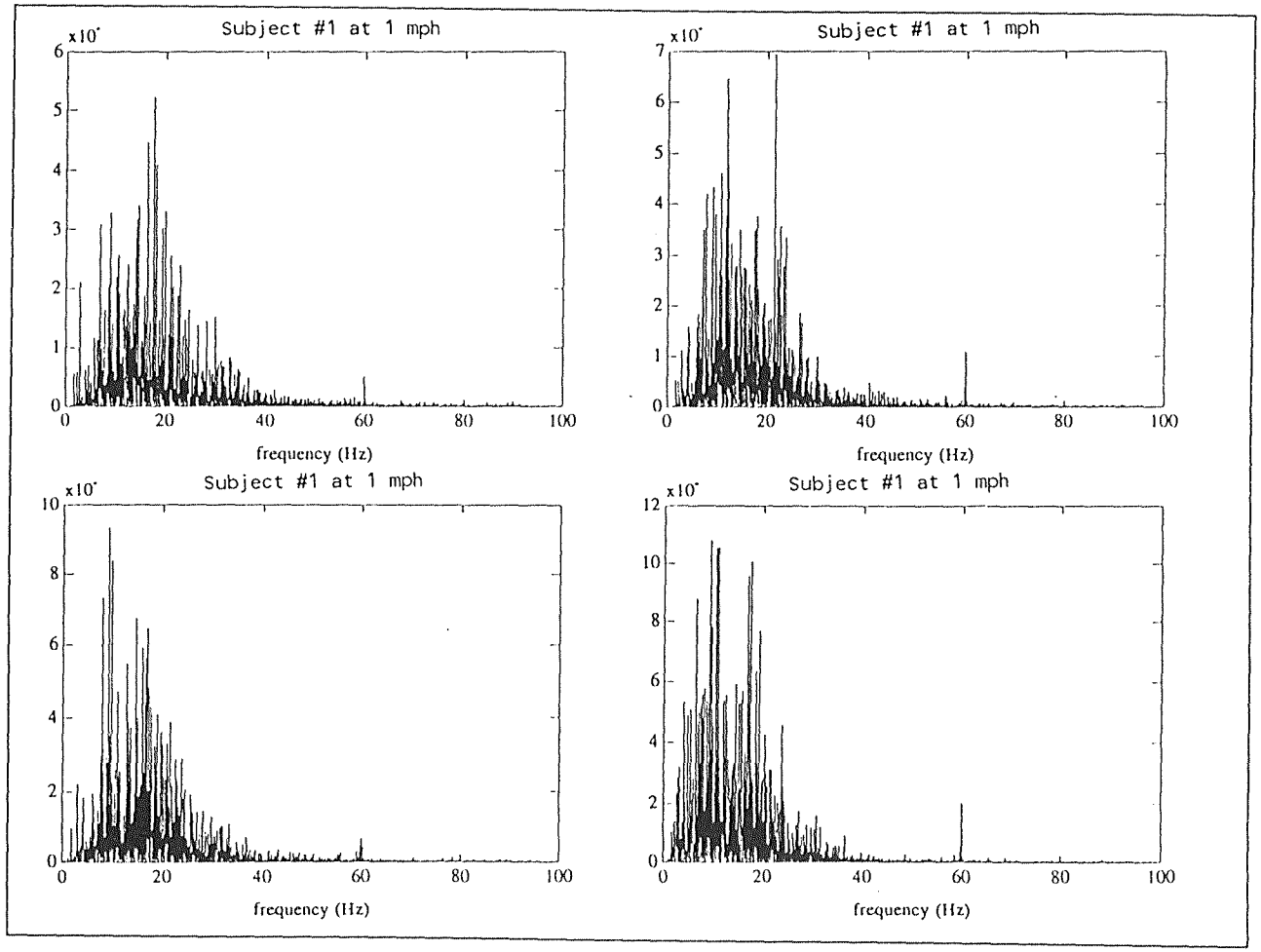

Figure 4 Power Spectra of 25 Second Time Windows for Intervals 5 to 8

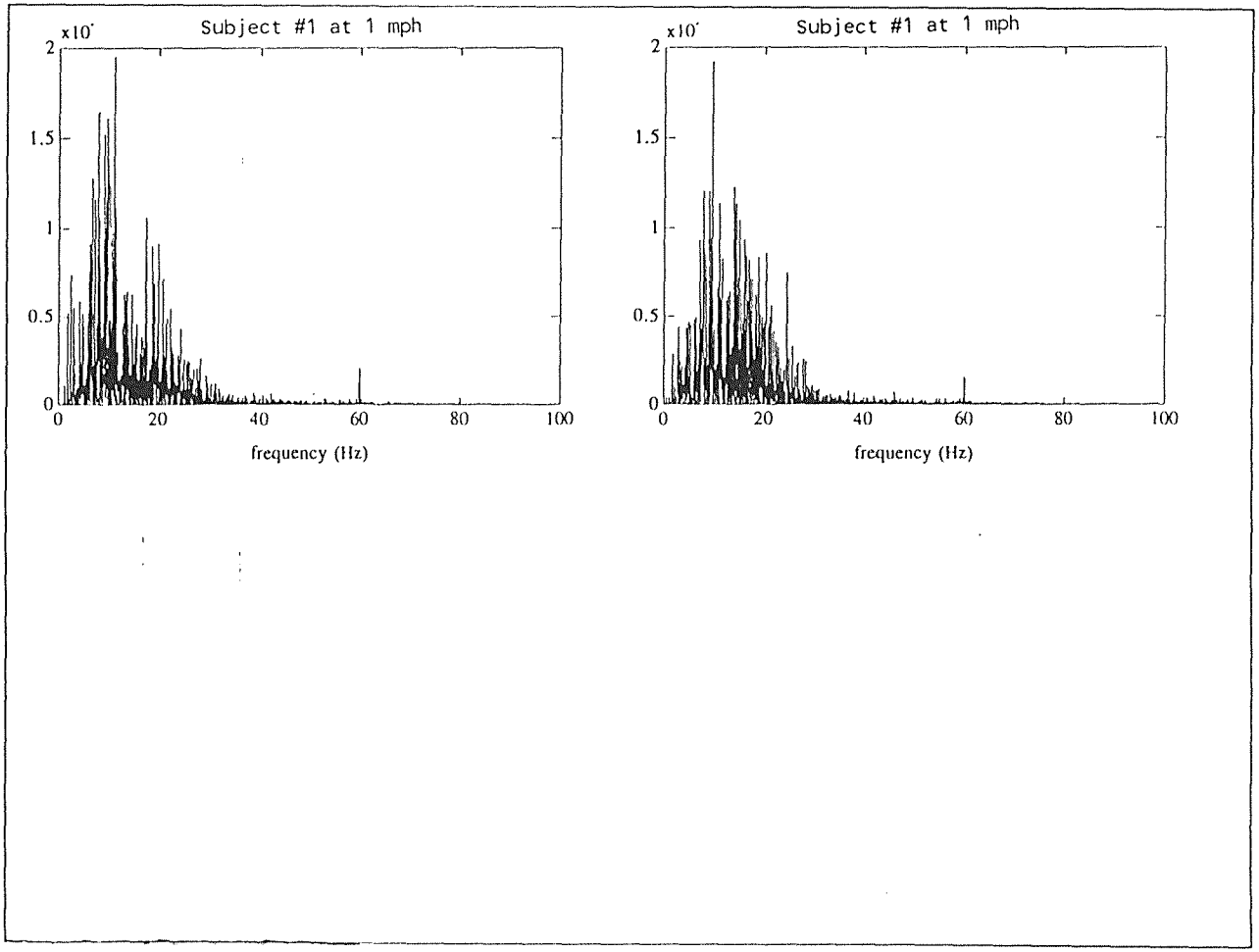

Figure 5 Power Spectra of 25 Second Time Windows for Intervals 9 and 10

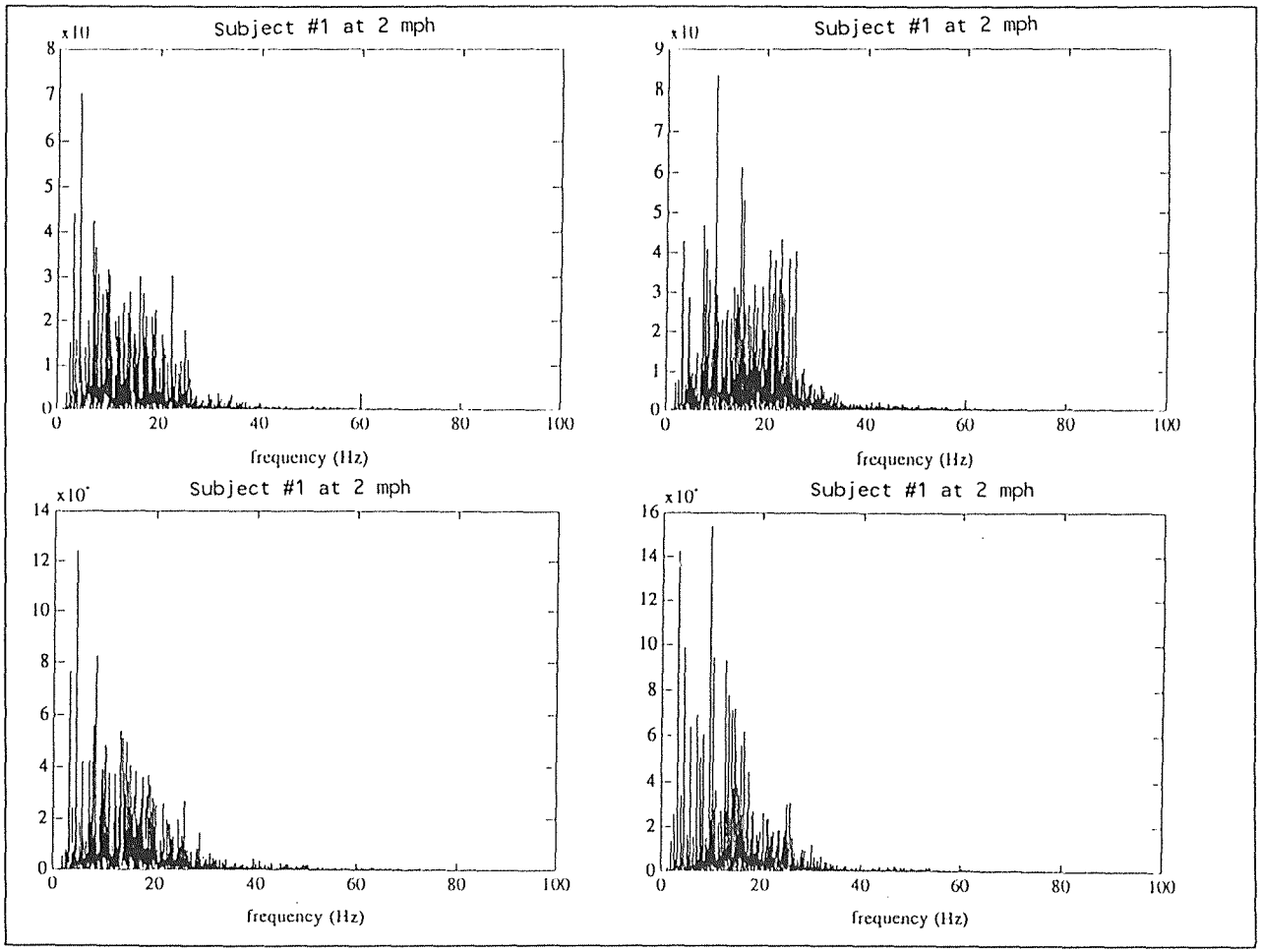

Figure 6 Power Spectra of 25 Second Time Windows for Intervals 1 to 4

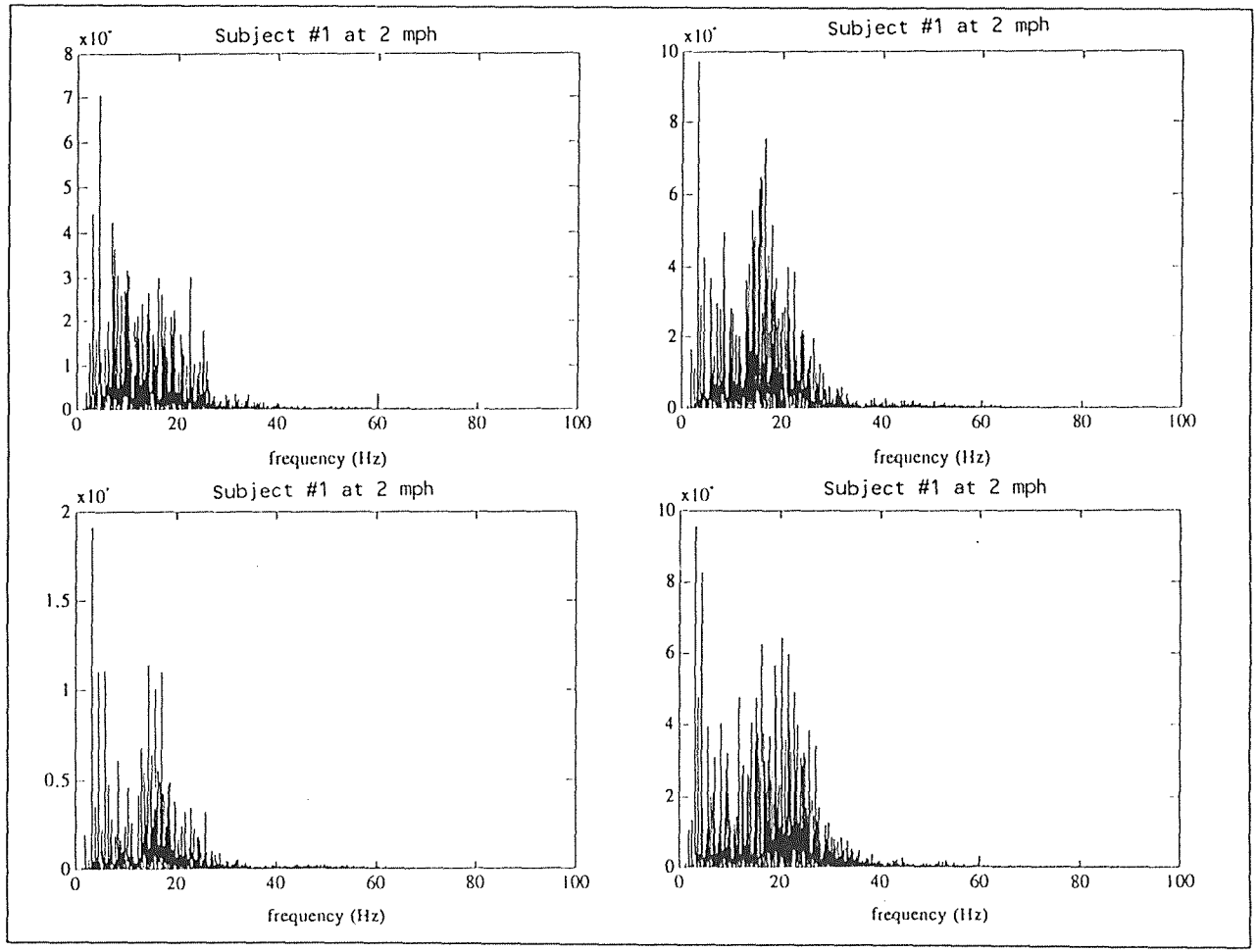

Figure 7 Power Spectra of 25 Second Time Windows for Intervals 5 to 8

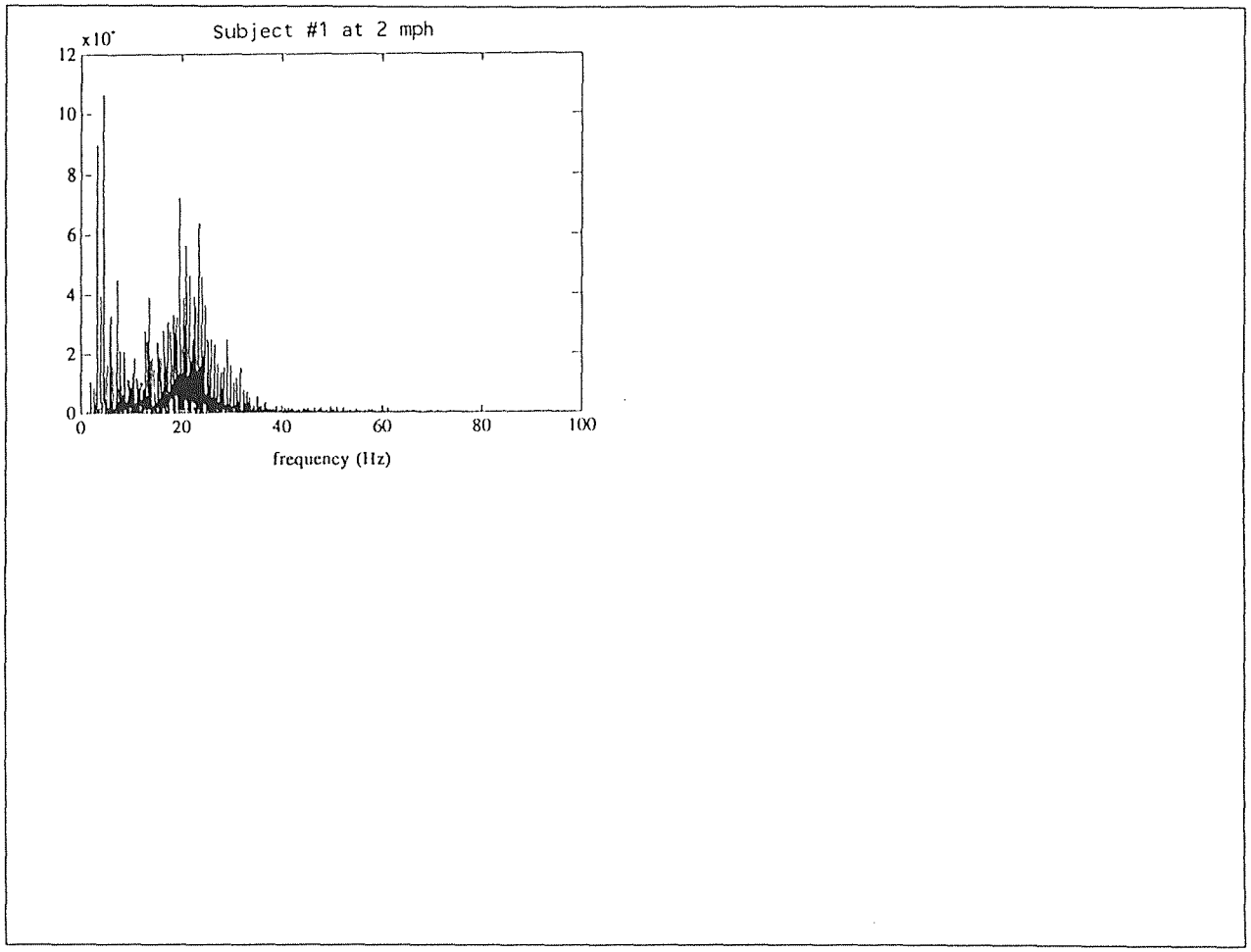

Figure 8 Power Spectra of a 25 Second Time Window for Interval 9

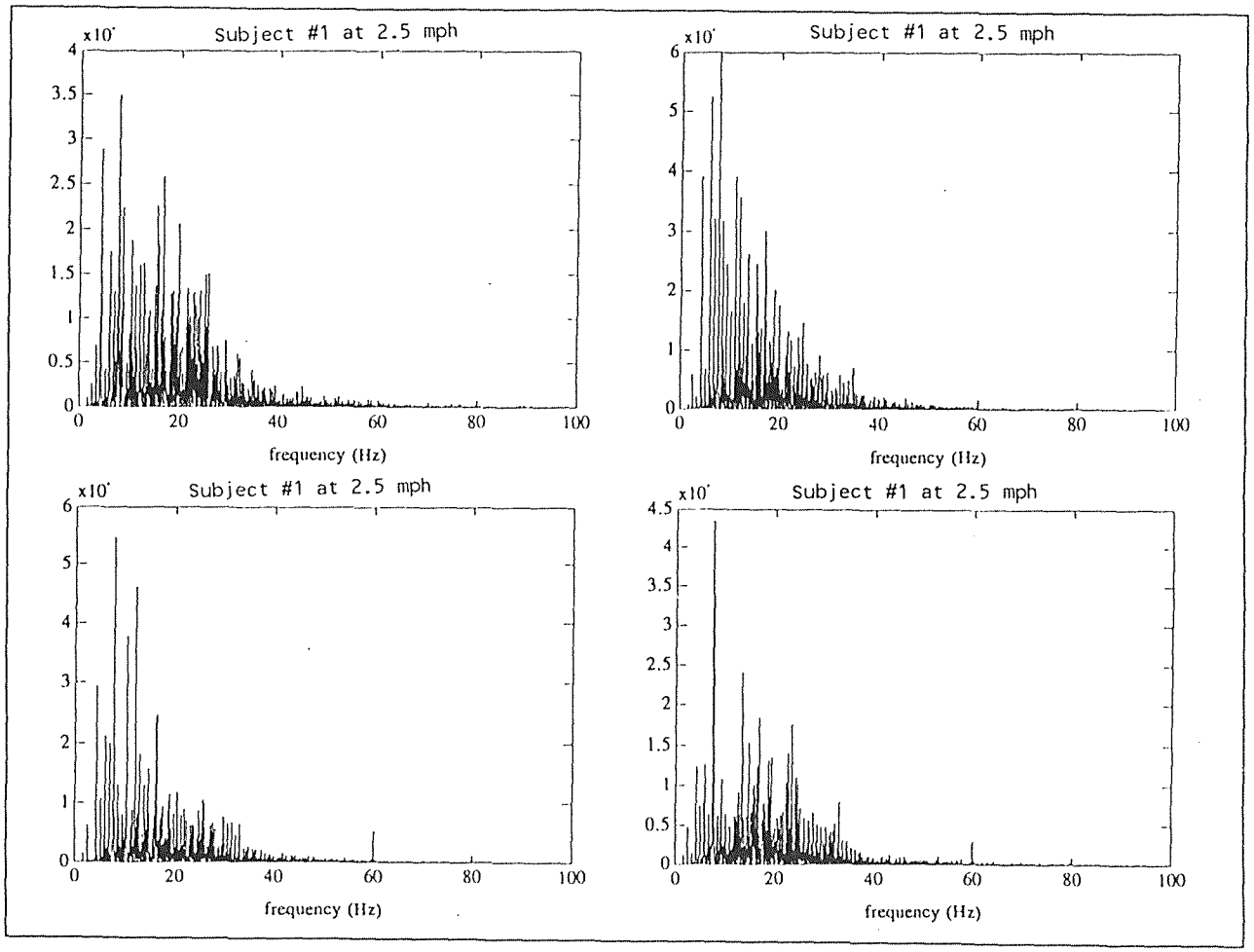

Figure 9 Power Spectra of 25 Second Time Windows for Intervals 1 to 4

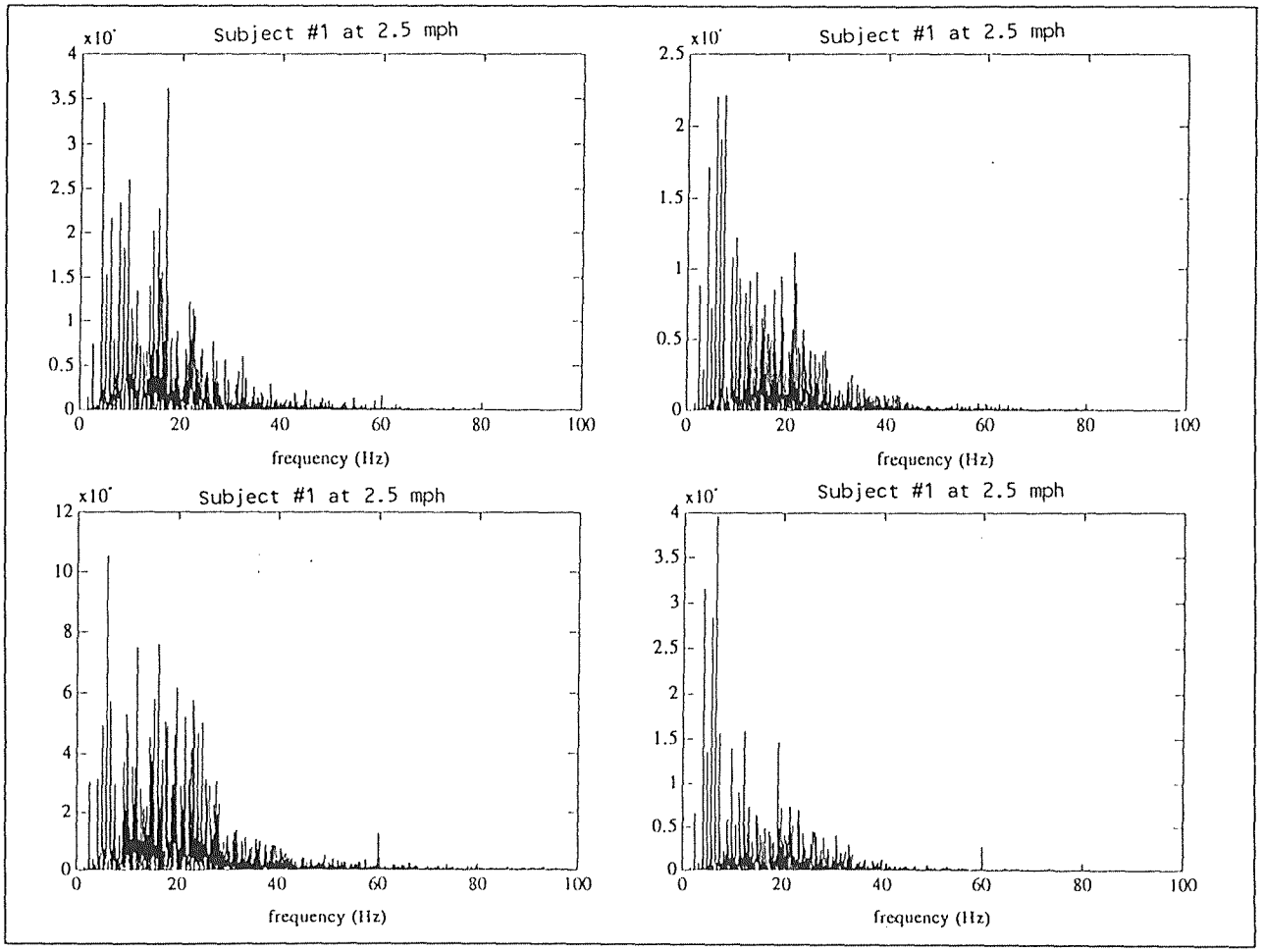

Figure 10 Power Spectra of 25 Second Time Windows for Intervals 5 to 8

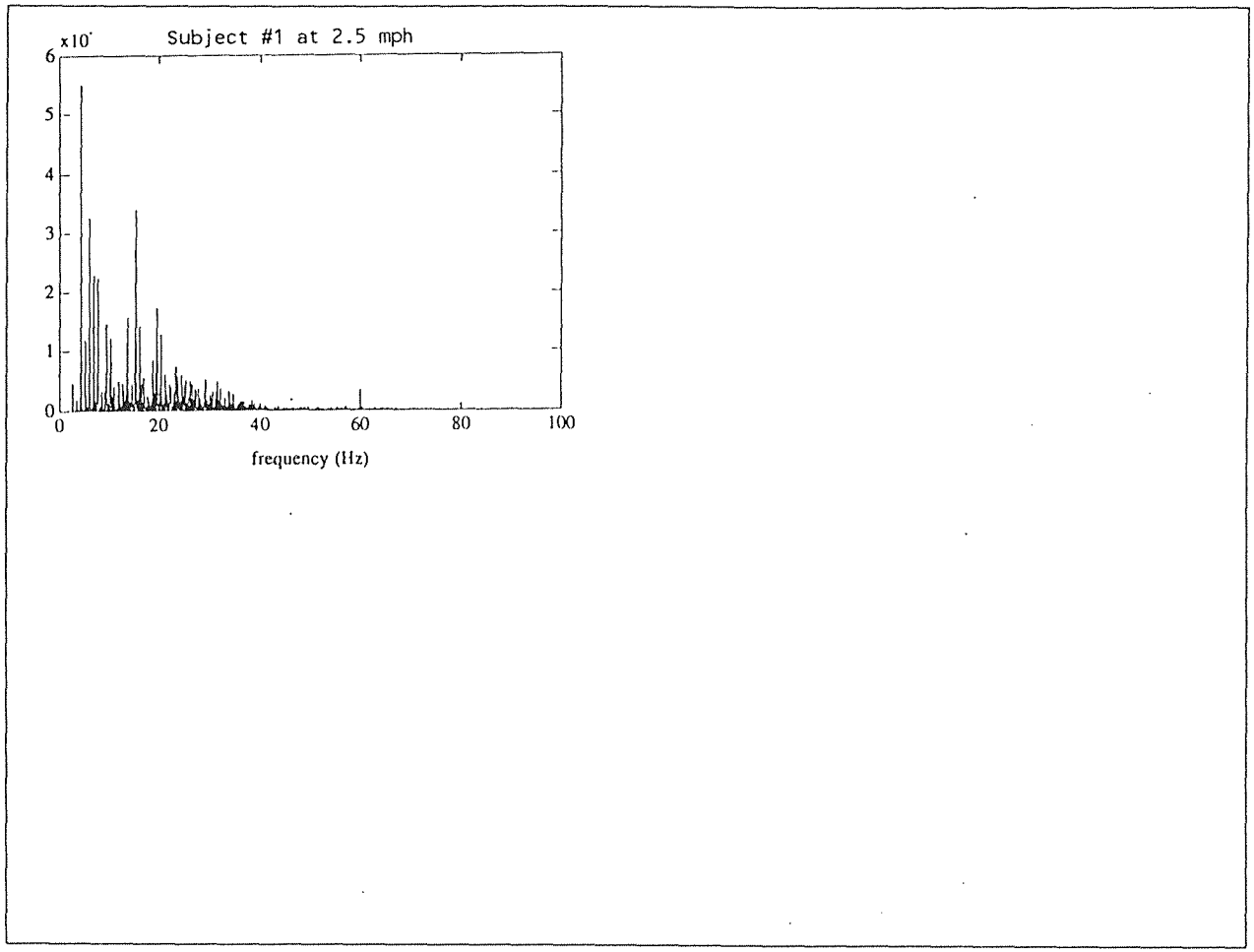

Figure 11 Power Spectra of a 25 Second Time Window for Interval 9

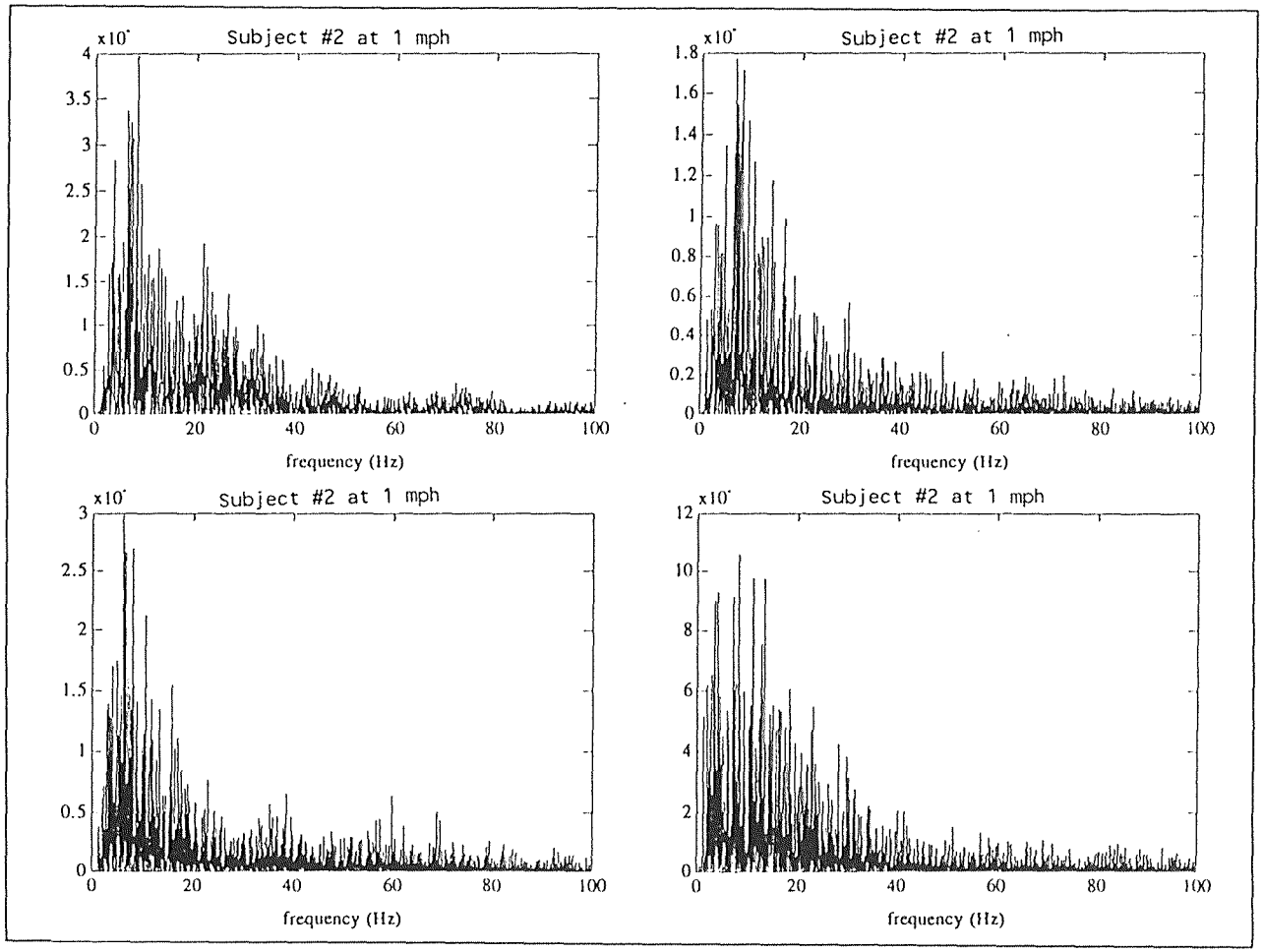

Figure 12 Power Spectra of 25 Second Time Windows for Intervals 1 to 4

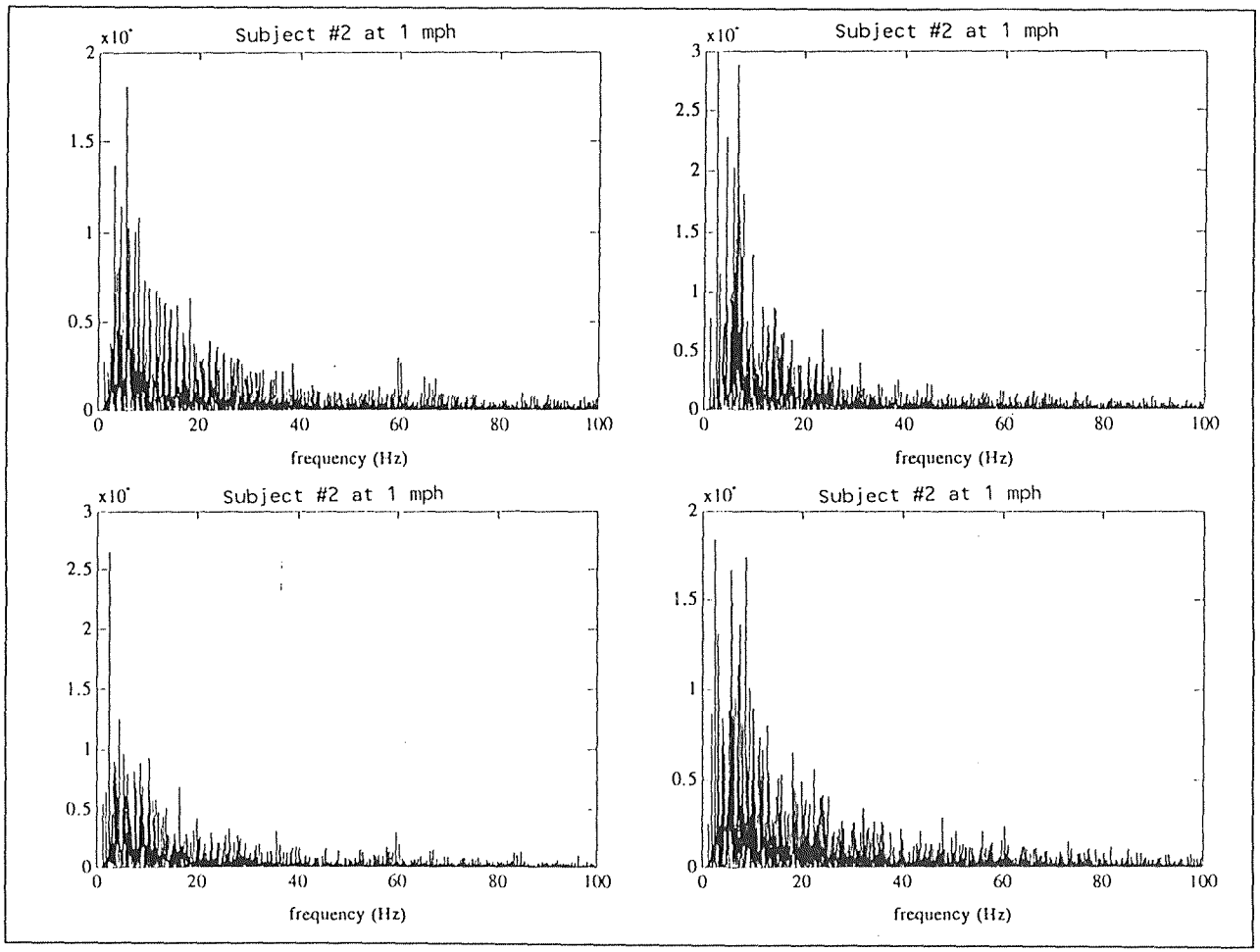

Figure 13 Power Spectra of 25 Second Time Windows for Intervals 5 to 8

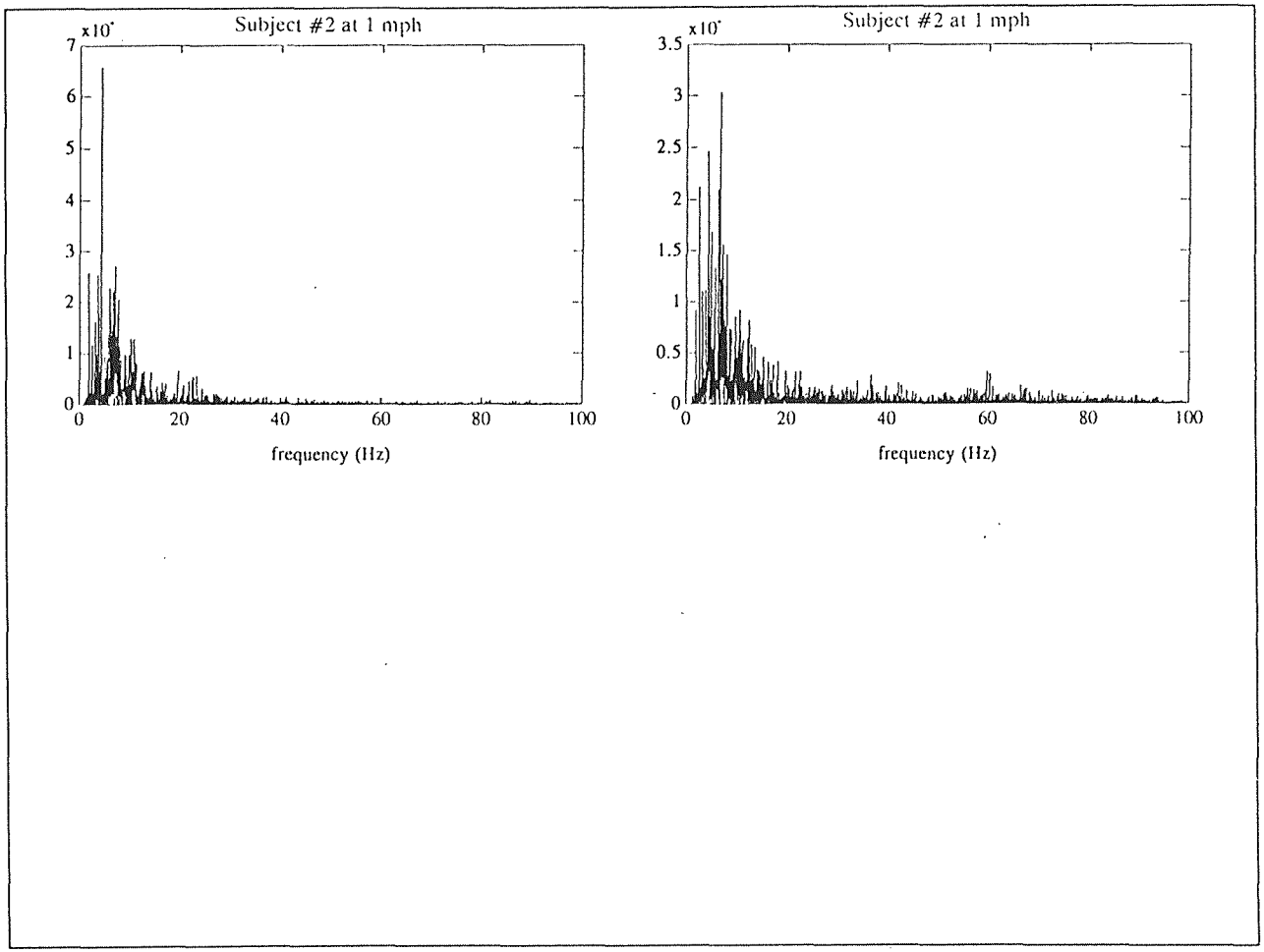

Figure 14 Power Spectra of 25 Second Time Windows for Intervals 9 and 10

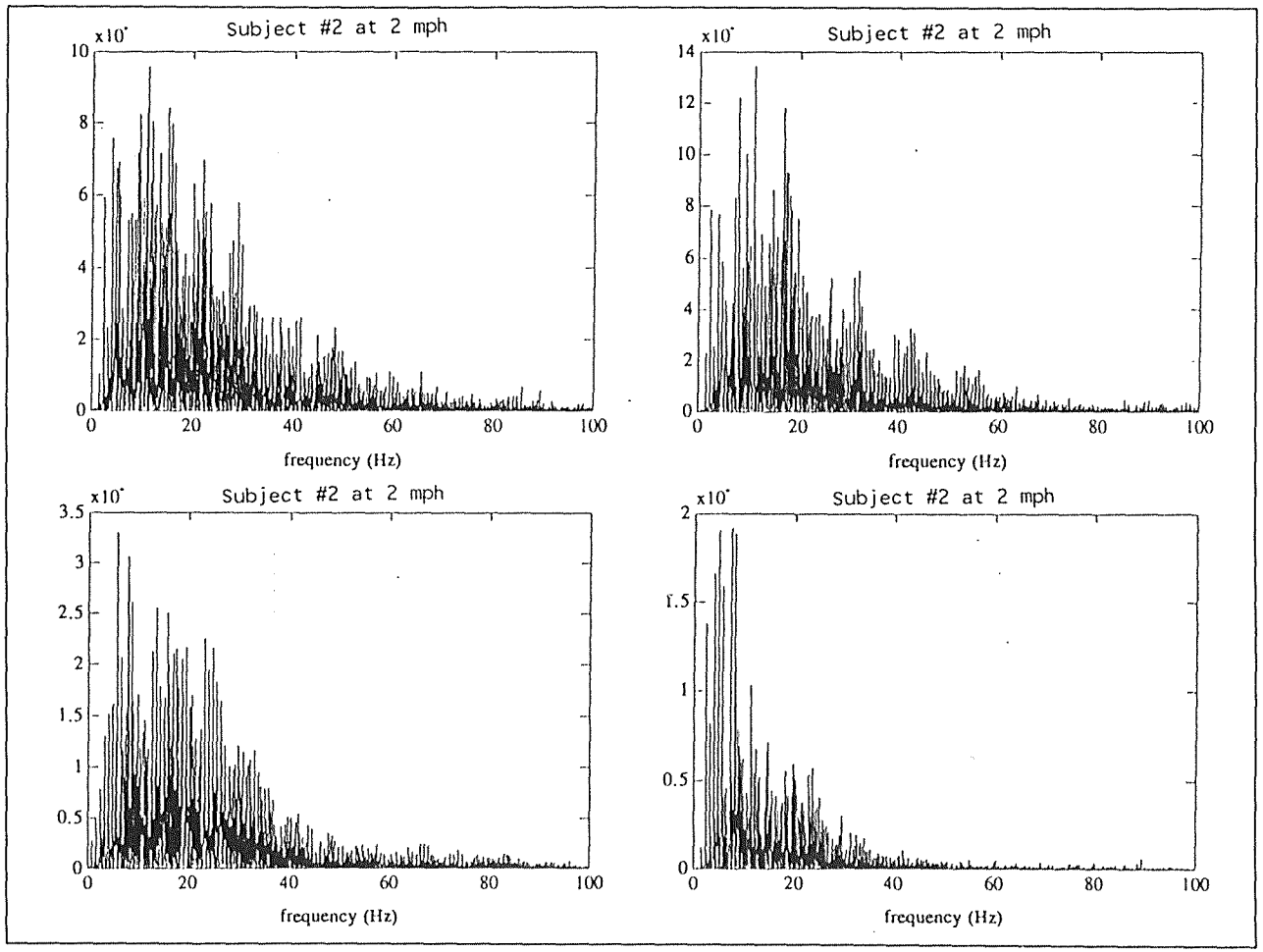

Figure 15 Power Spectra of 25 Second Time Windows for Intervals 1 to 4

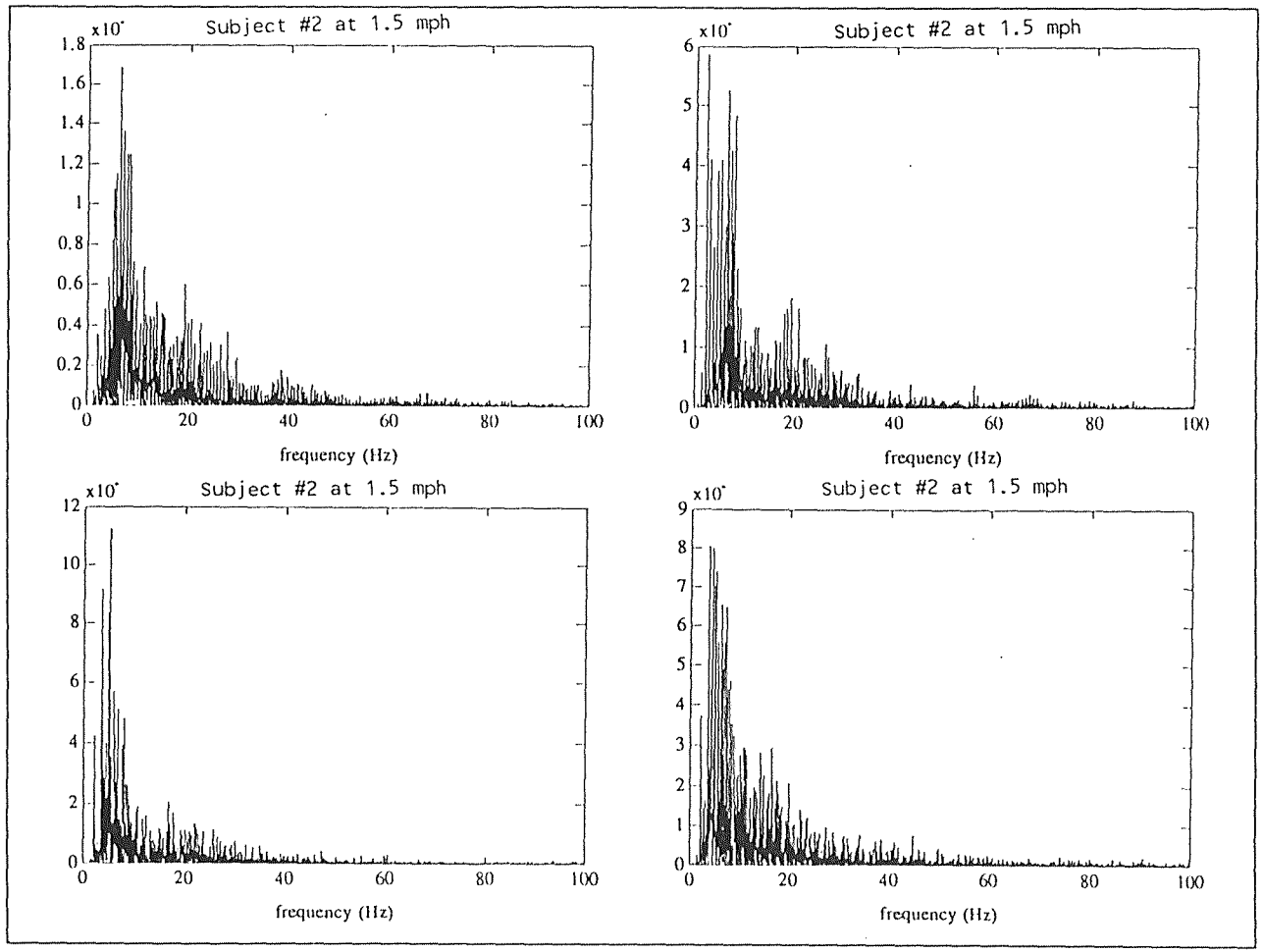

Figure 16 Power Spectra of 25 Second Time Windows for Intervals 1 to 4

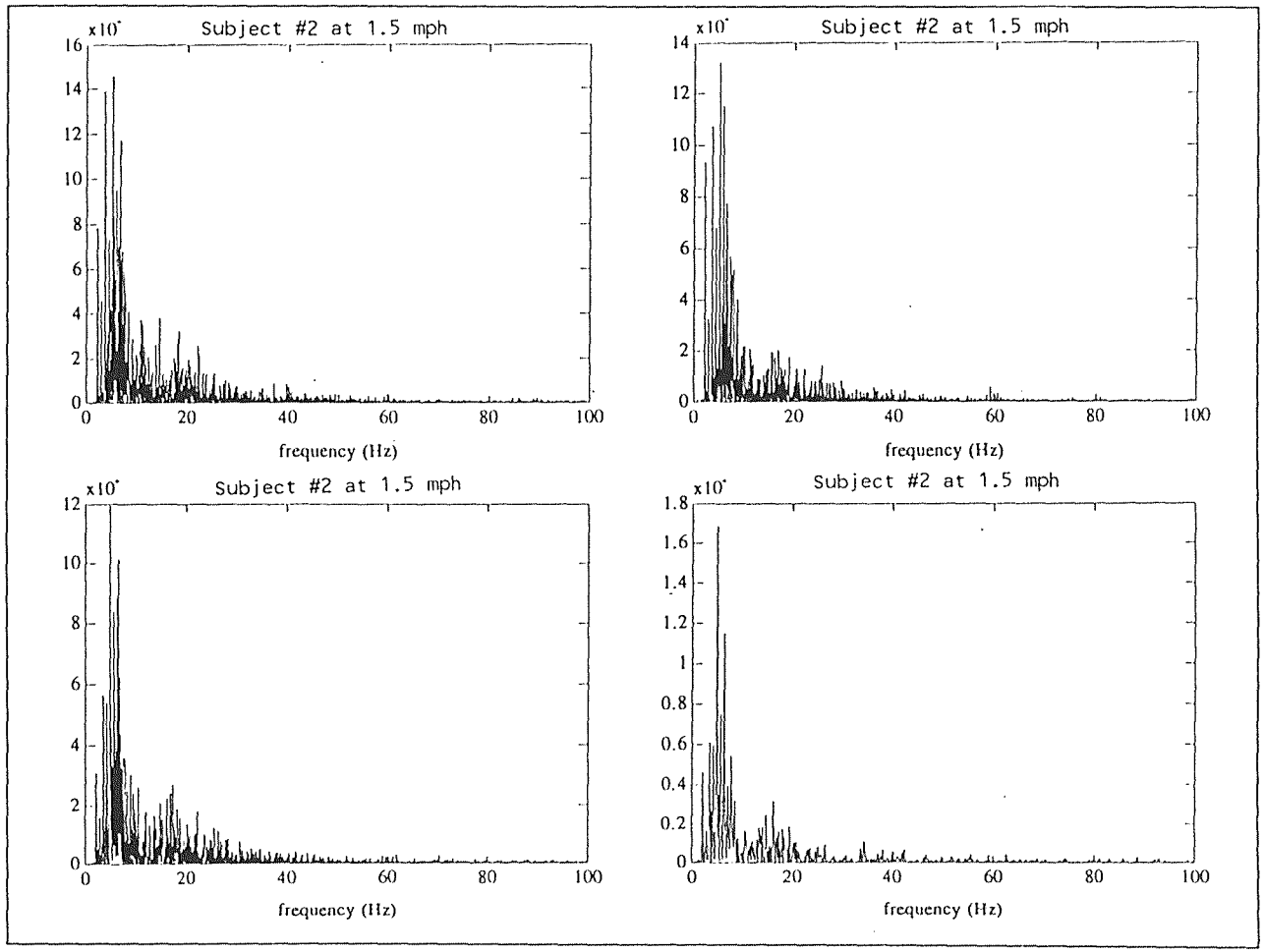

Figure 17 Power Spectra of 25 Second Time Windows for Intervals 5 to 8

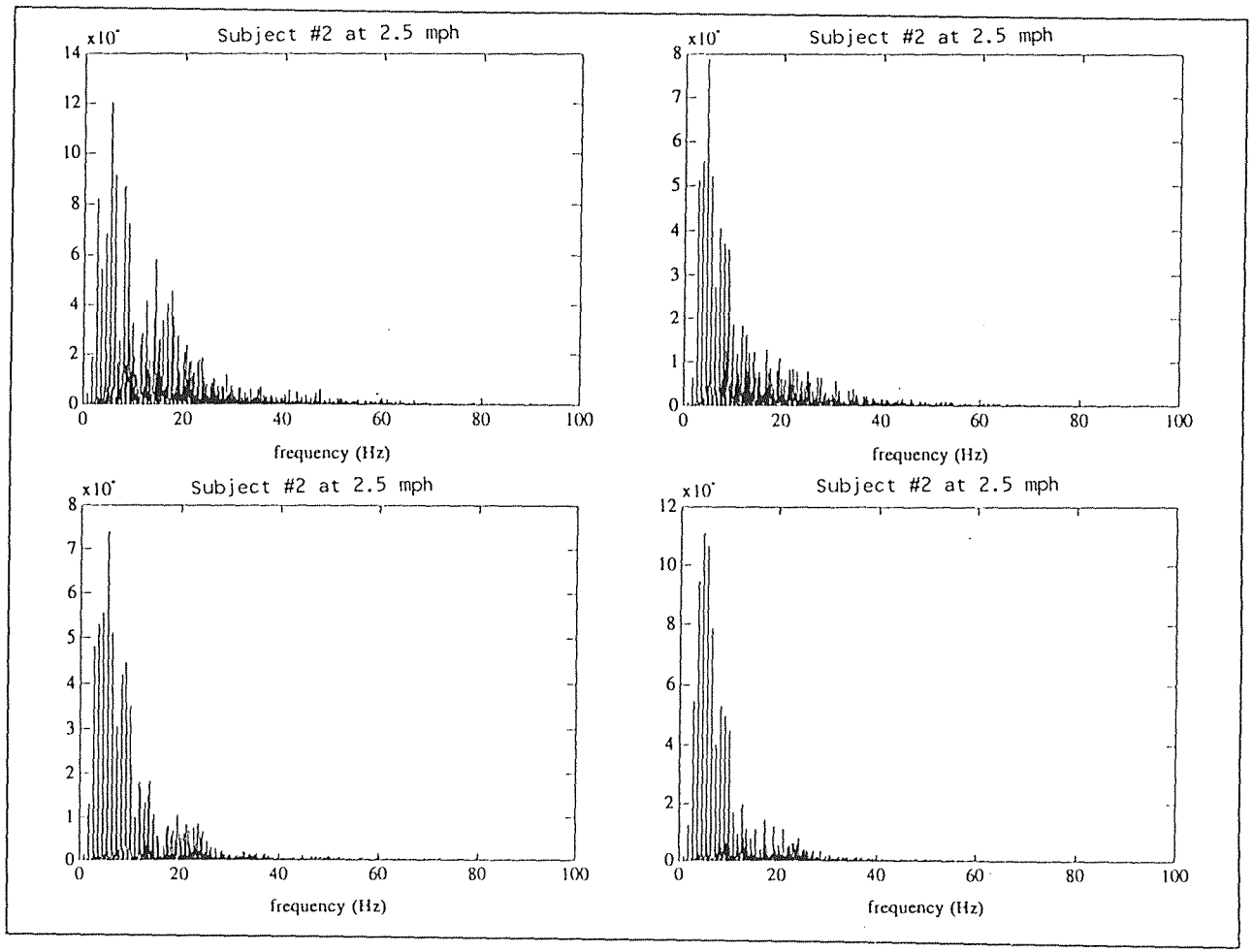

Figure 18 Power Spectra of 25 Second Time Windows for Intervals 1 to 4

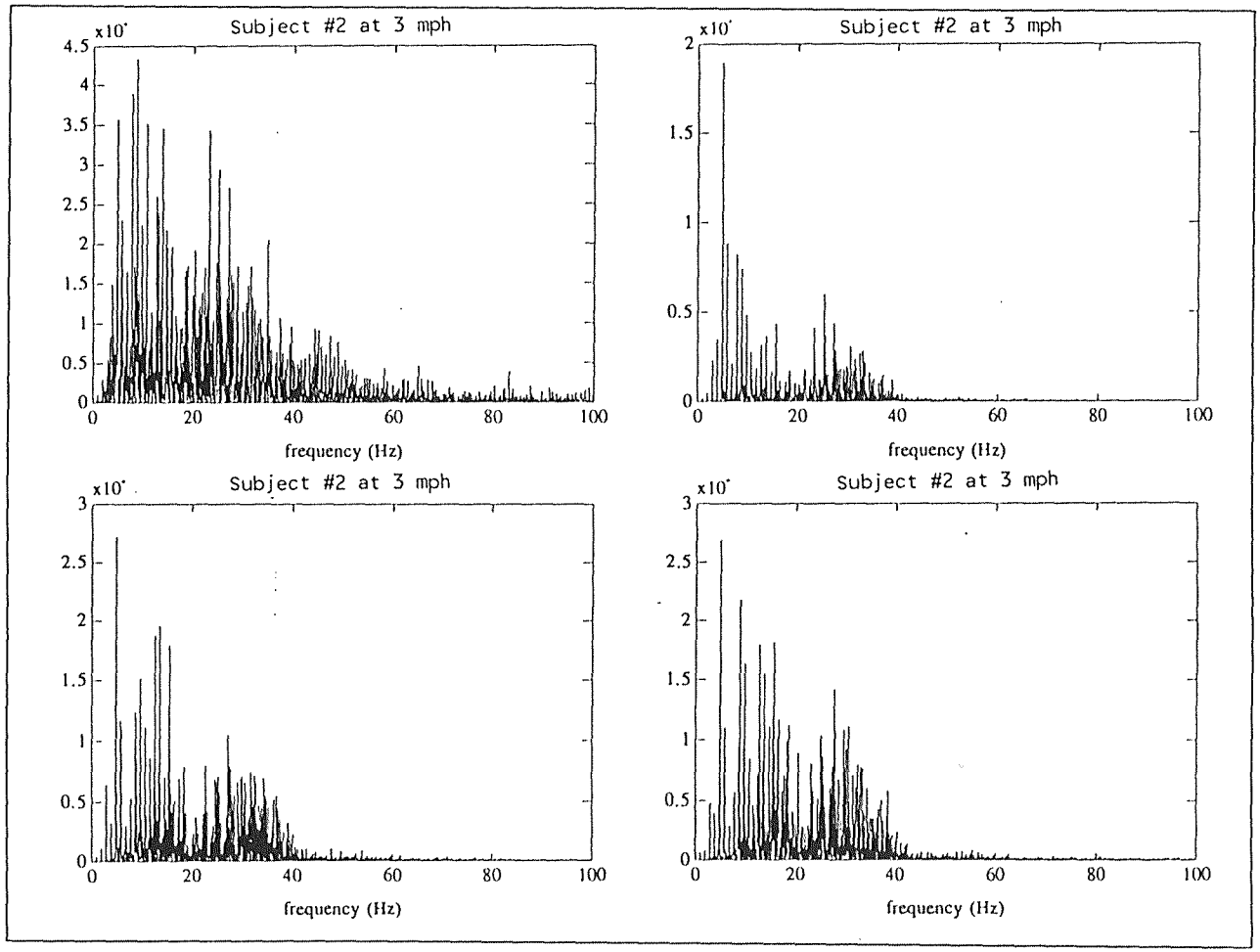

Figure 19 Power Spectra of 25 Second Time Windows for Intervals 1 to 4

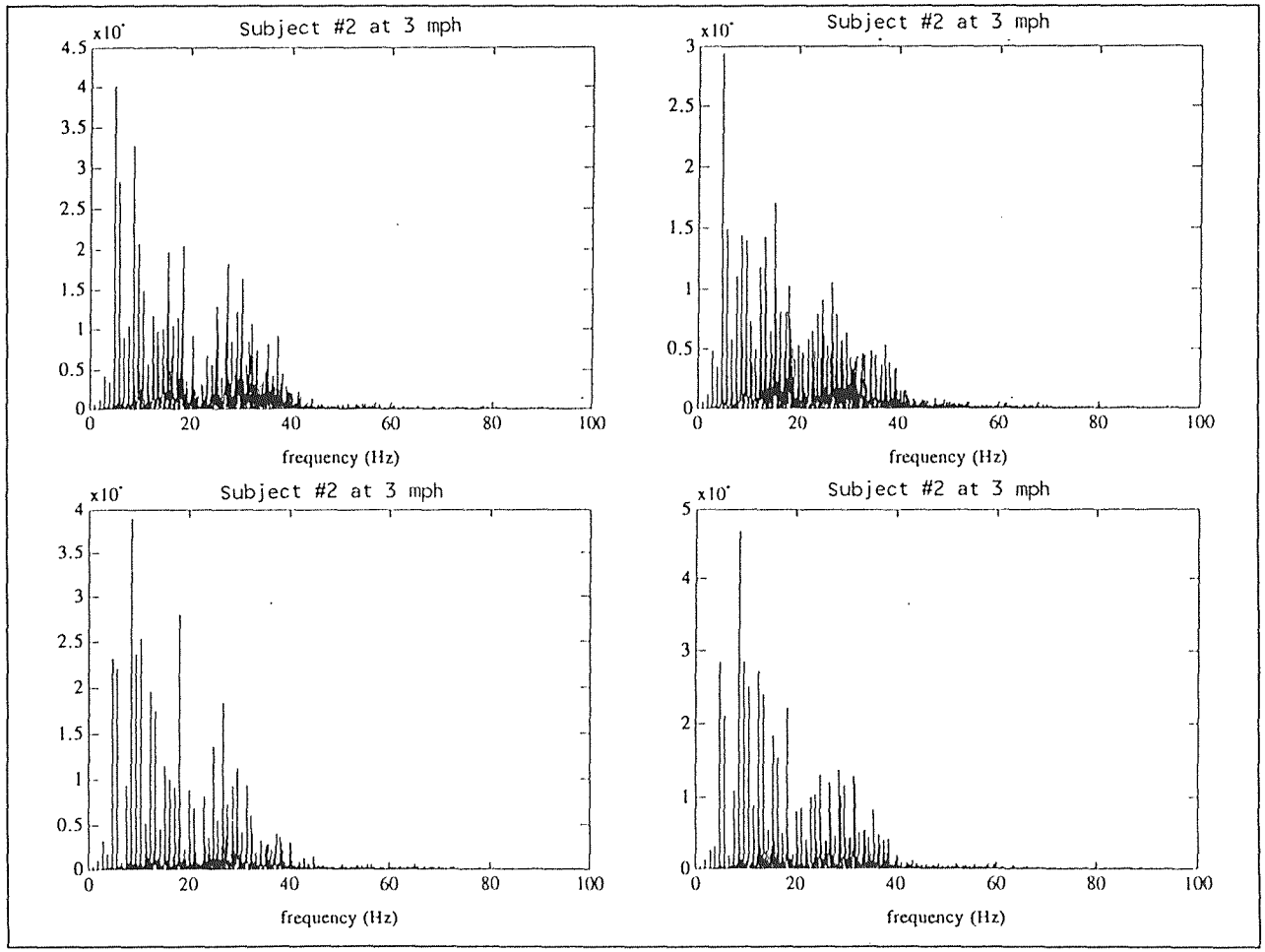

Figure 20 Power Spectra of 25 Second Time Windows for Intervals 5 to 8

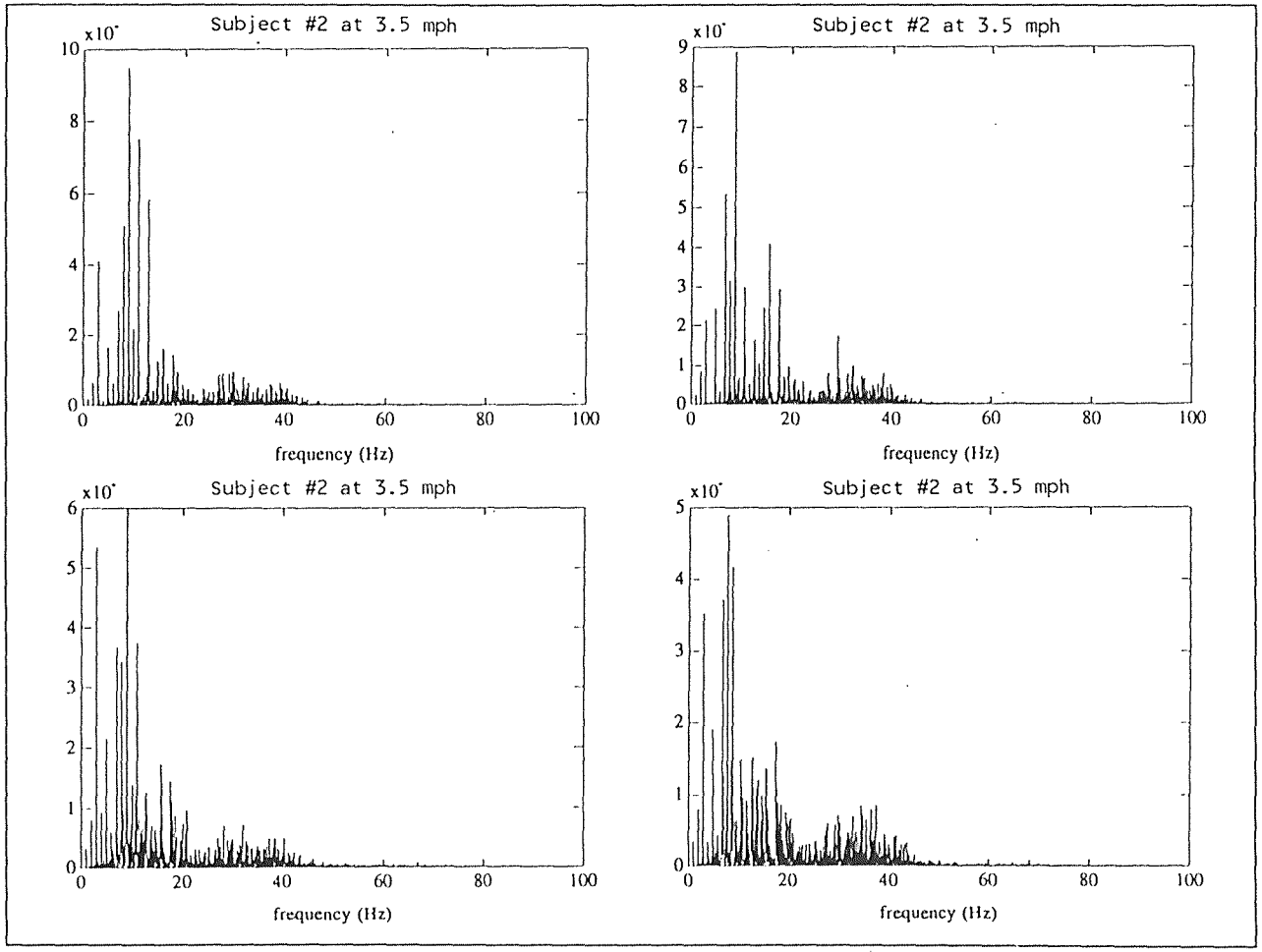

Figure 21 Power Spectra of 25 Second Time Windows for Intervals 1 to 4

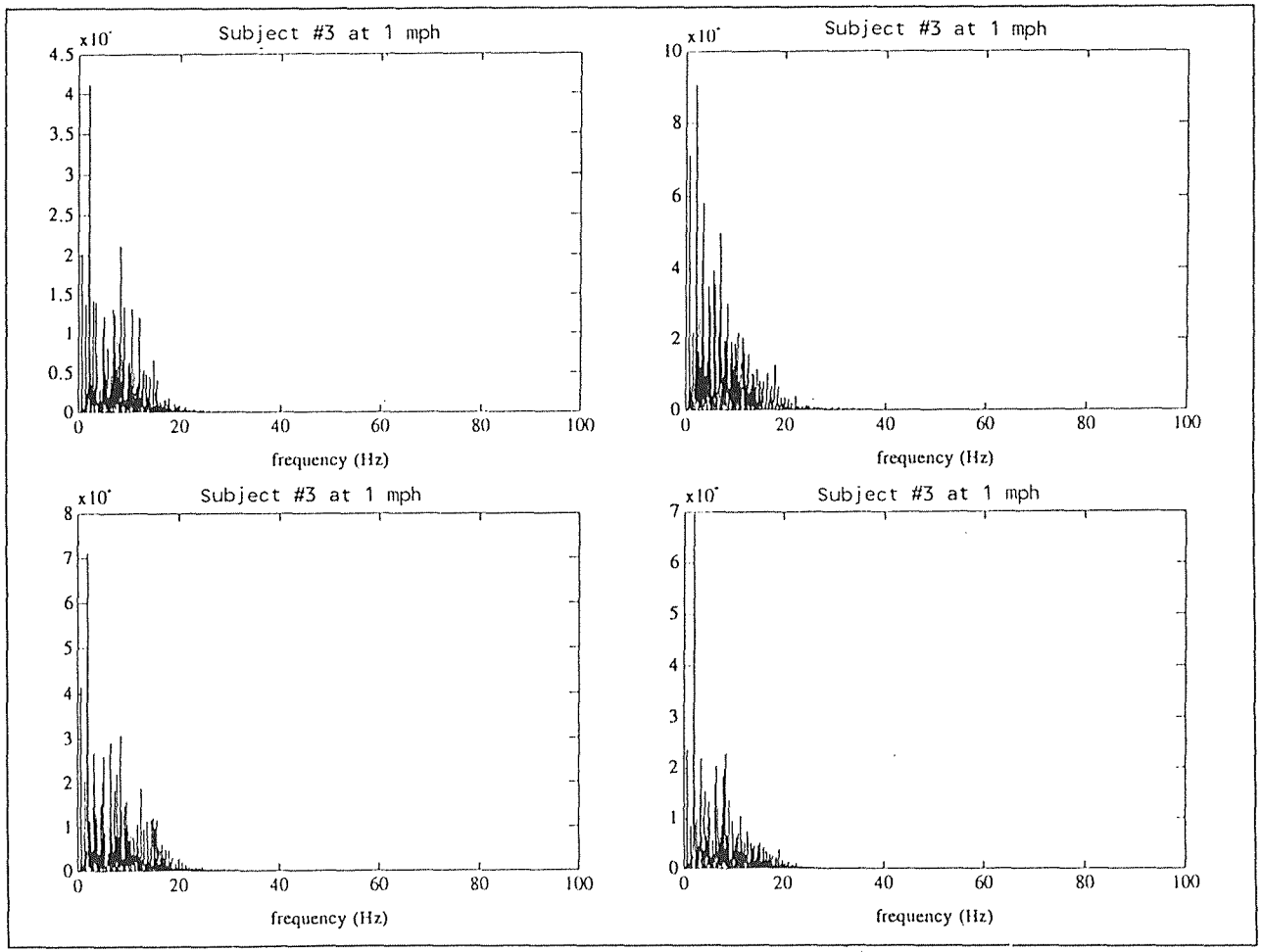

Figure 22 Power Spectra of 25 Second Time Windows for Intervals 1 to 4

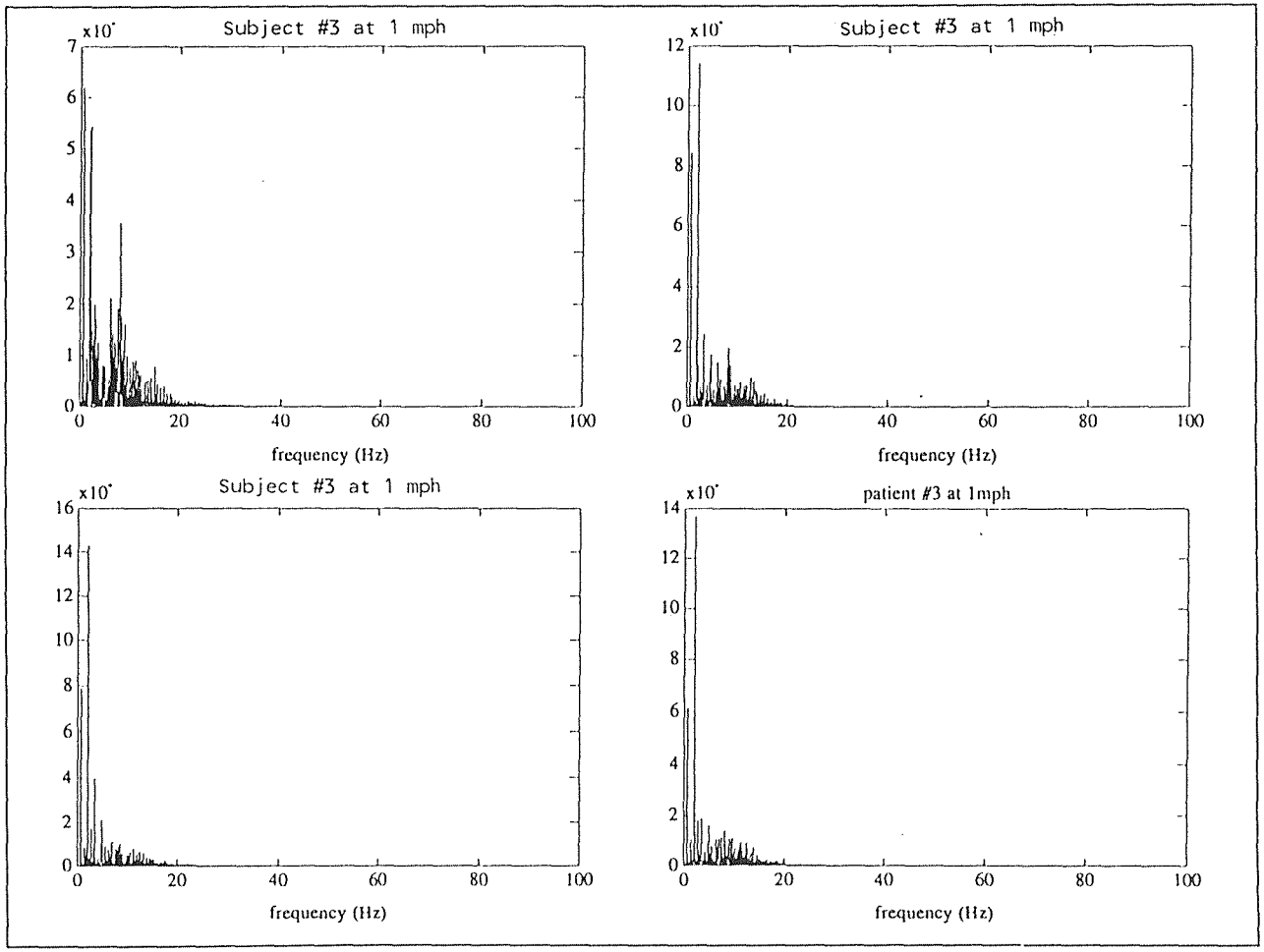

Figure 23 Power Spectra of 25 Second Time Windows for Intervals 5 to 8

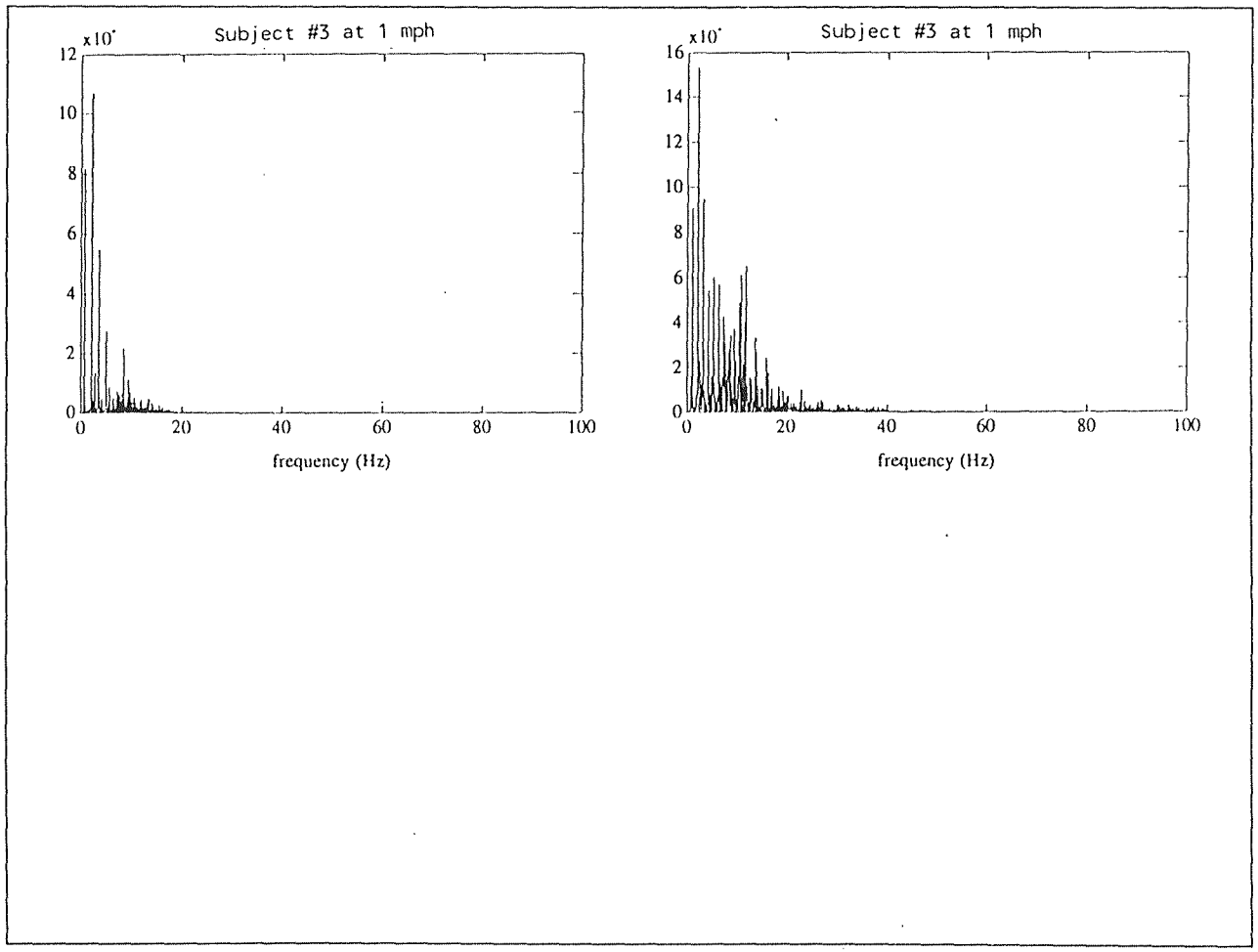

Figure 24 Power Spectra of 25 Second Time Windows for Intervals 9 and 10

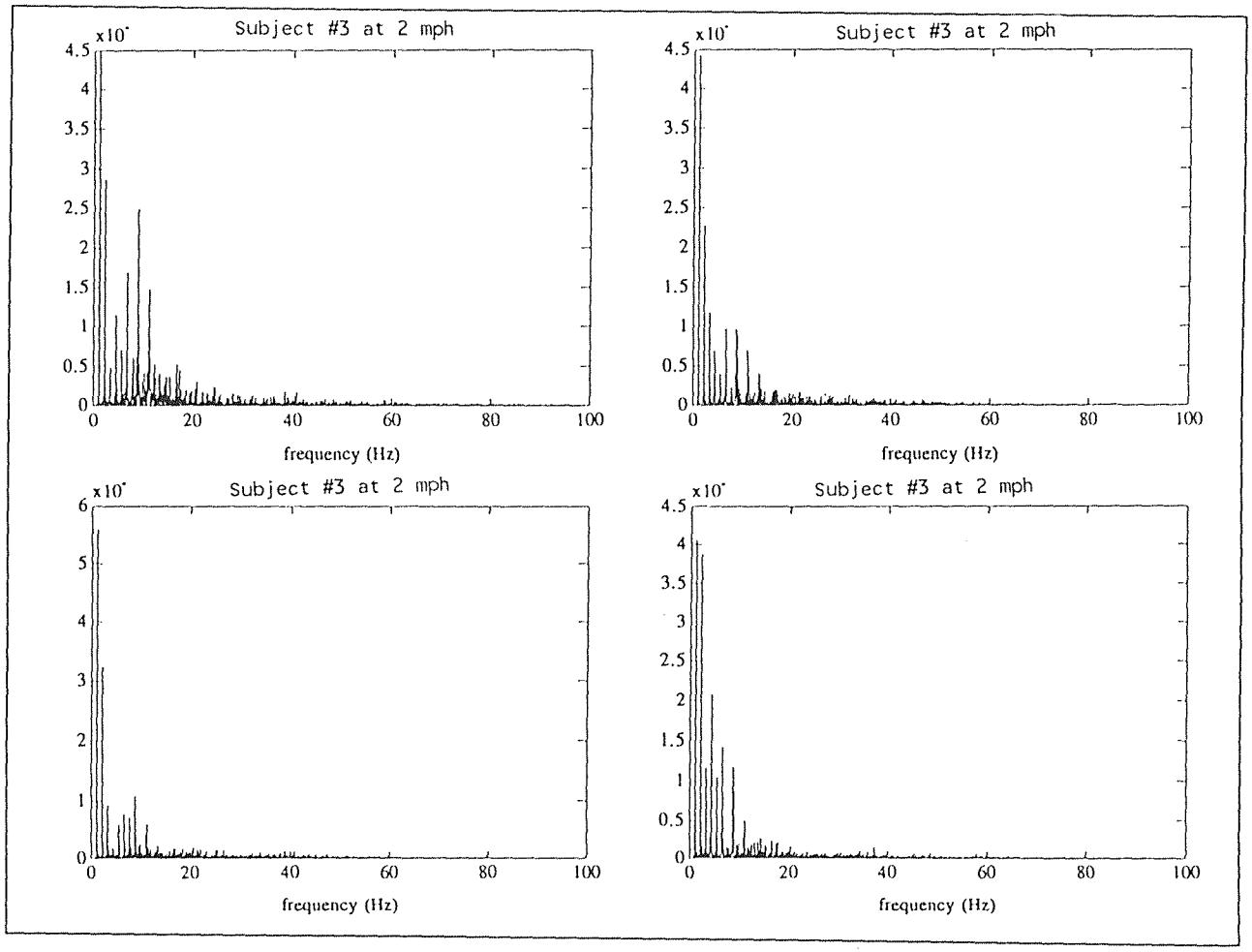

Figure 25 Power Spectra of 25 Second Time Windows for Intervals 1 to 4

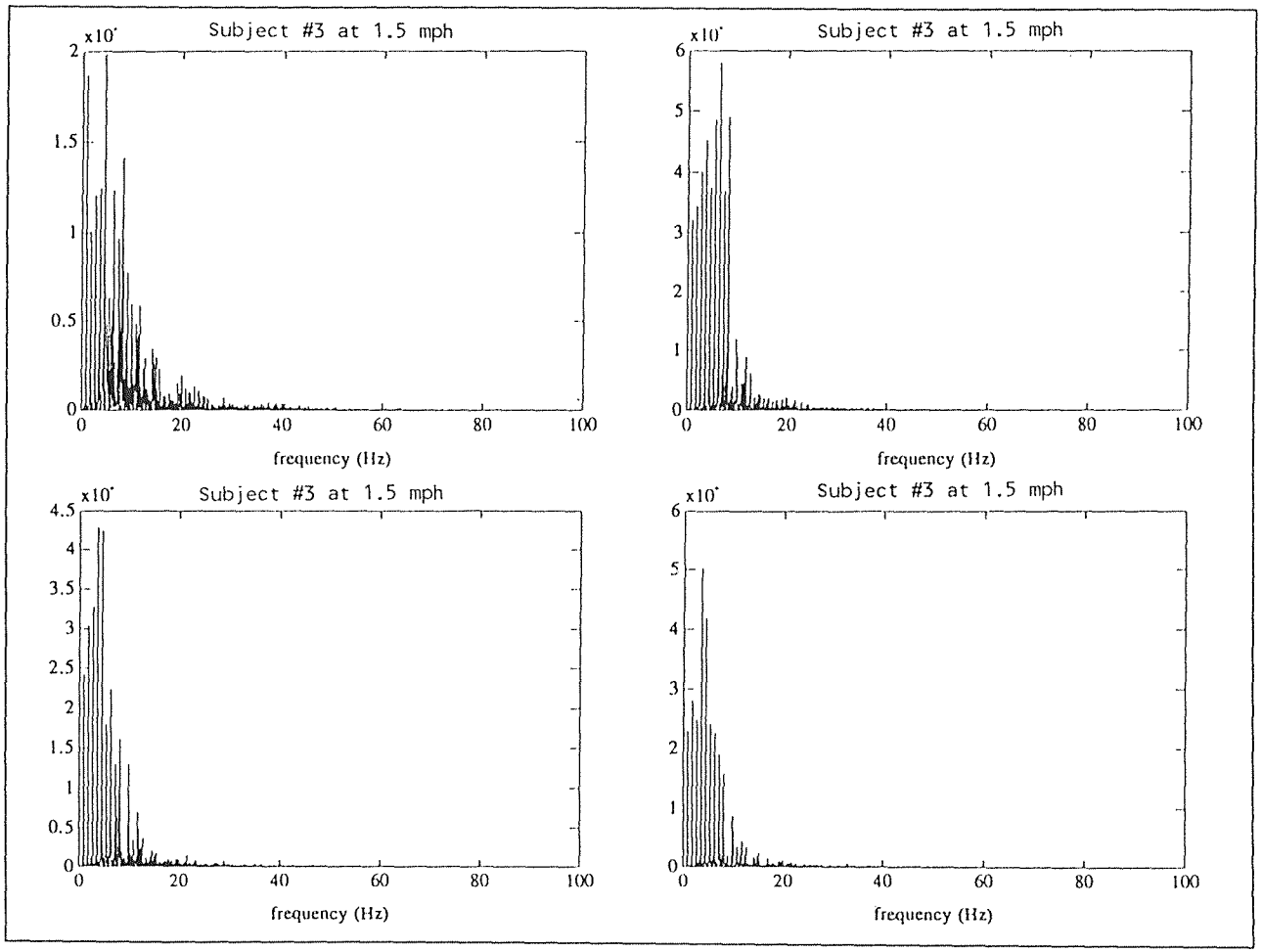

Figure 26 Power Spectra of 25 Second Time Windows for Intervals 1 to 4

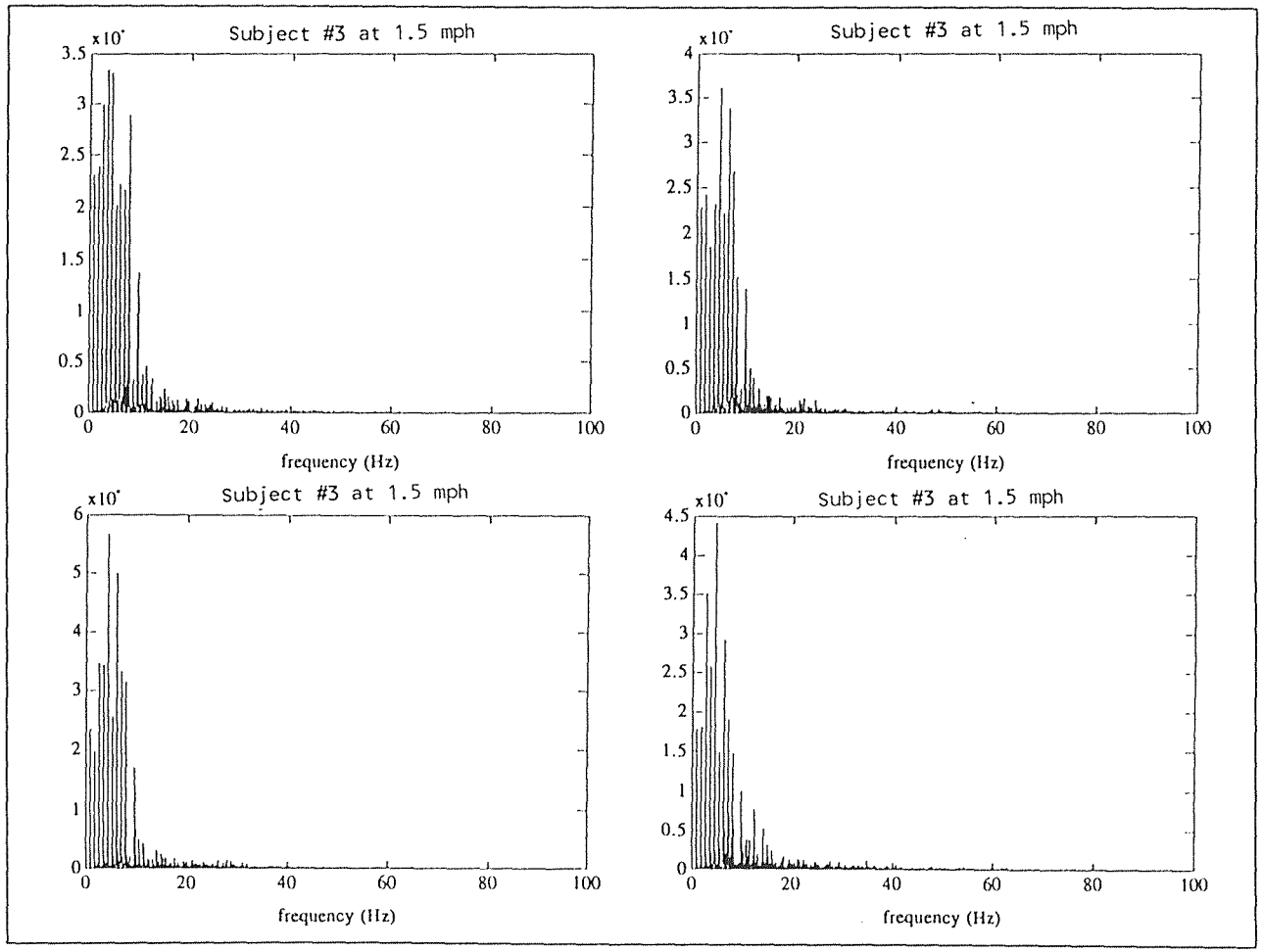

Figure 27 Power Spectra of 25 Second Time Windows for Intervals 5 to 8

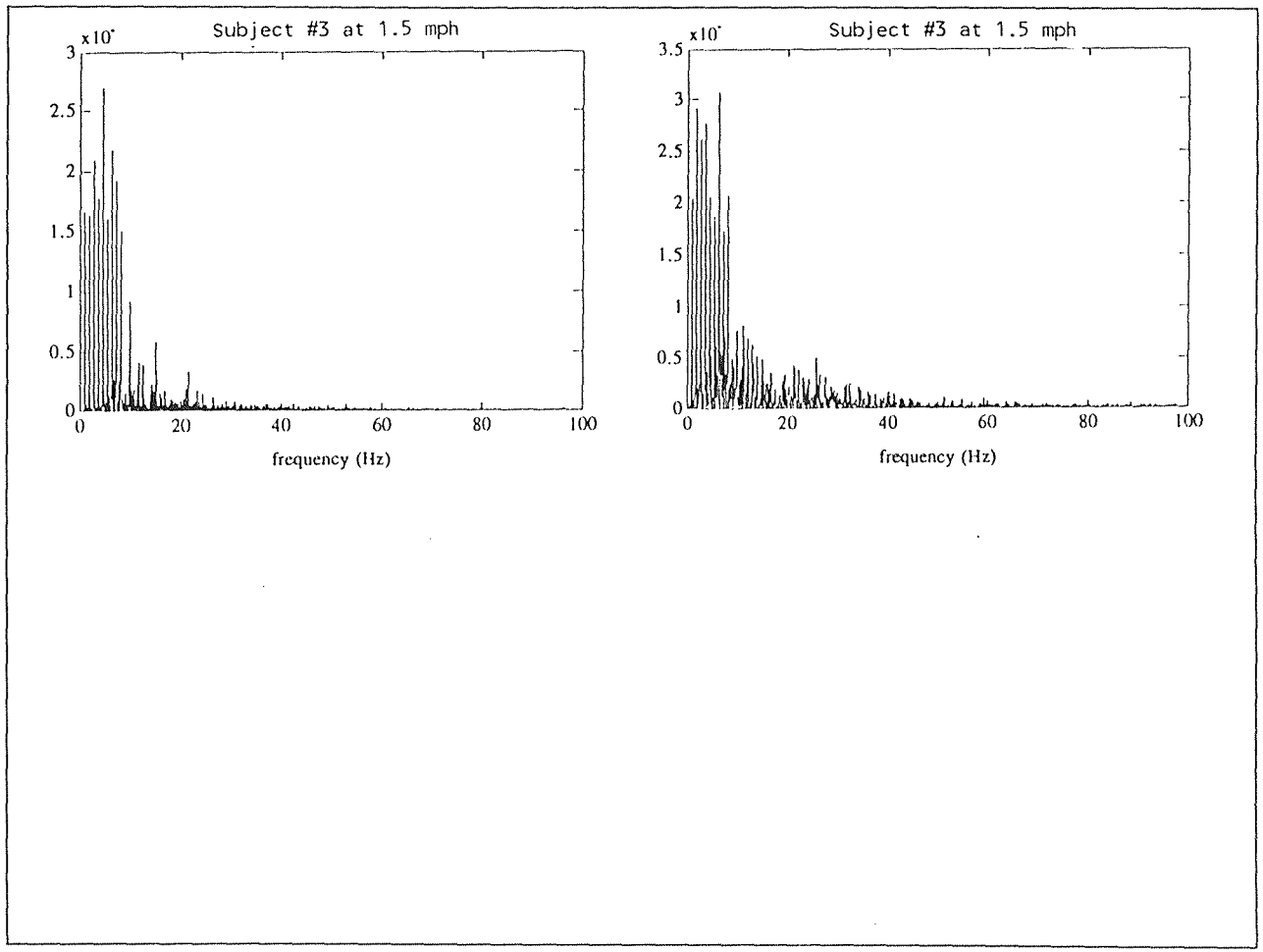

Figure 28 Power Spectra of 25 Second Time Windows for Intervals 9 and 10

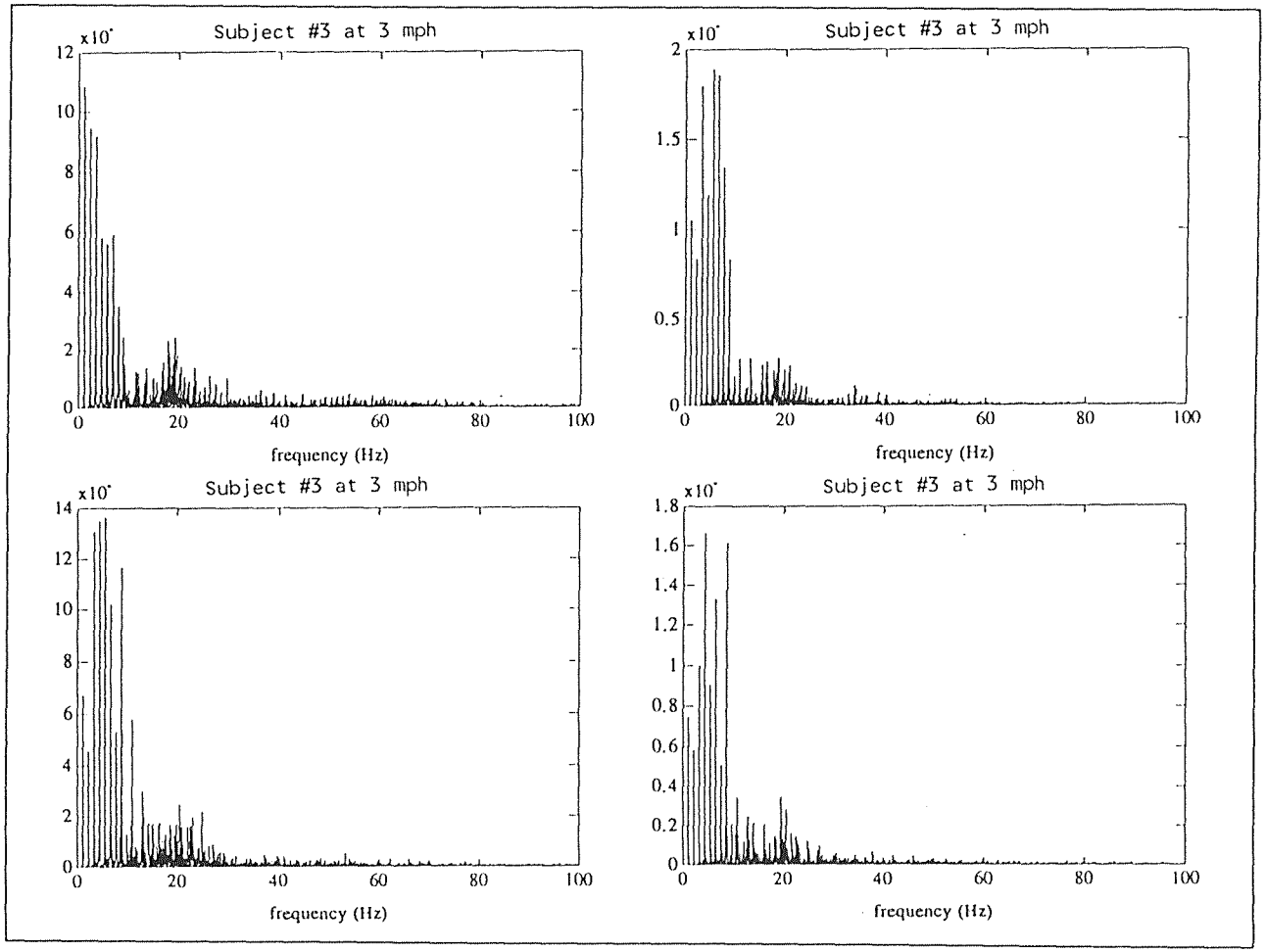

Figure 29 Power Spectra of 25 Second Time Windows for Intervals 1 to 4

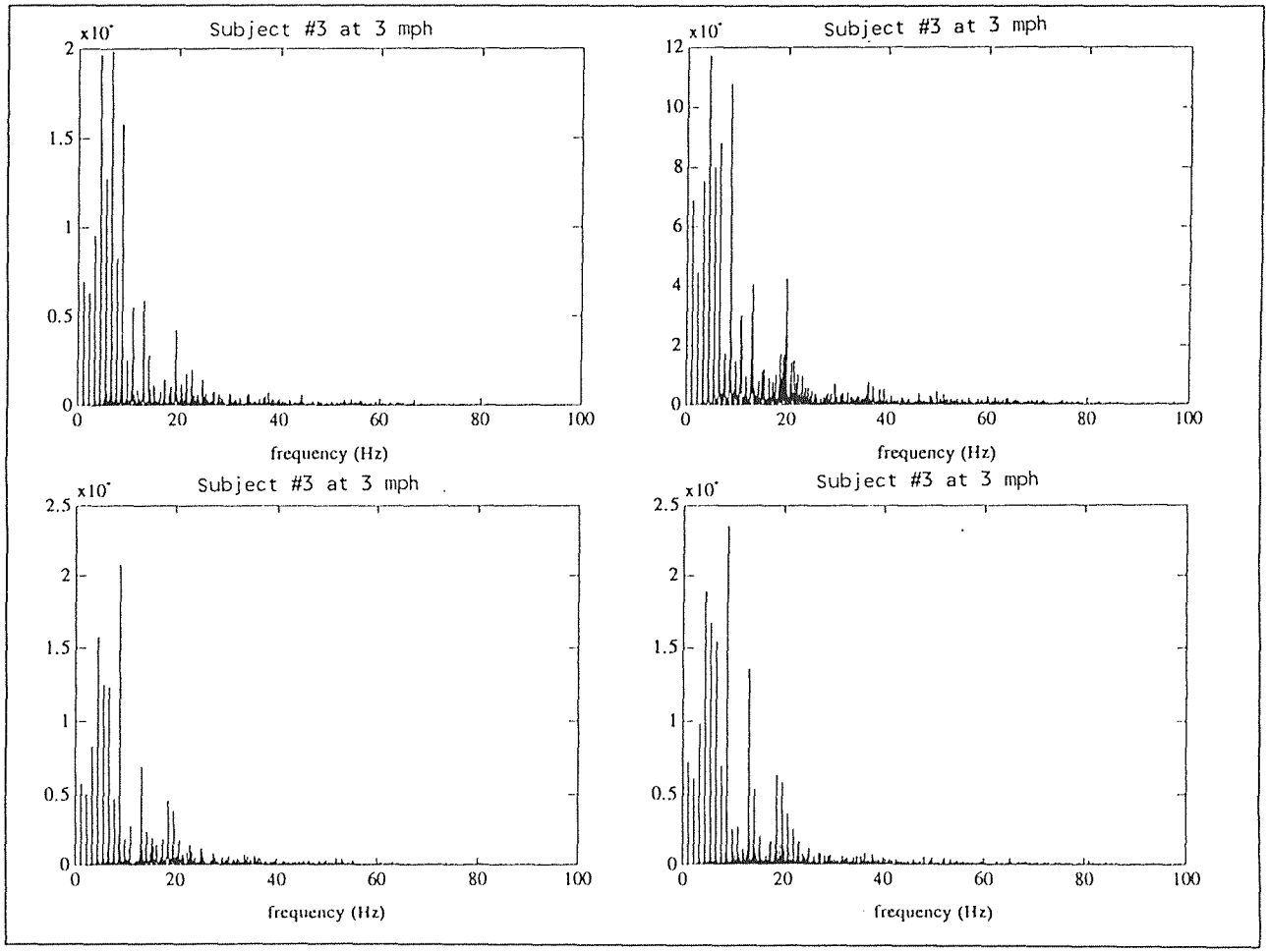

Figure 30 Power Spectra of 25 Second Time Windows for Intervals 5 to 8

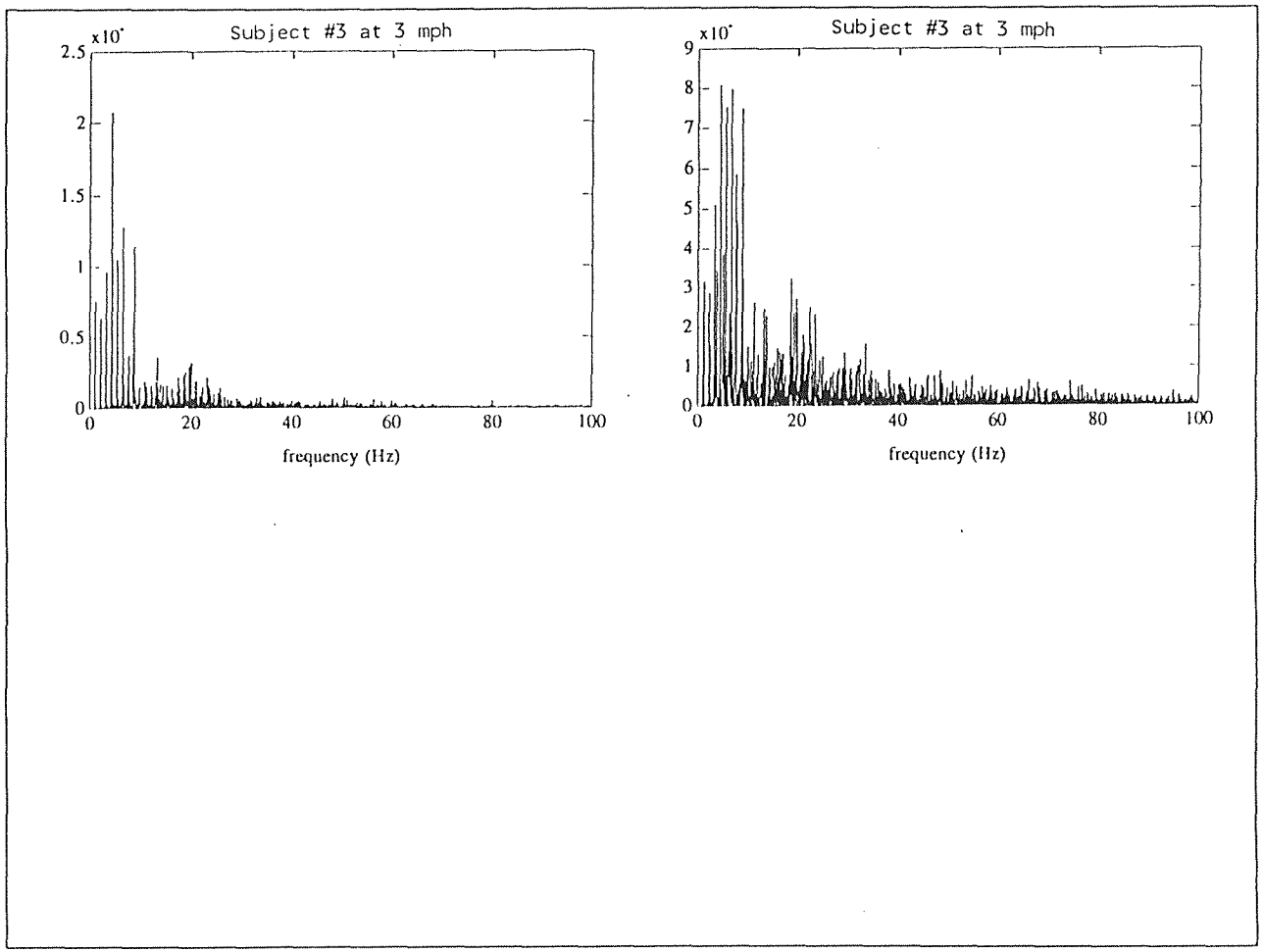

Figure 31 Power Spectra of 25 Second Time Windows for Intervals 9 and 10

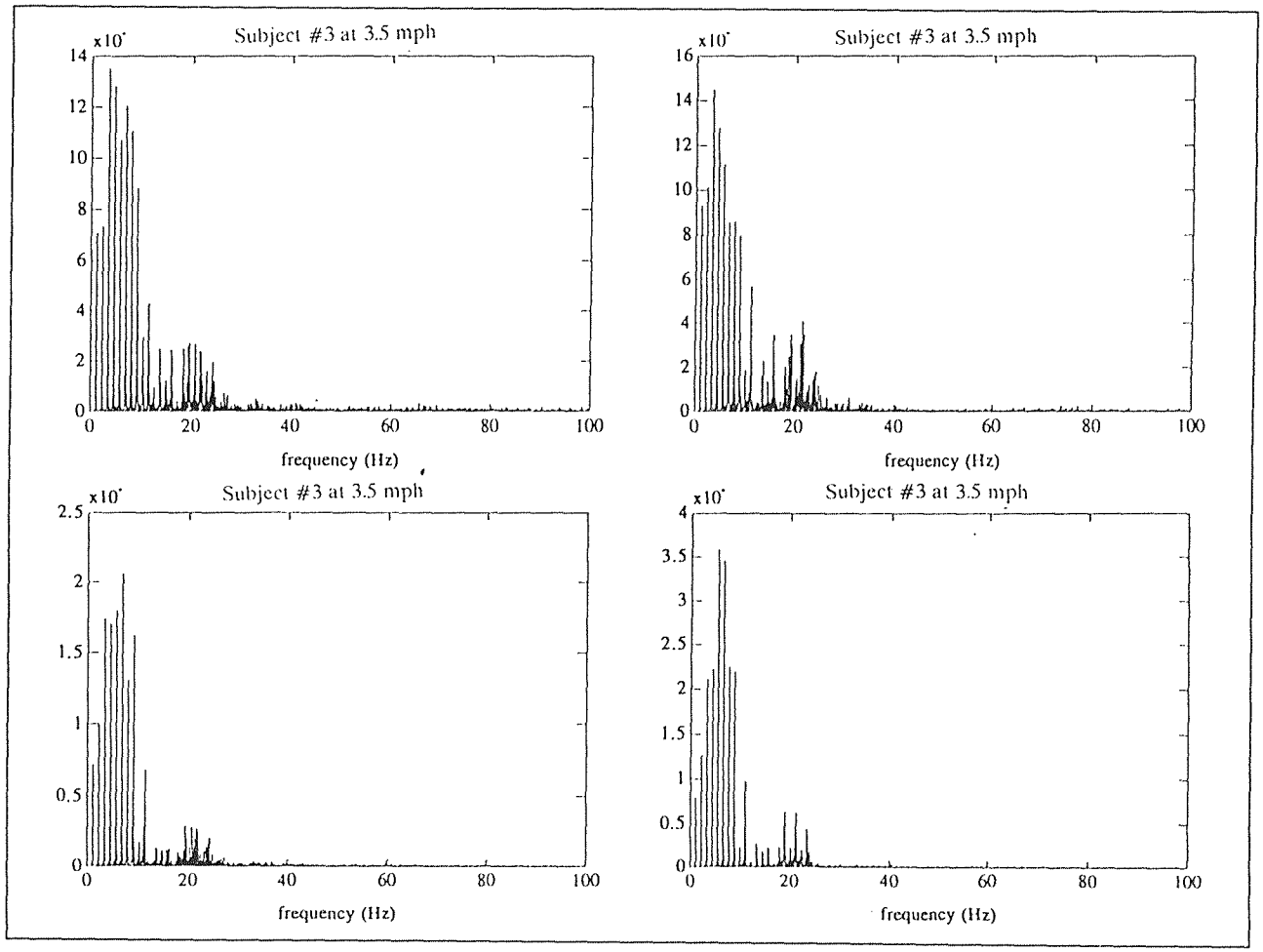

Figure 32 Power Spectra of 25 Second Time Windows for Intervals 1 to 4

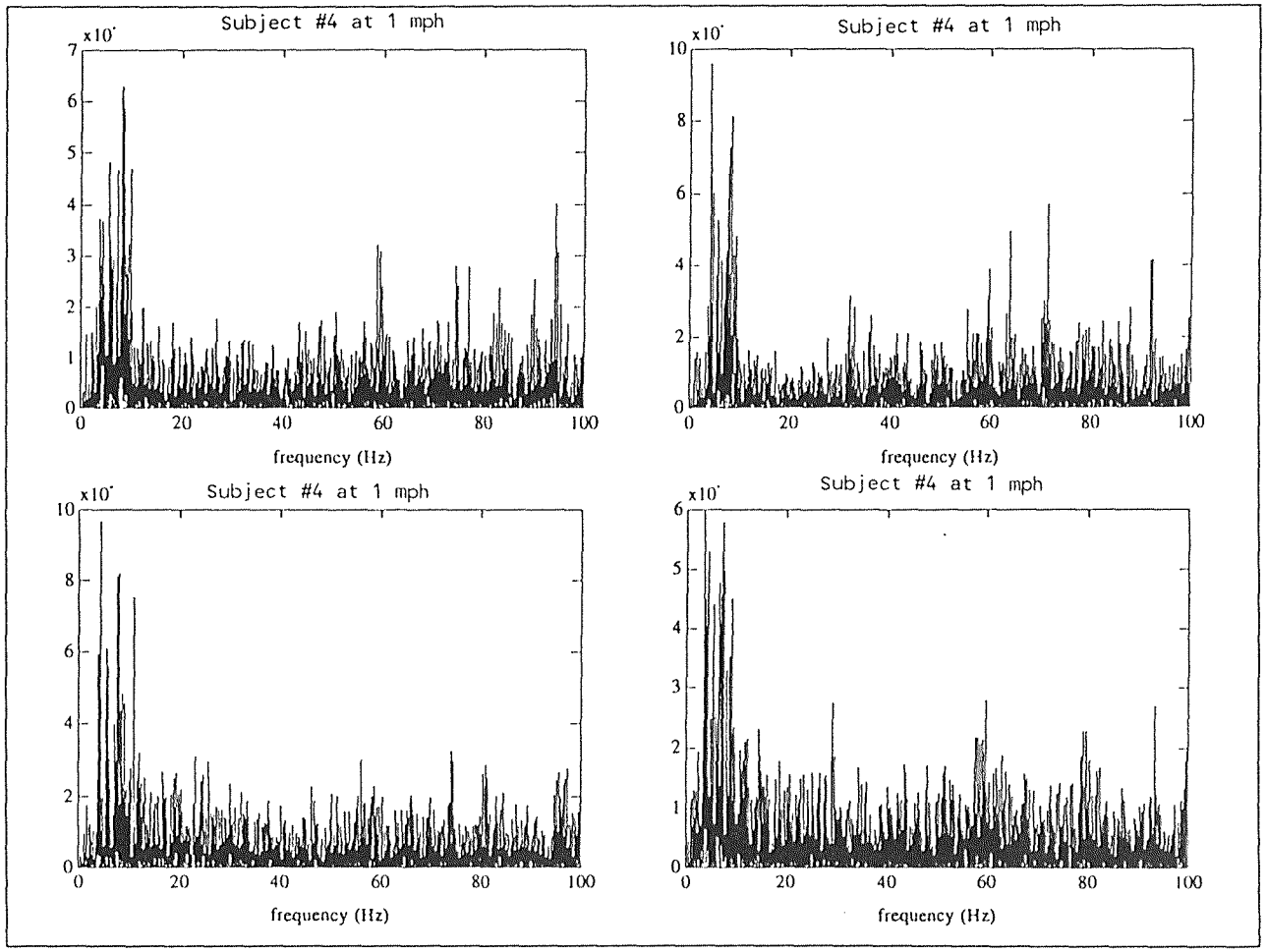

Figure 33 Power Spectra of 25 Second Time Windows for Intervals 1 to 4

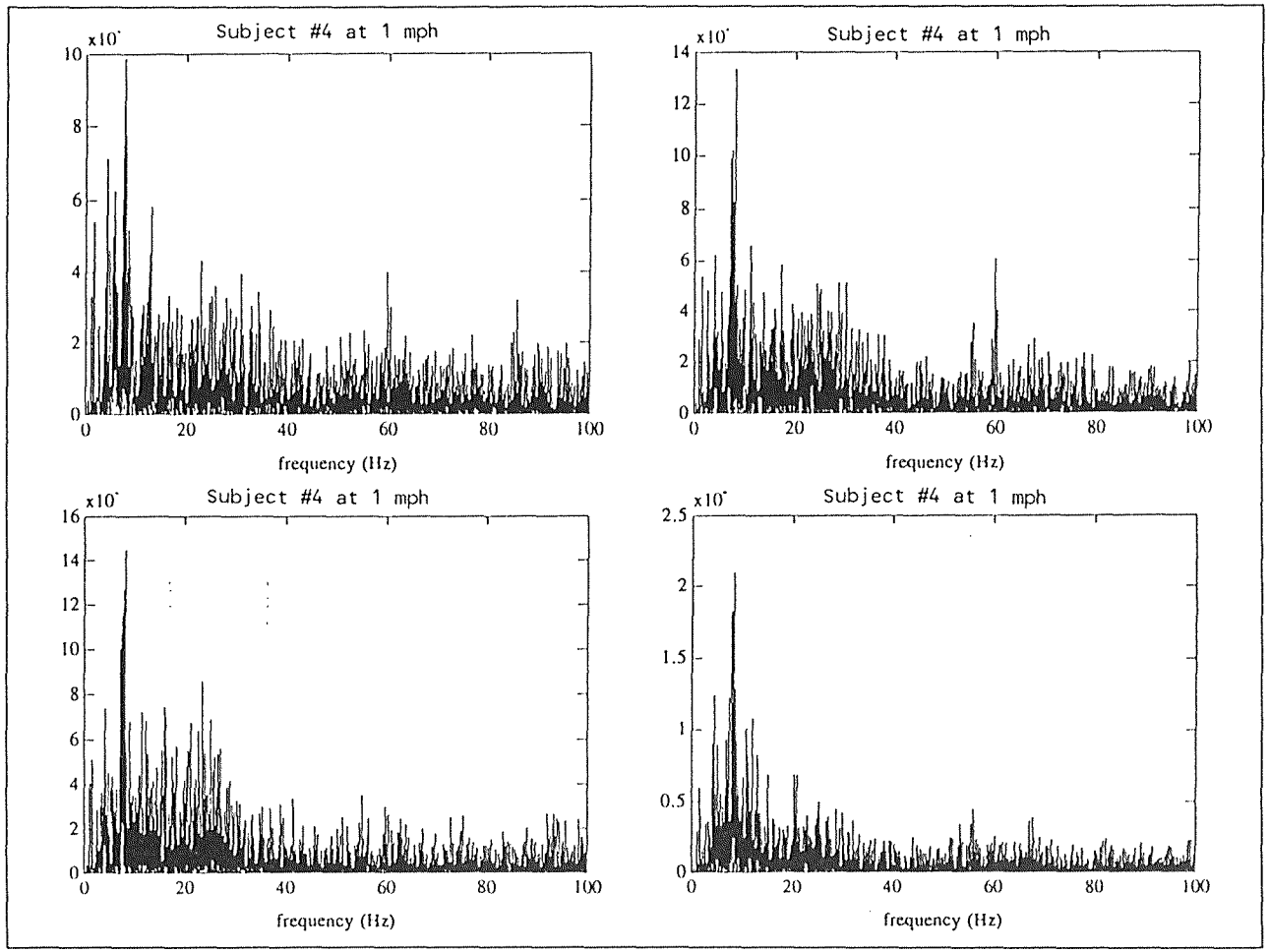

Figure 34 Power Spectra of 25 Second Time Windows for Intervals 5 to 8

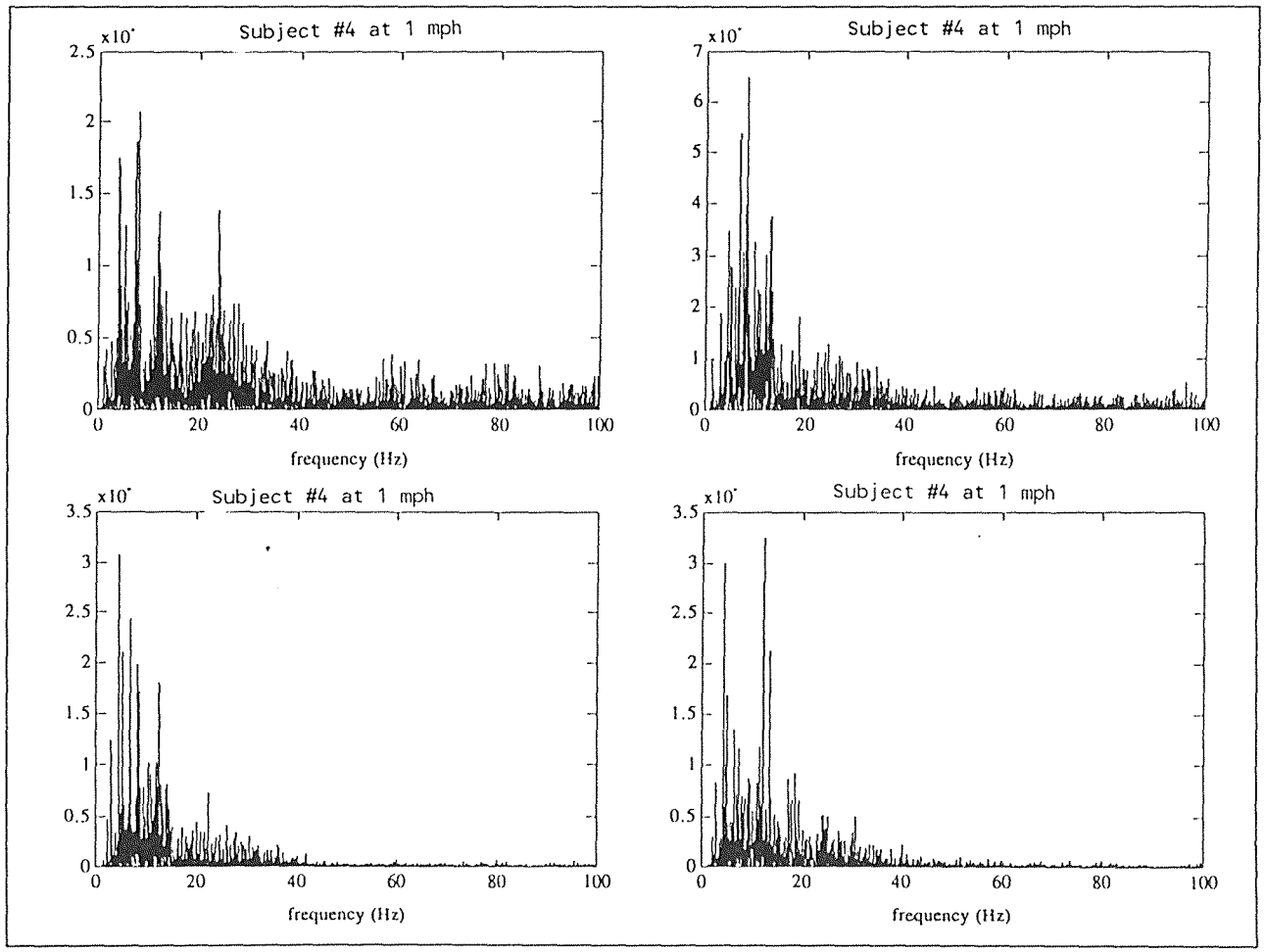

Figure 35 Power Spectra of 25 Second Time Windows for Intervals 9 to 12

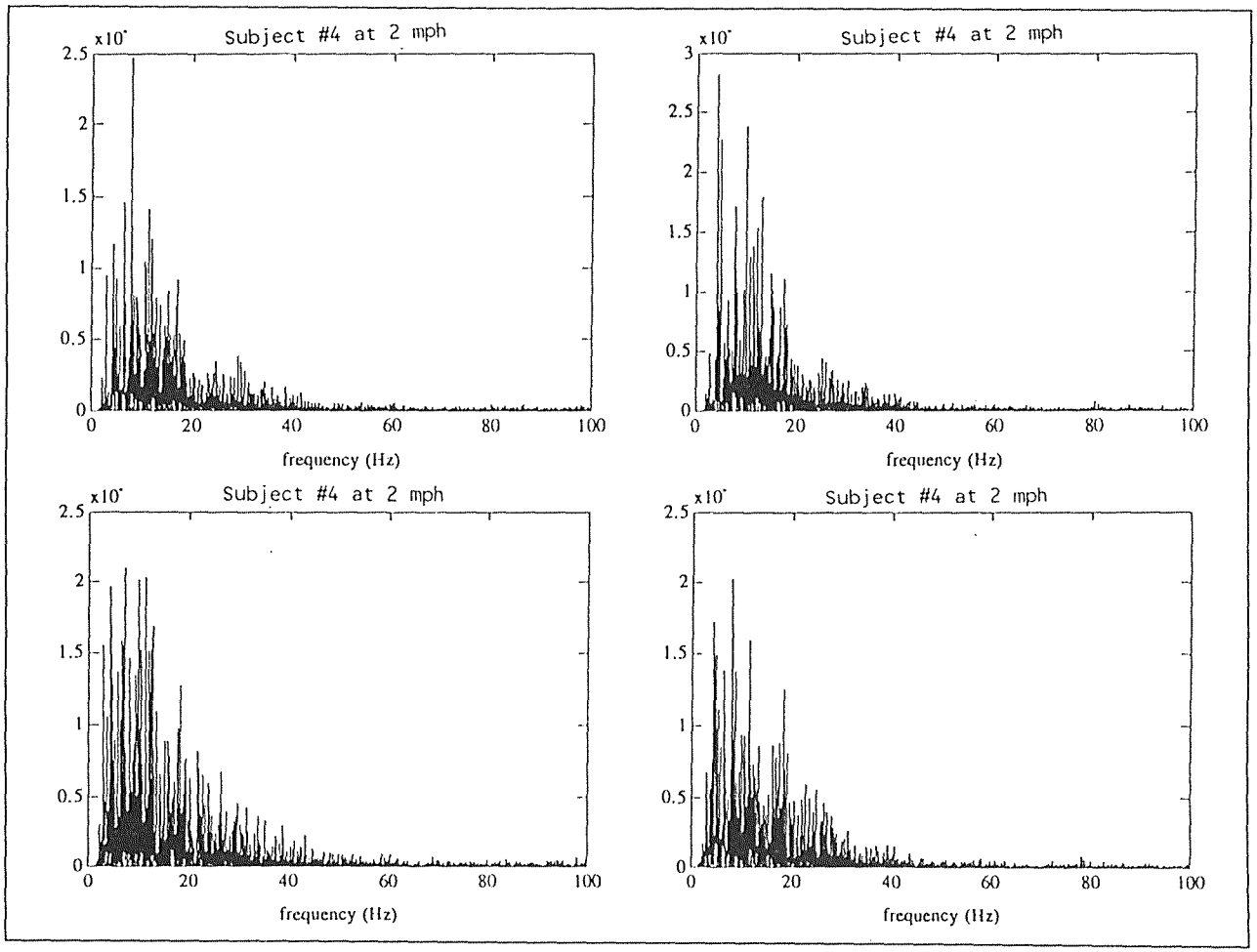

Figure 36 Power Spectra of 25 Second Time Windows for Intervals 1 to 4

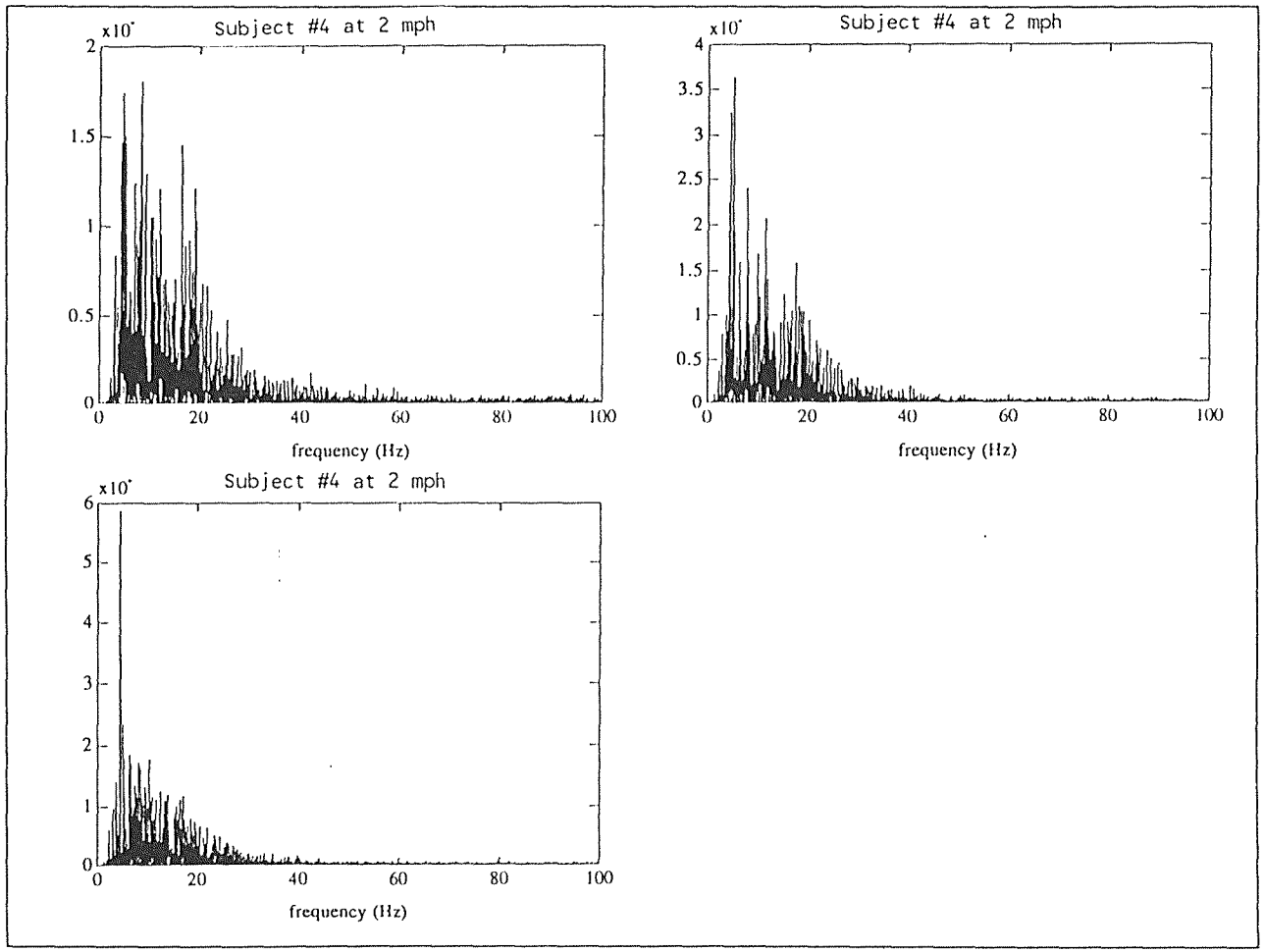

Figure 37 Power Spectra of 25 Second Time Windows for Intervals 5 to 7

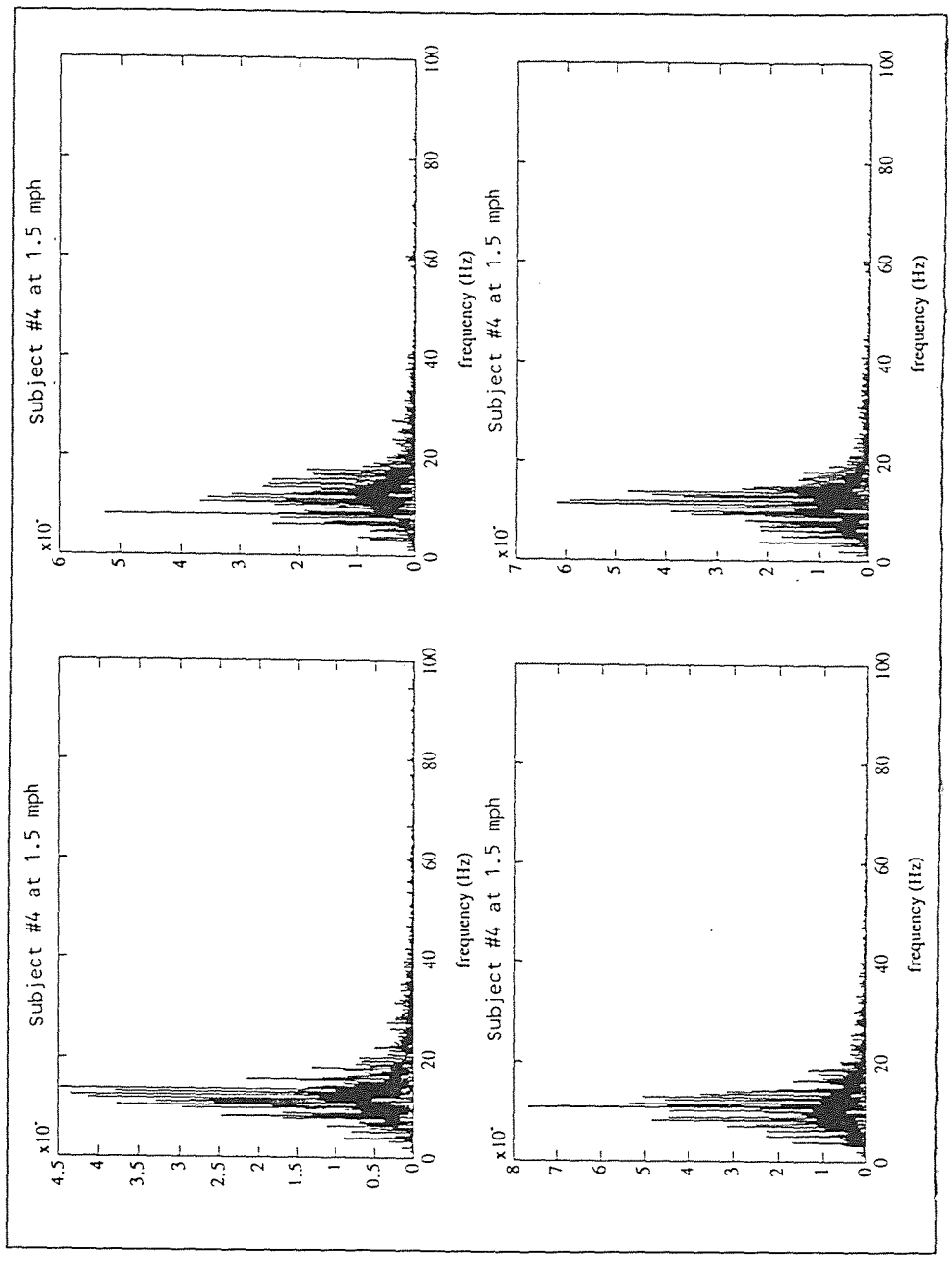

Figure 38 Power Spectra of 25 Second Time Windows for Intervals 1 to 4

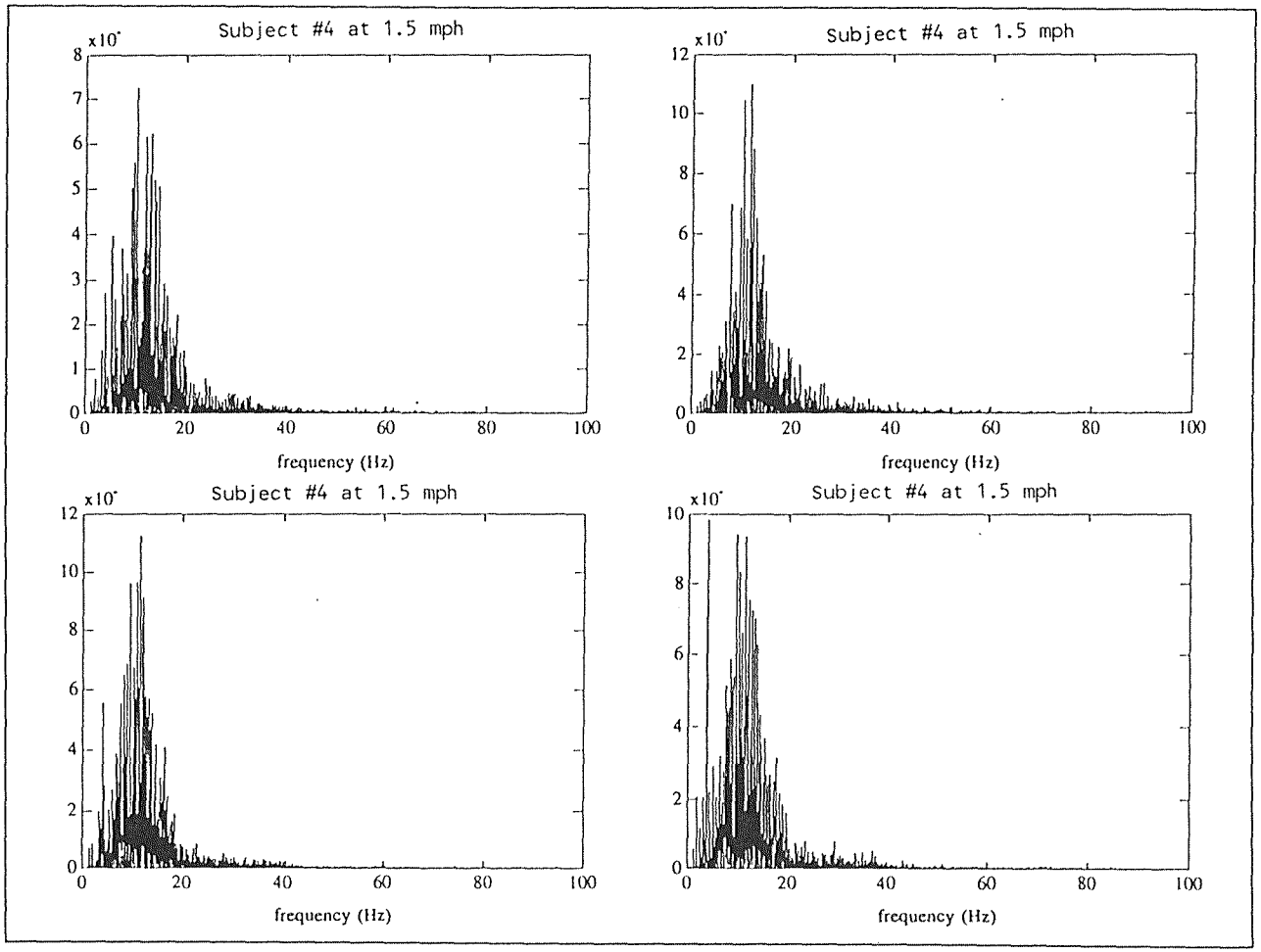

Figure 39 Power Spectra of 25 Second Time Windows for Intervals 5 to 8

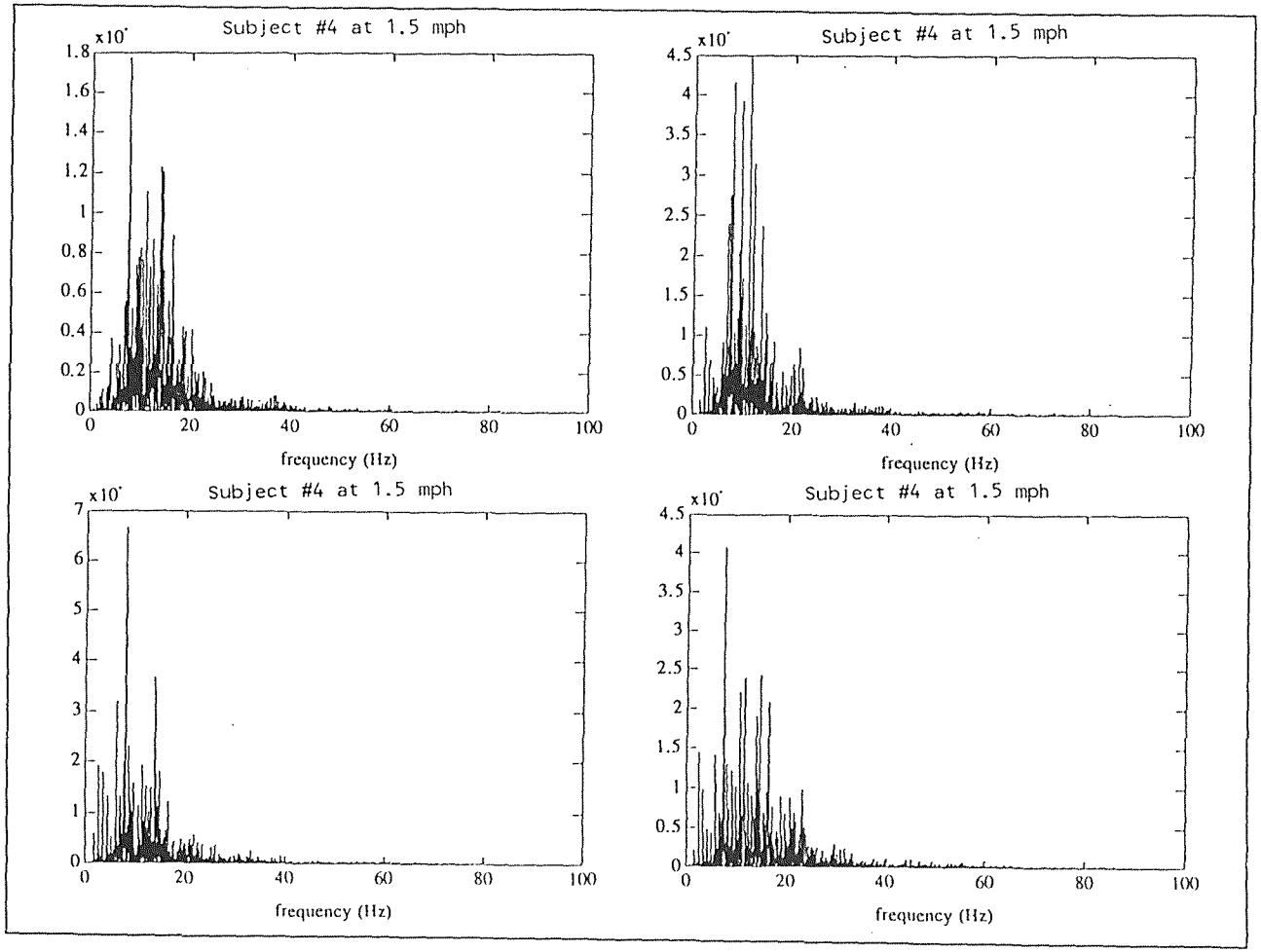

Figure 40 Power Spectra of 25 Second Time Windows for Intervals 9 to 12

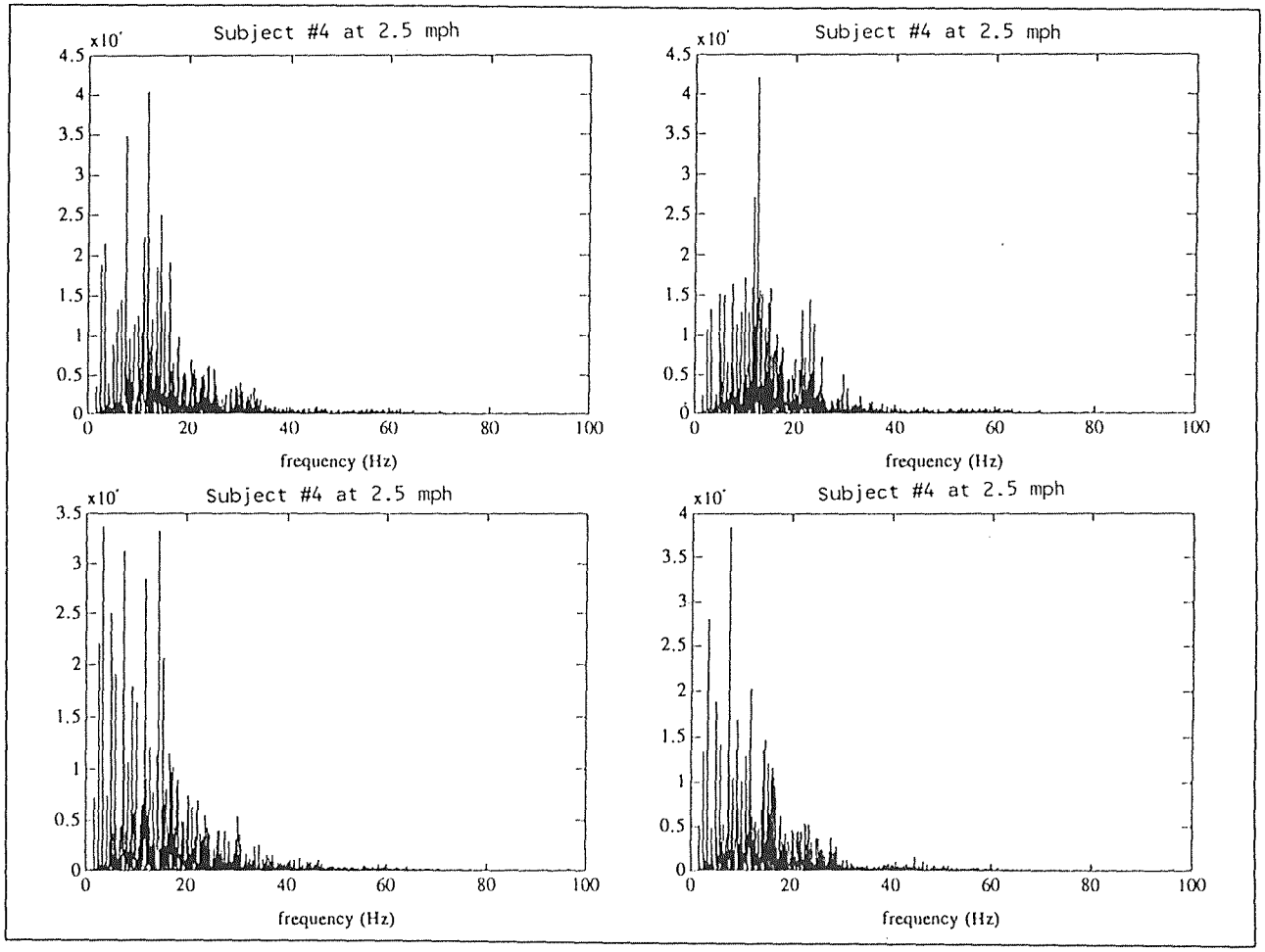

Figure 41 Power Spectra of 25 Second Time Windows for Intervals 1 to 4

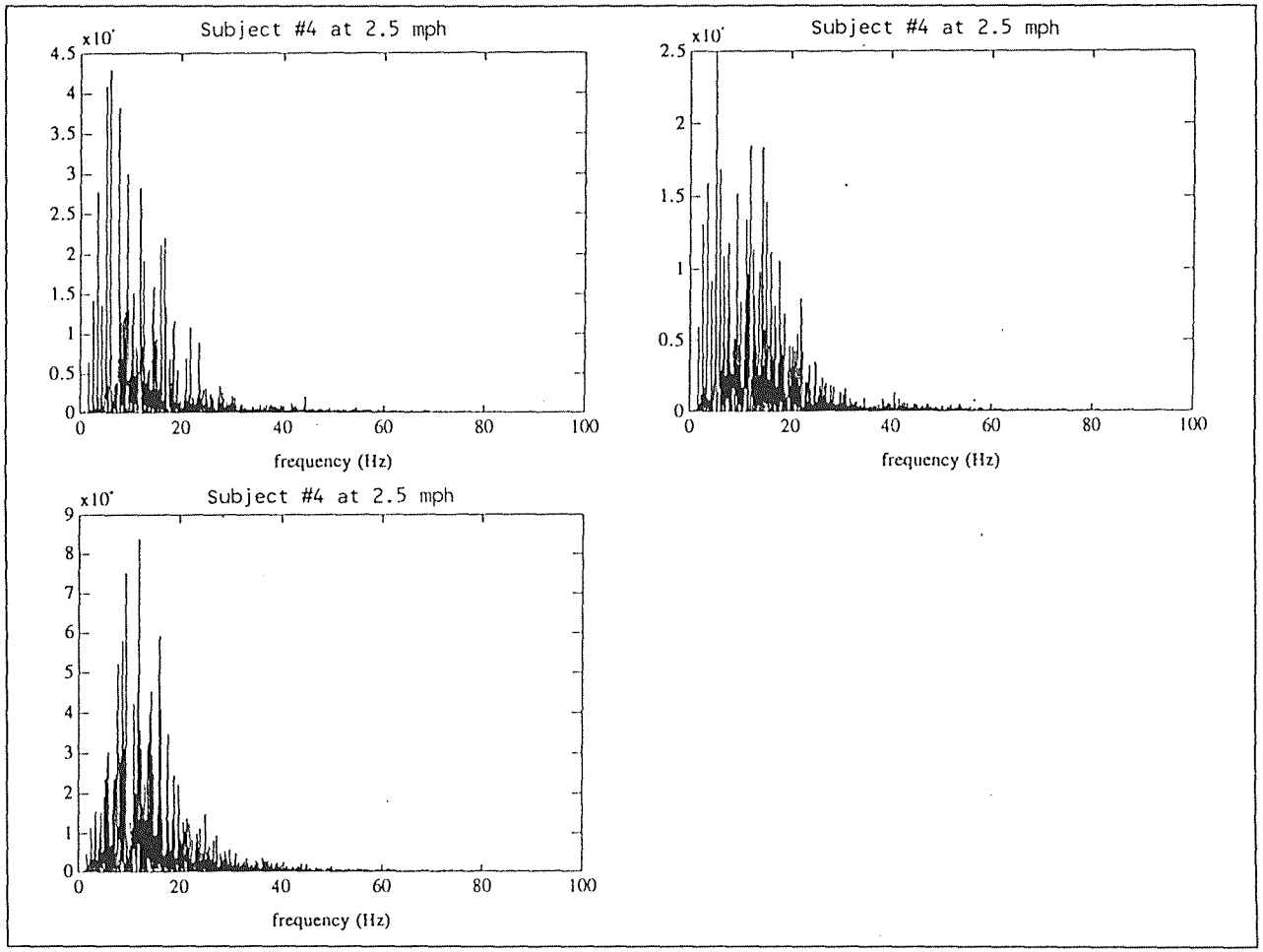

Figure 42 Power Spectra of 25 Second Time Windows for Intervals 5 to 7

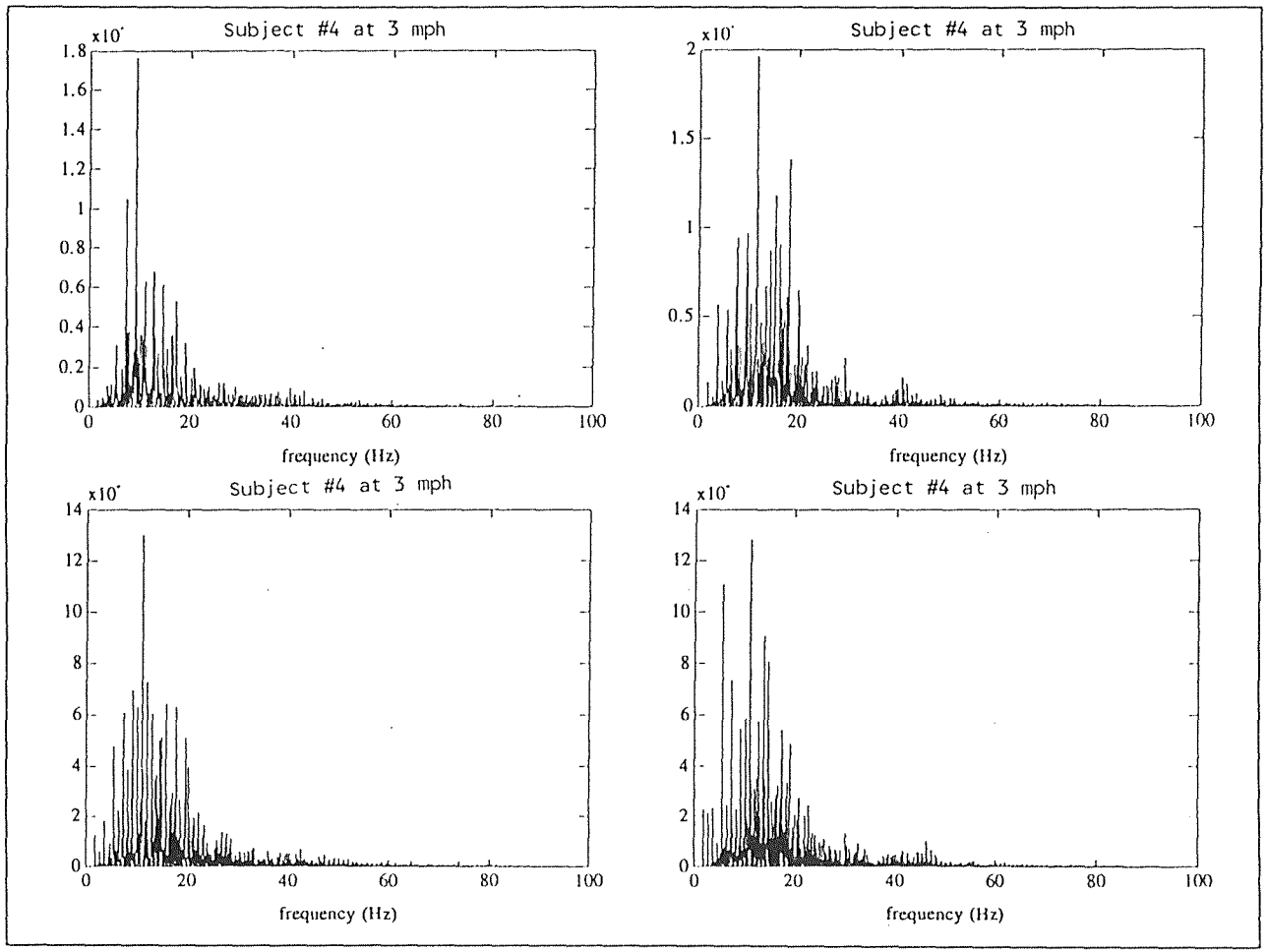

Figure 43 Power Spectra of 25 Second Time Windows for Intervals 1 to 4

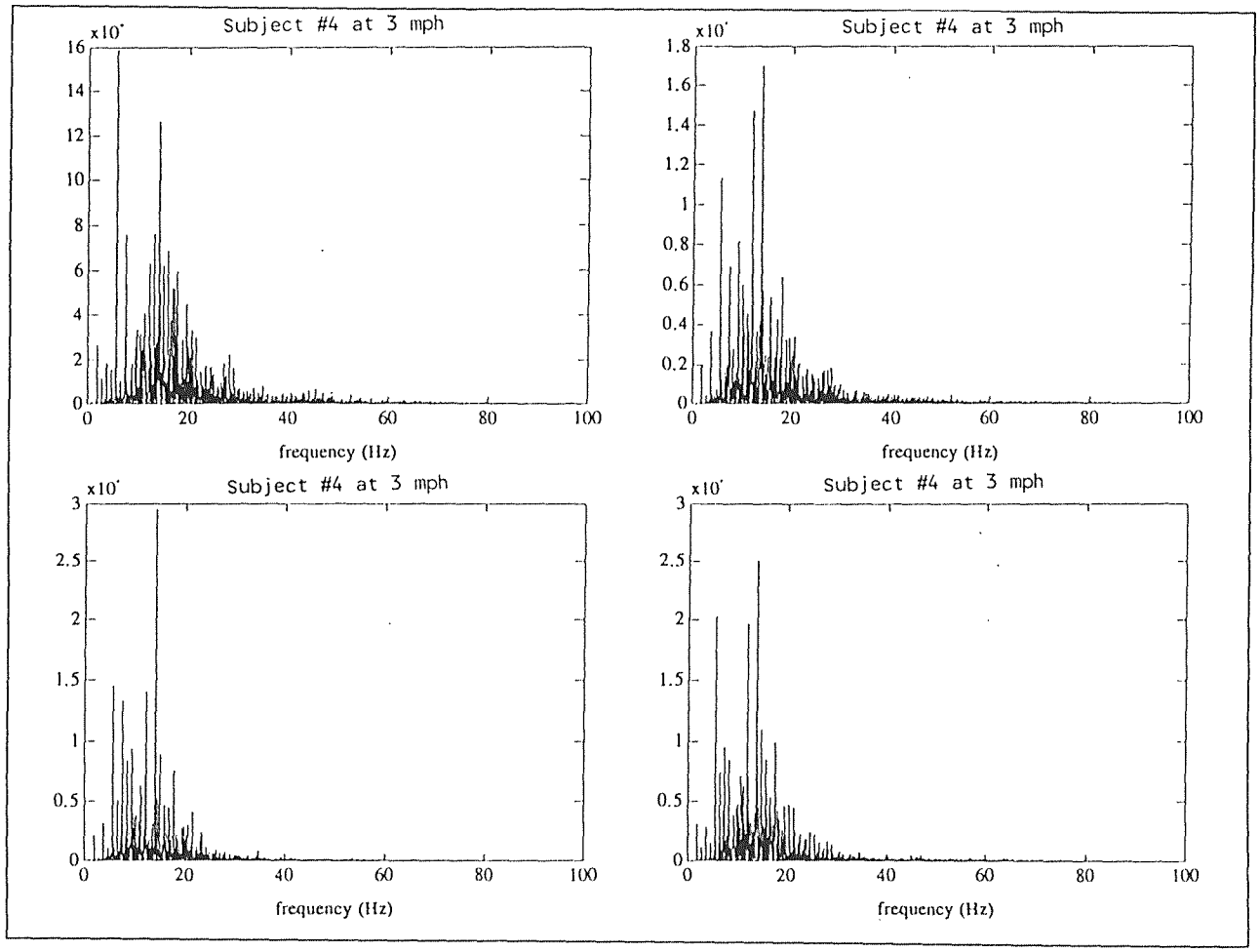

Figure 44 Power Spectra of 25 Second Time Windows for Intervals 5 to 8

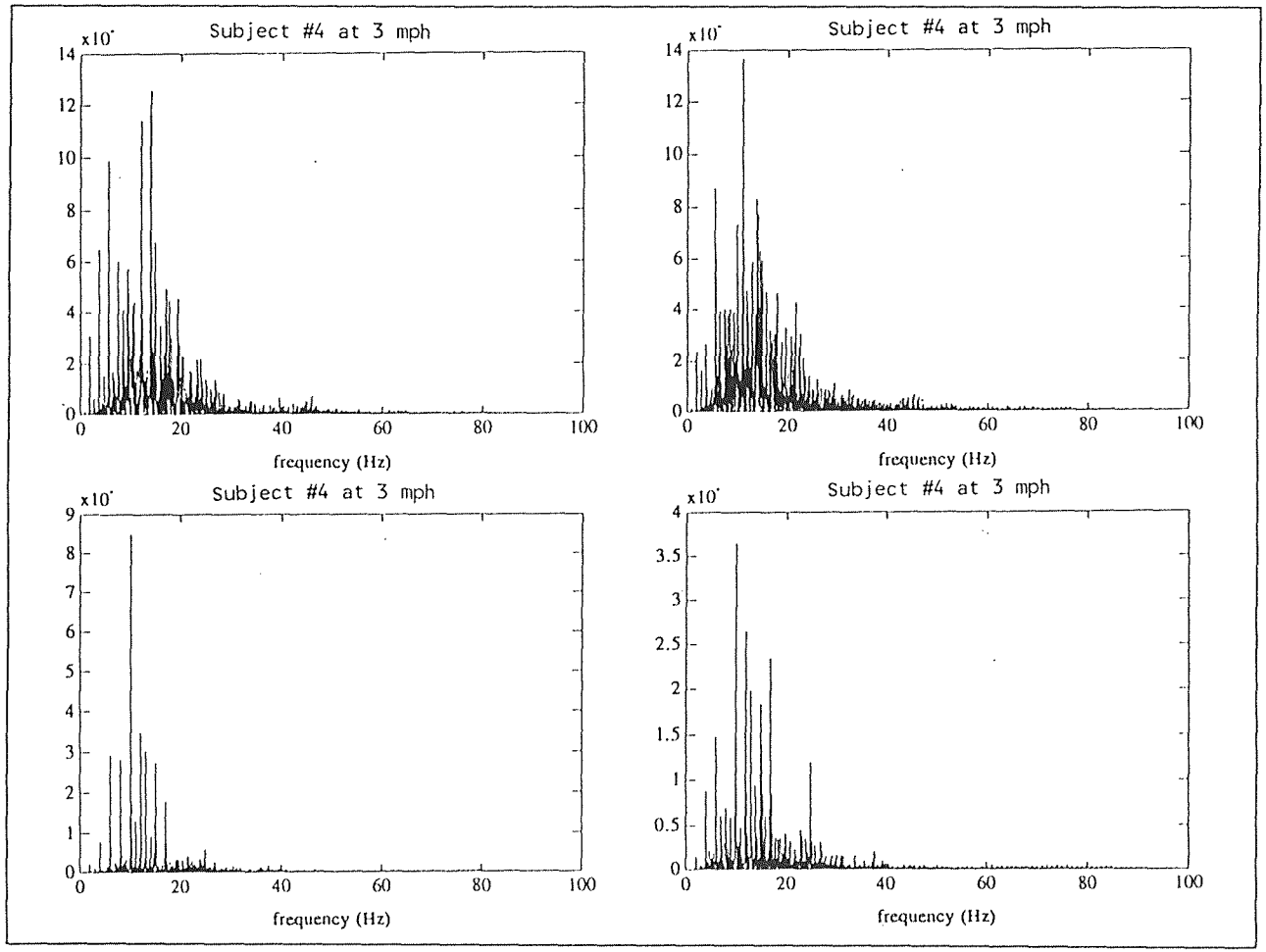

Figure 45 Power Spectra of 25 Second Time Windows for Intervals 9 to 12

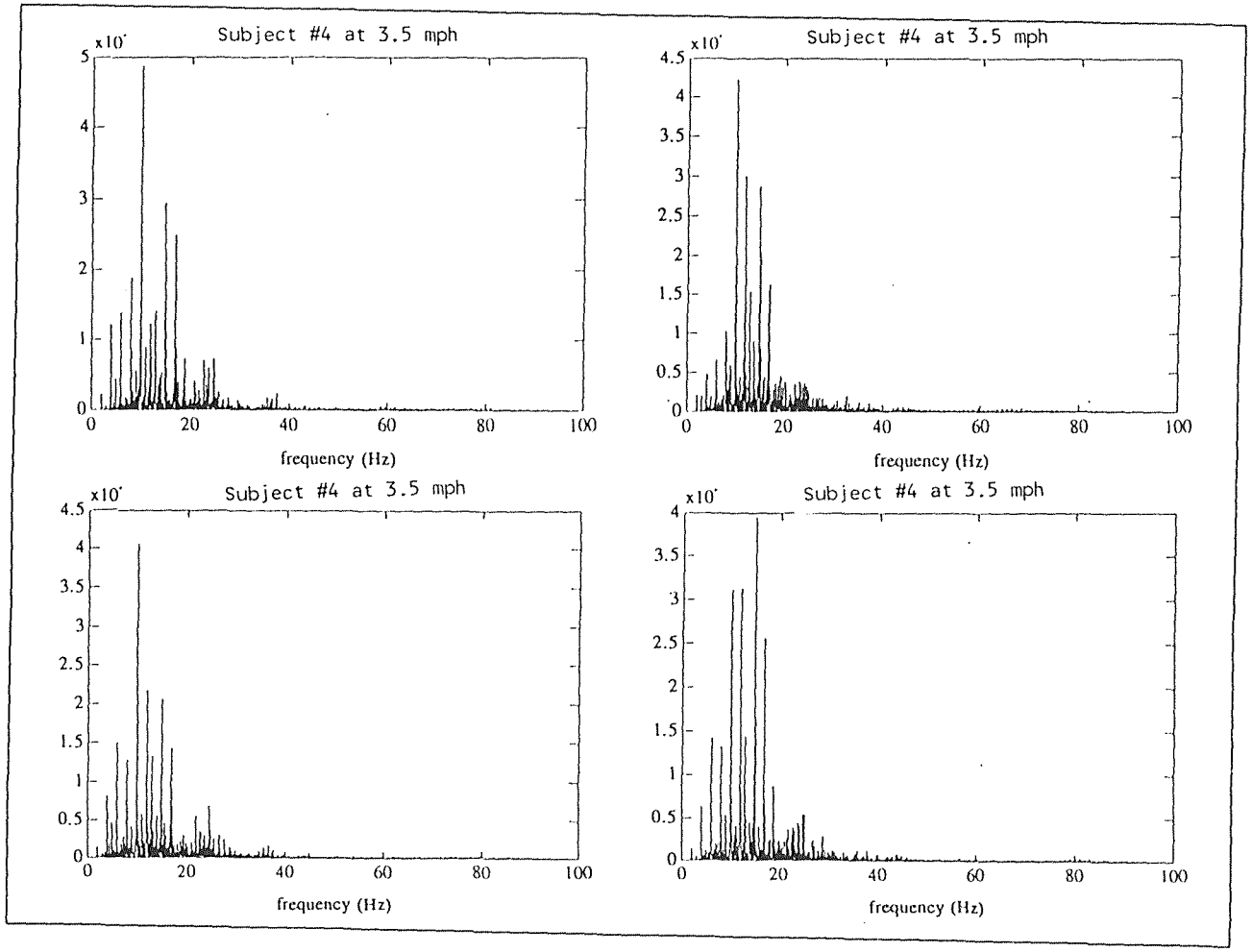

Figure 46 Power Spectra of 25 Second Time Windows for Intervals 1 to 4

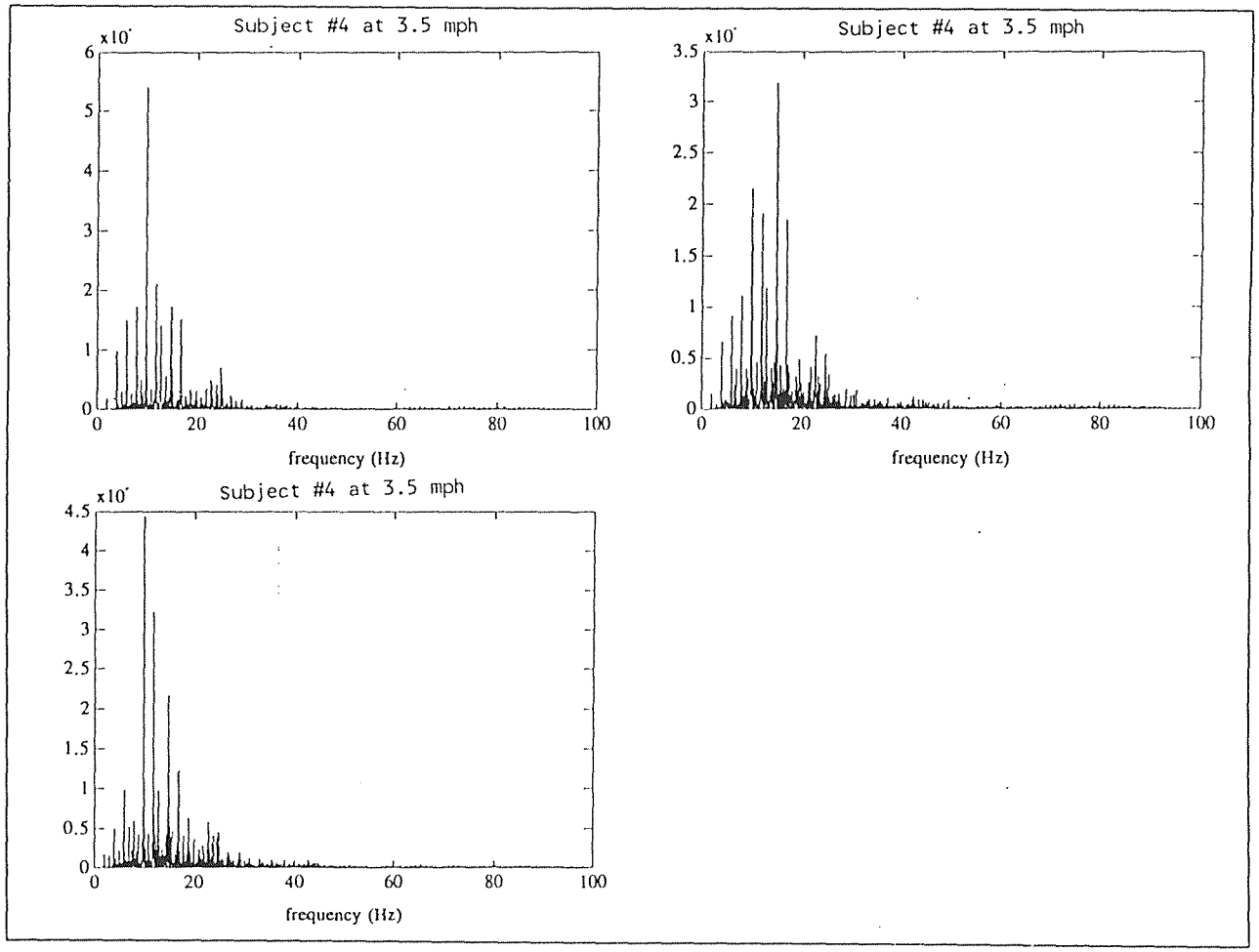

Figure 47 Power Spectra of 25 Second Time Windows for Intervals 5 to 7

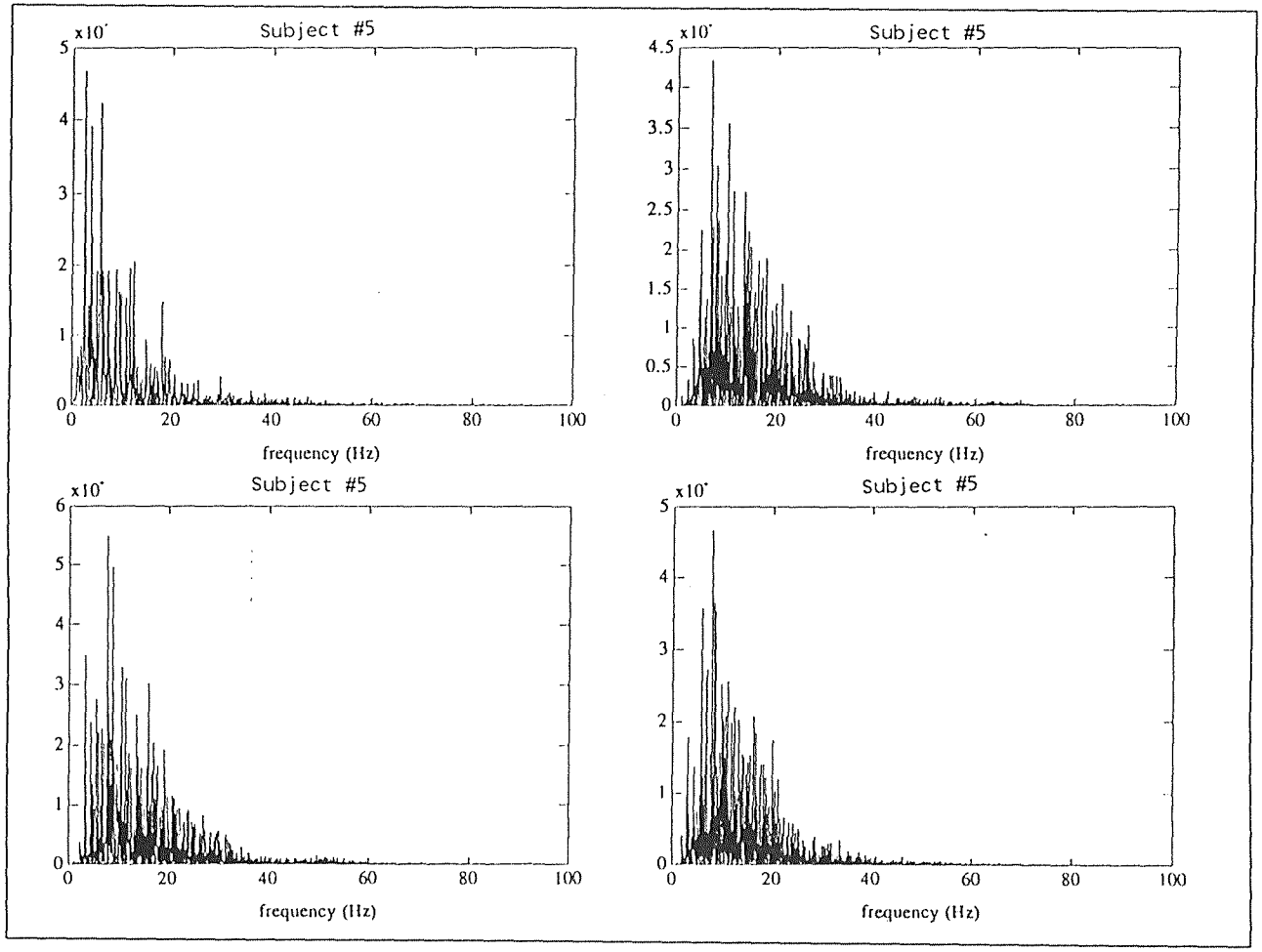

Figure 48 Power Spectra of 25 Second Time Windows for Intervals 1 to 4

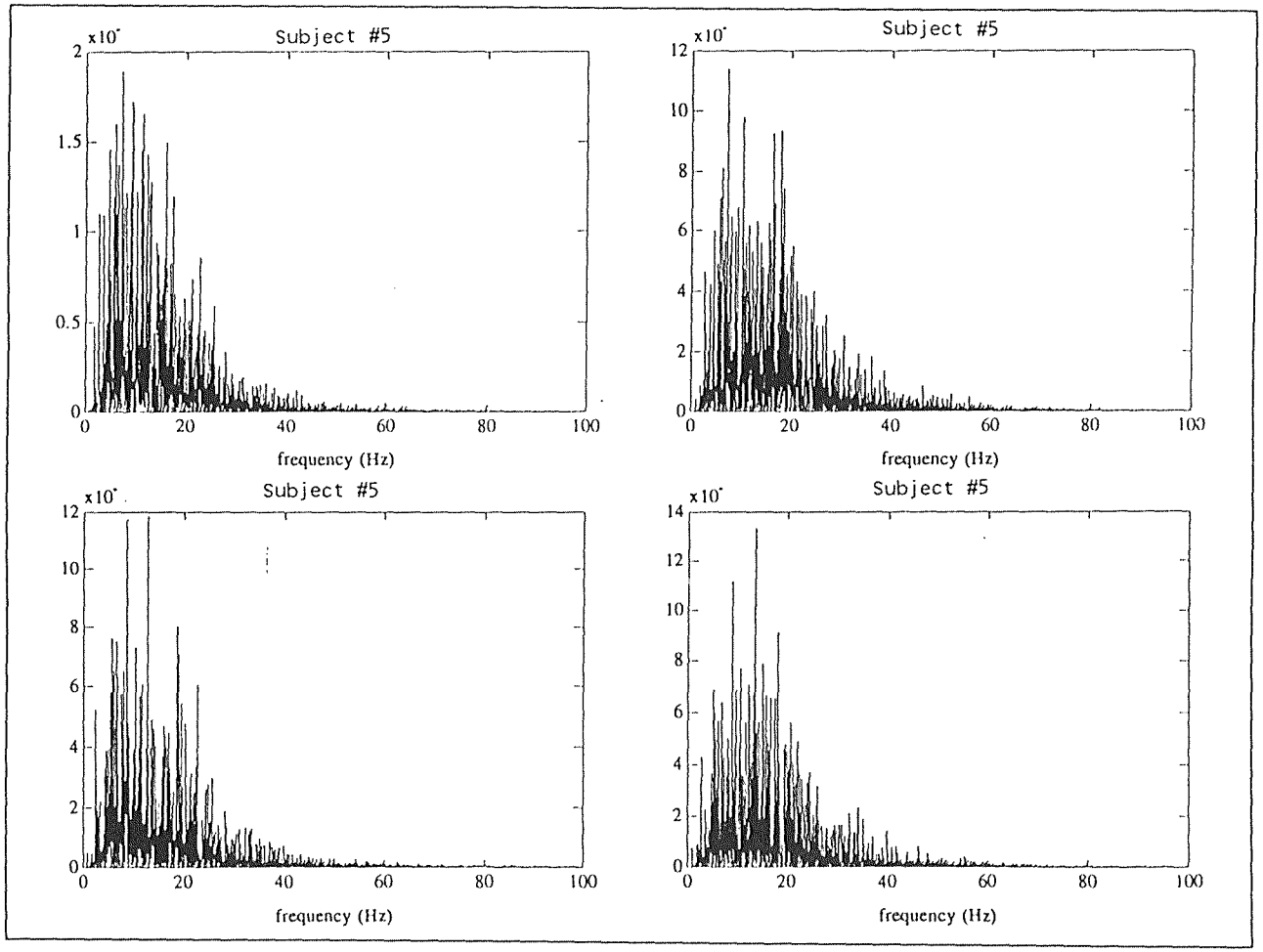

Figure 49 Power Spectra of 25 Second Time Windows for Intervals 5 to 8

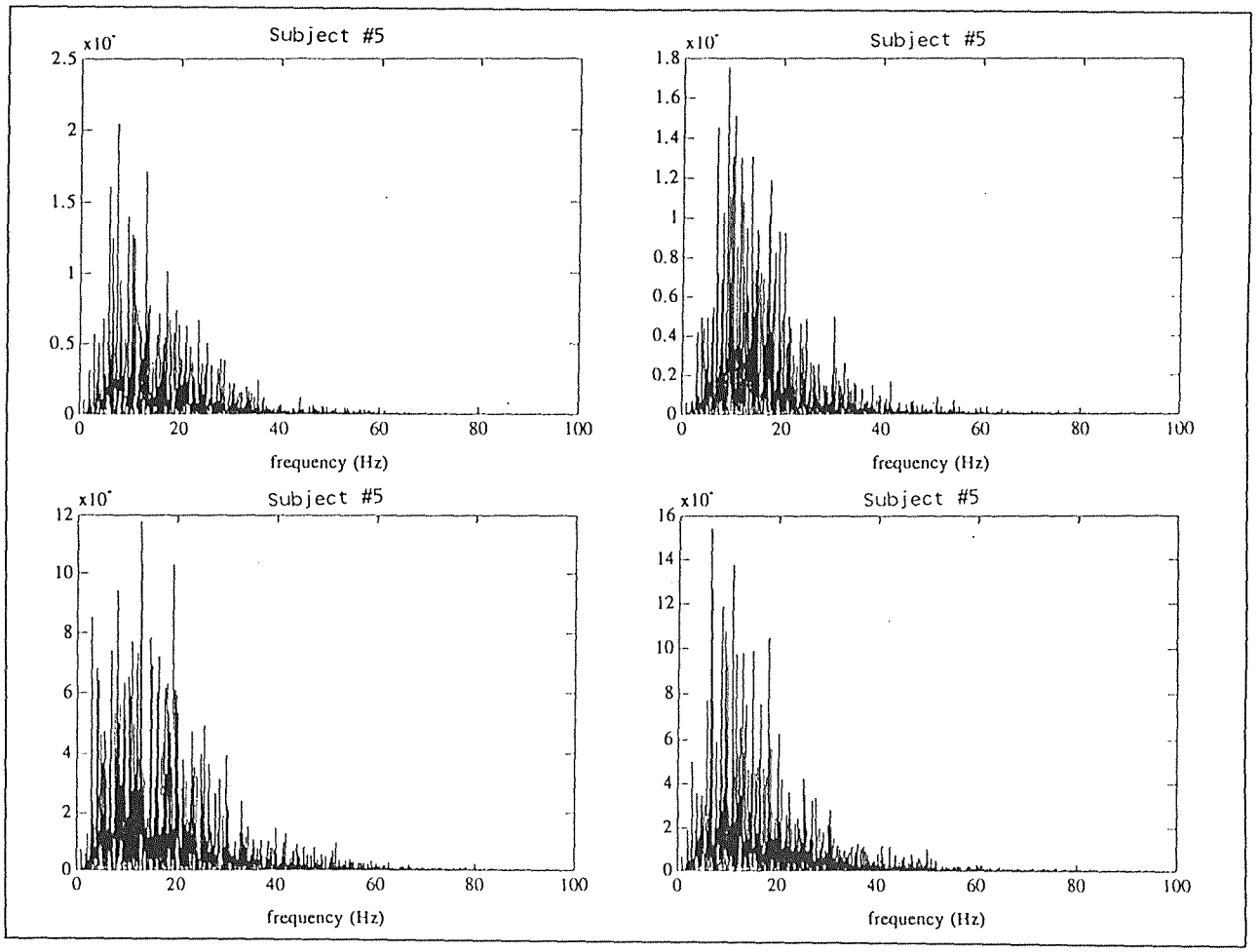

Figure 50 Power Spectra of 25 Second Time Windows for Intervals 9 to 12

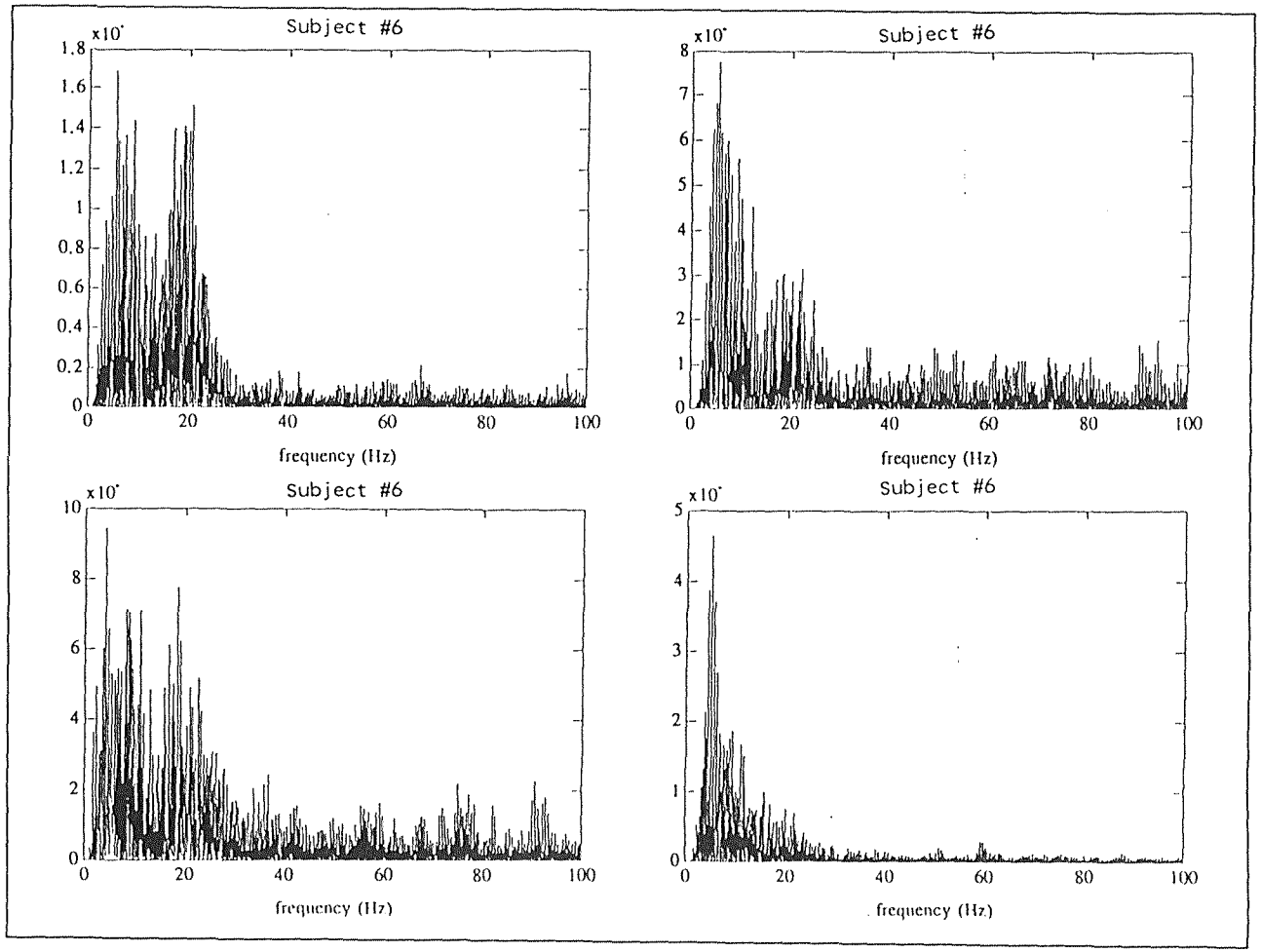

Figure 51 Power Spectra of 25 Second Time Windows for Intervals 1 to 4

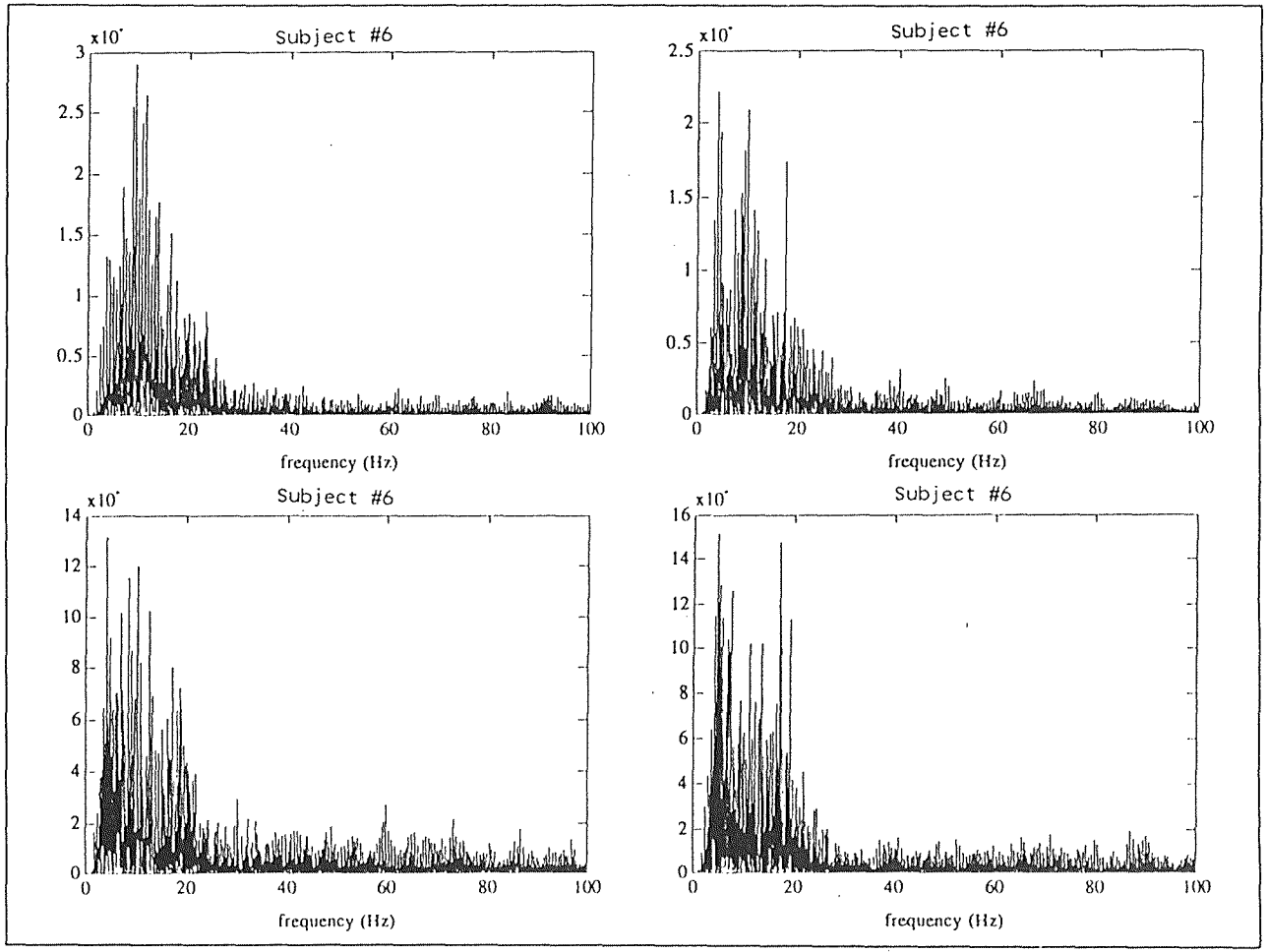

Figure 52 Power Spectra of 25 Second Time Windows for Intervals 5 to 8

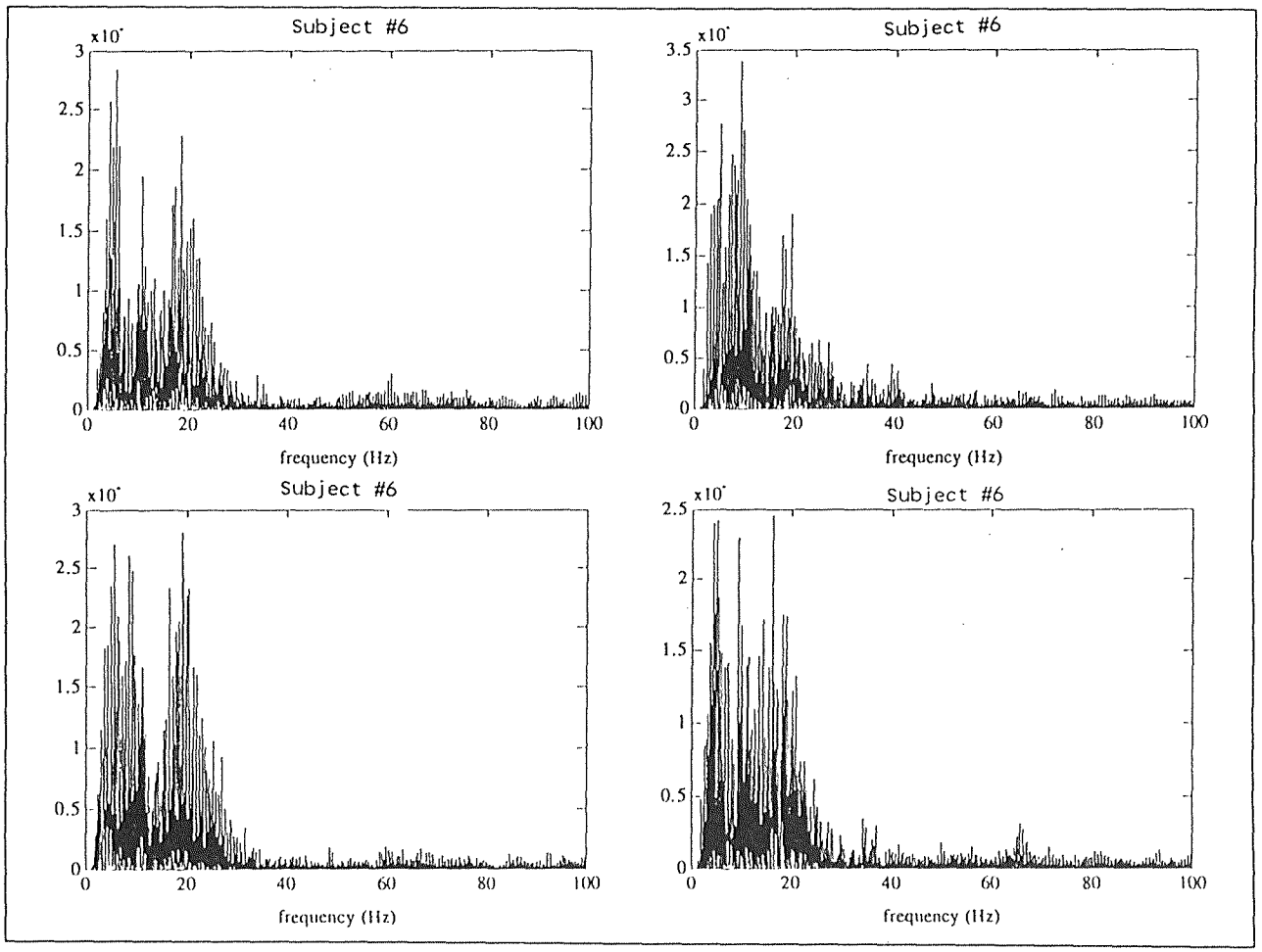

Figure 53 Power Spectra of 25 Second Time Windows for Intervals 9 to 12

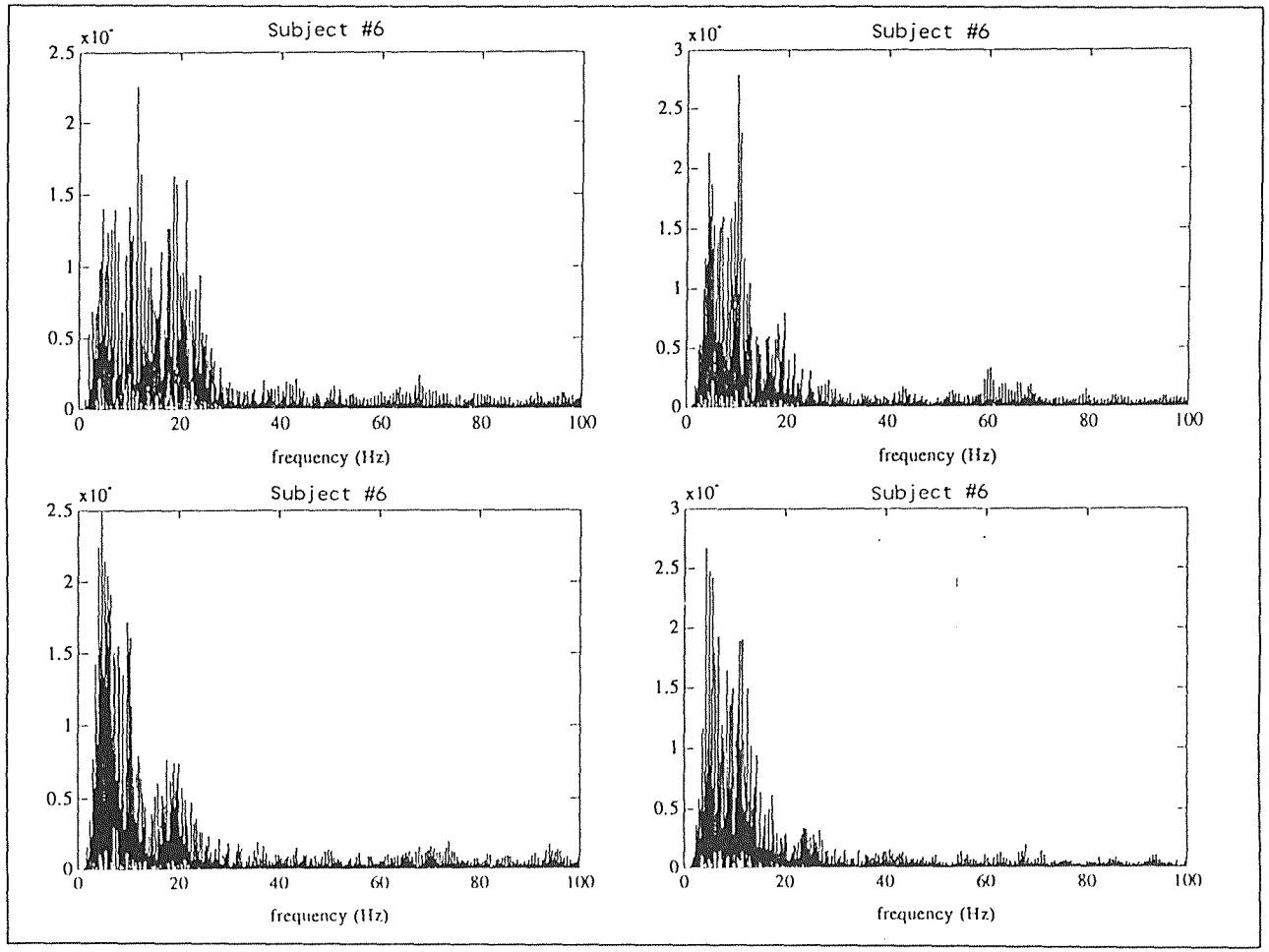

Figure 54 Power Spectra of 25 Second Time Windows for Intervals 13 to 16

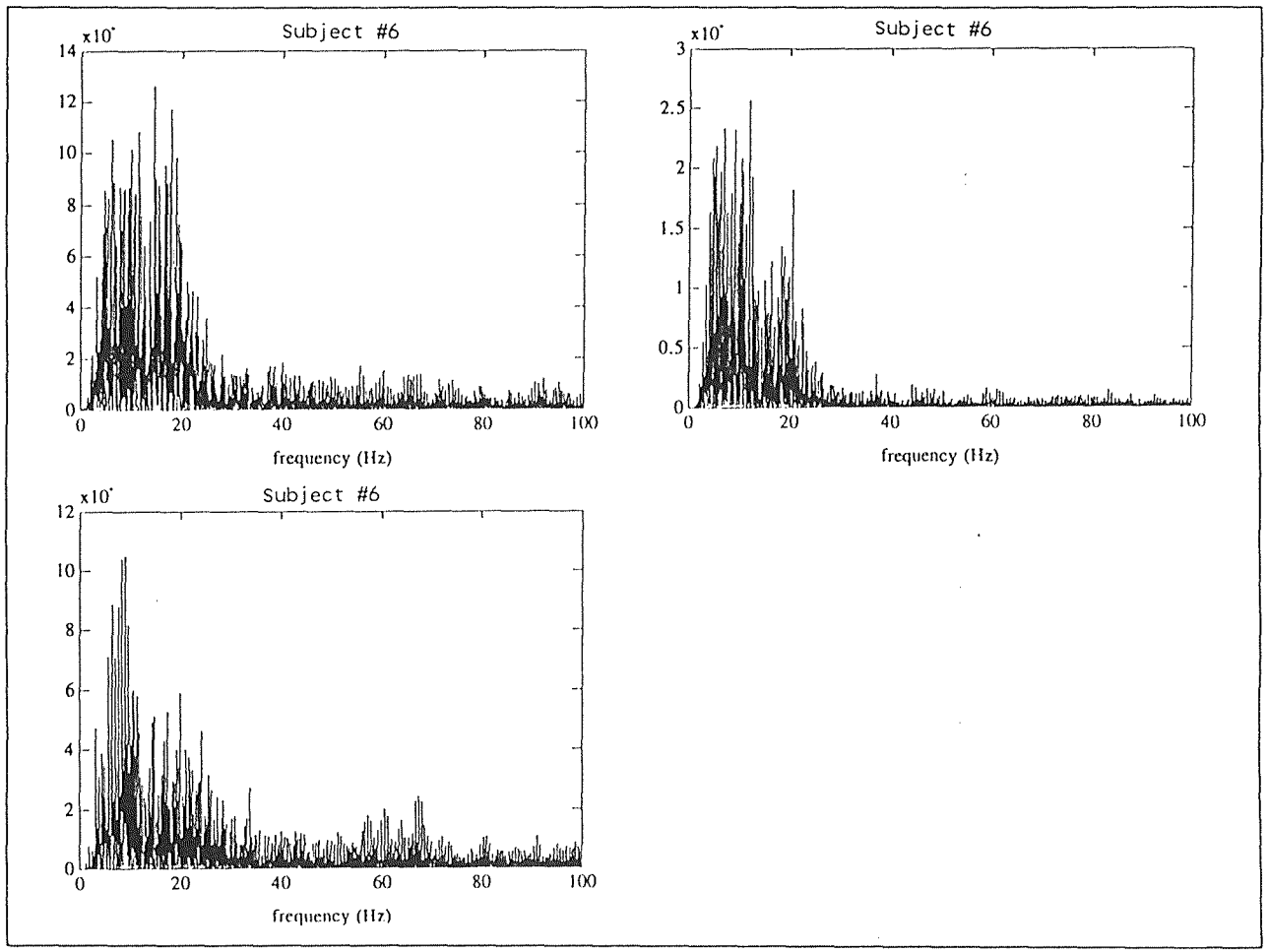

Figure 55 Power Spectra of 25 Second Time Windows for Intervals 17 to 19

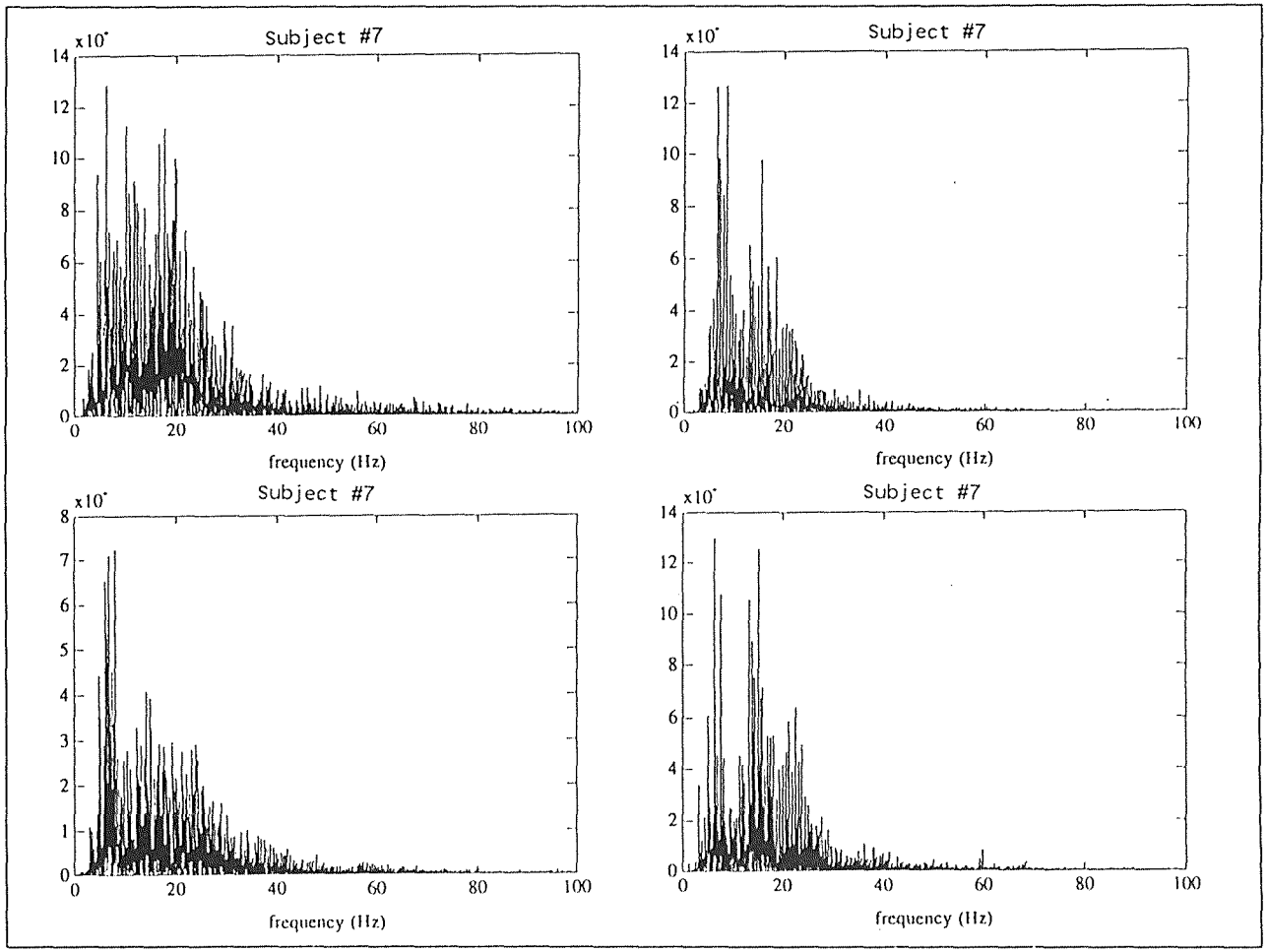

Figure 56 Power Spectra of 25 Second Time Windows for Intervals 1 to 4

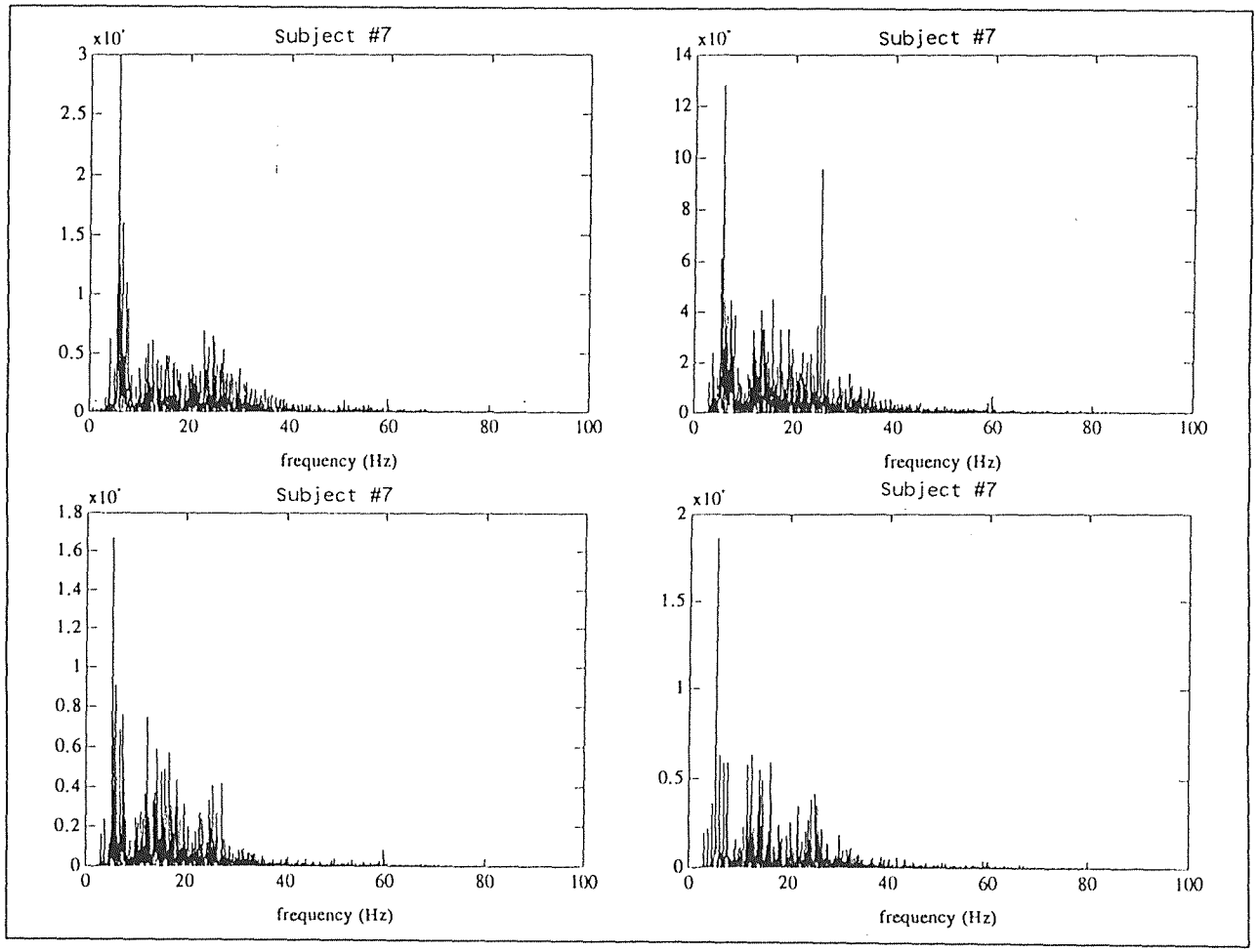

Figure 57 Power Spectra of 25 Second Time Windows for Intervals 5 to 8

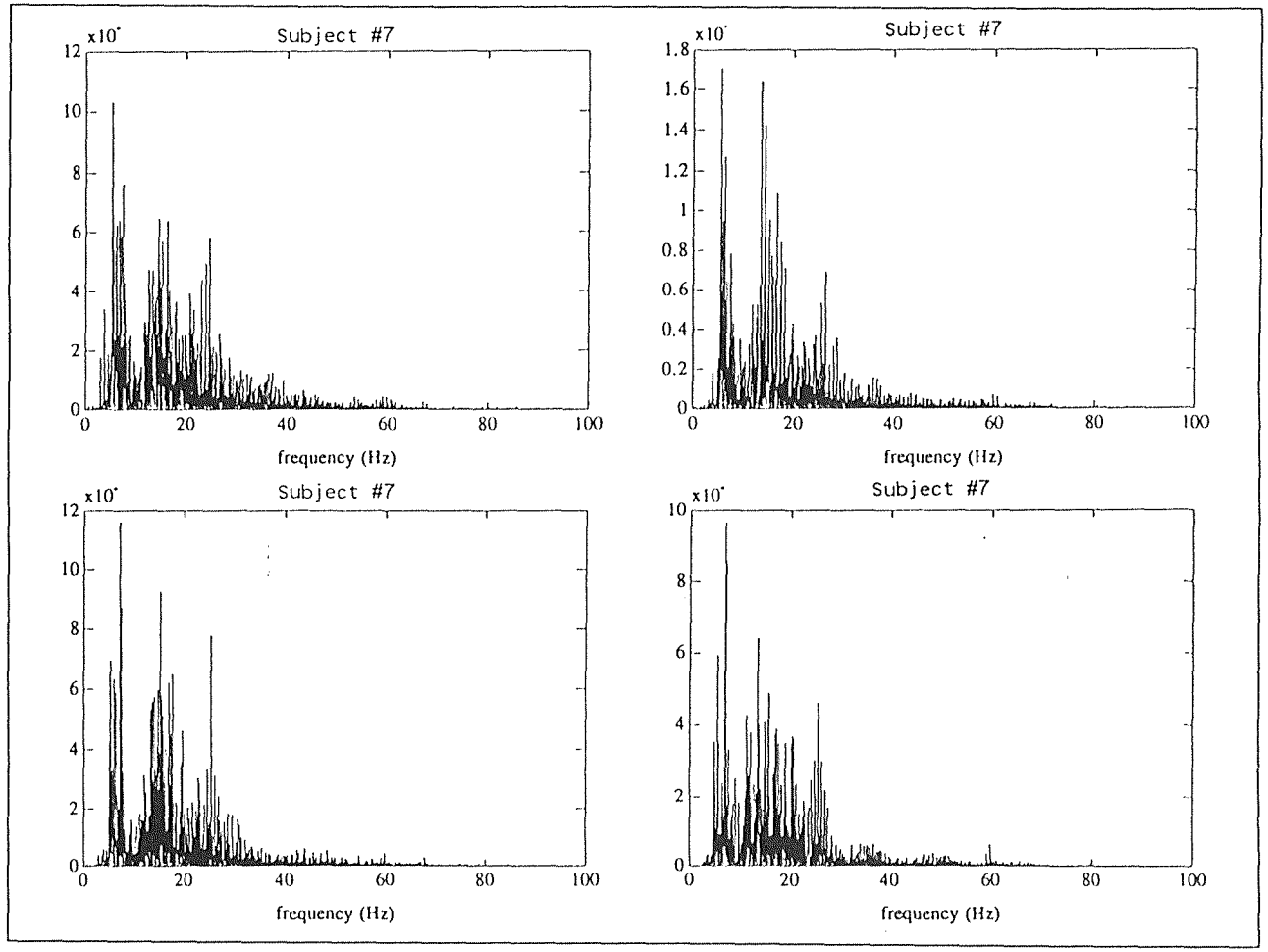

Figure 58 Power Spectra of 25 Second Time Windows for Intervals 9 to 12

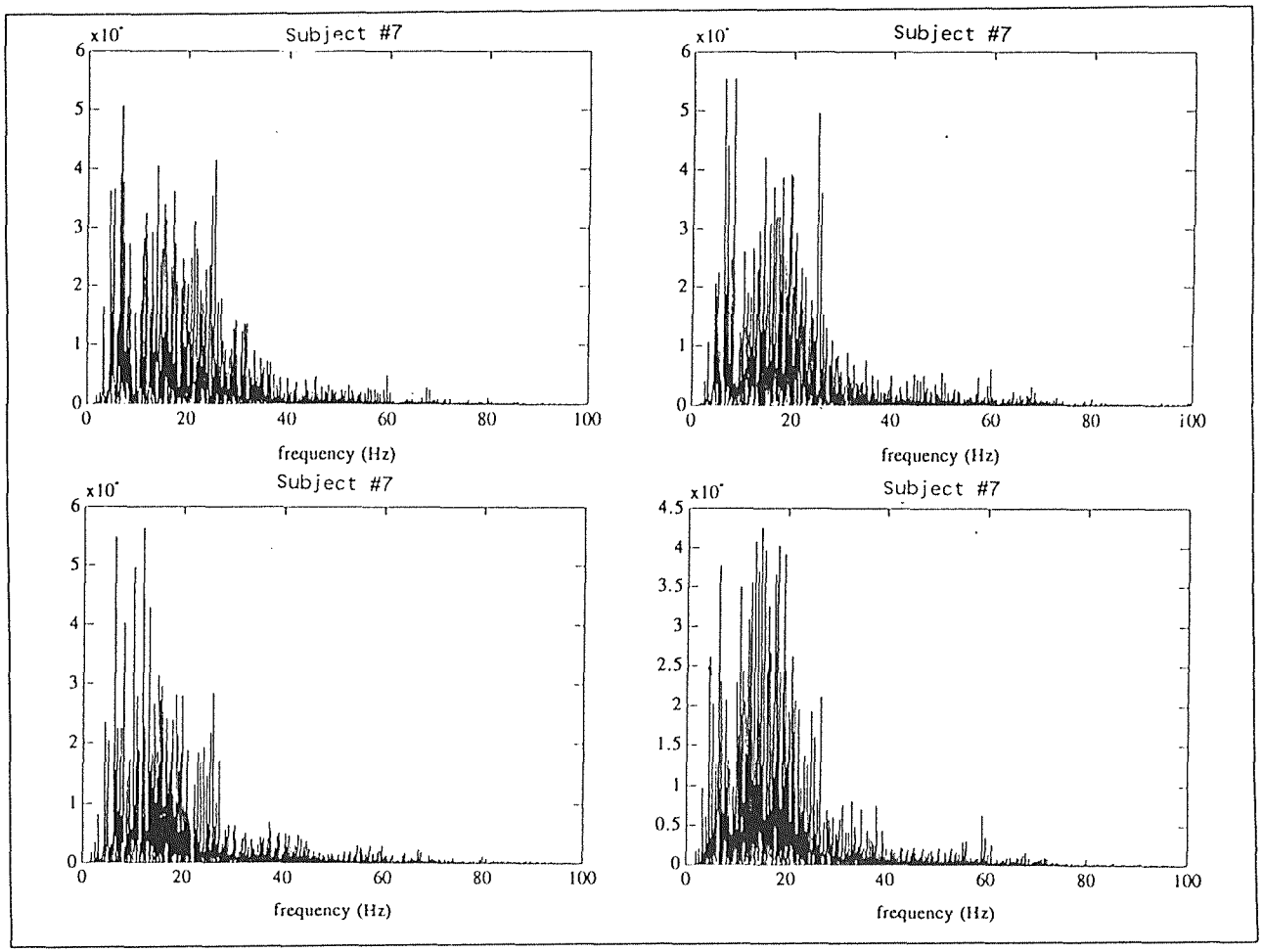

Figure 59 Power Spectra of 25 Second Time Windows for Intervals 13 to 16

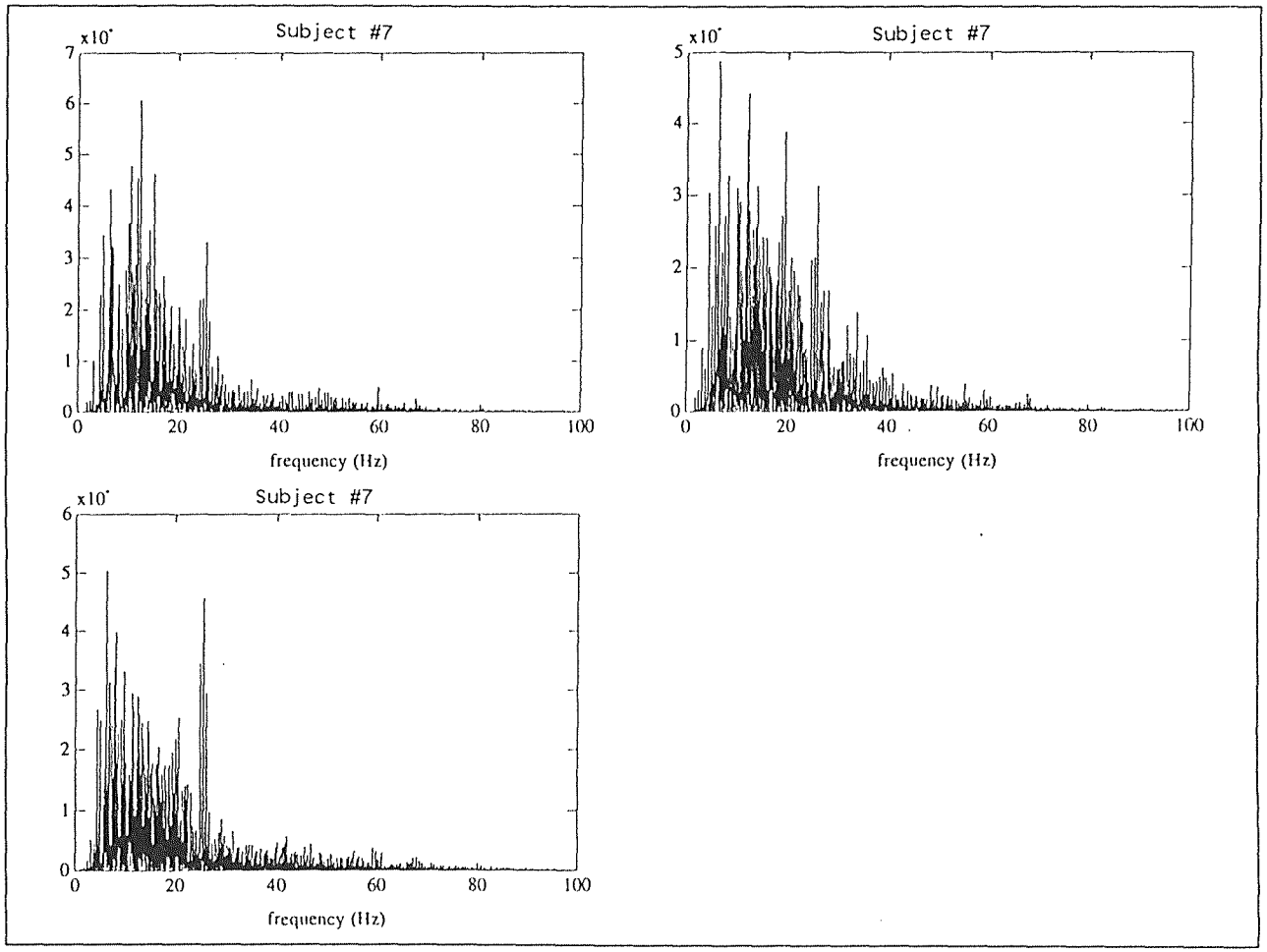

Figure 60 Power Spectra of 25 Second Time Windows for Intervals 17 to 19

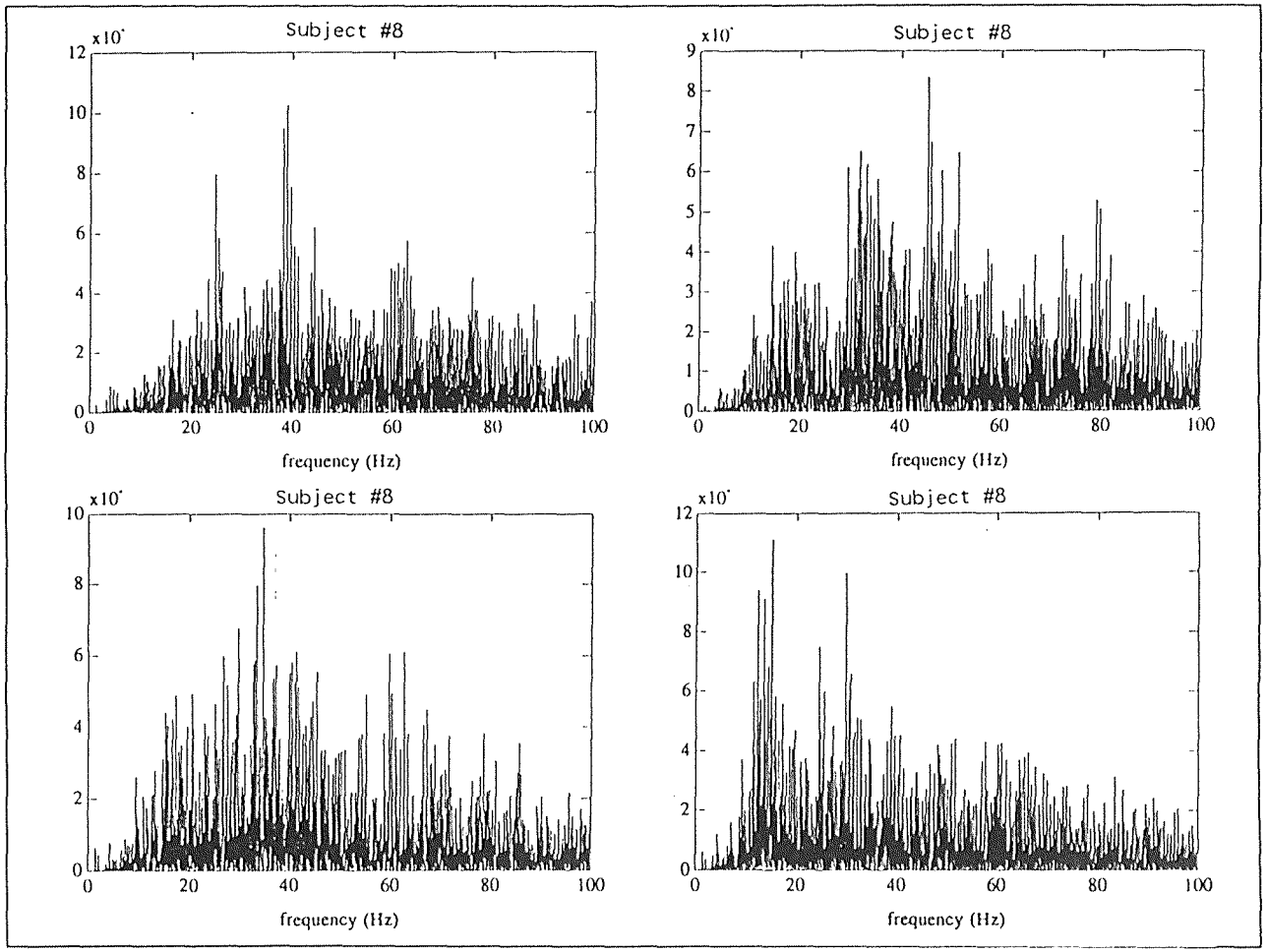

Figure 61 Power Spectra of 25 Second Time Windows for Intervals 1 to 4

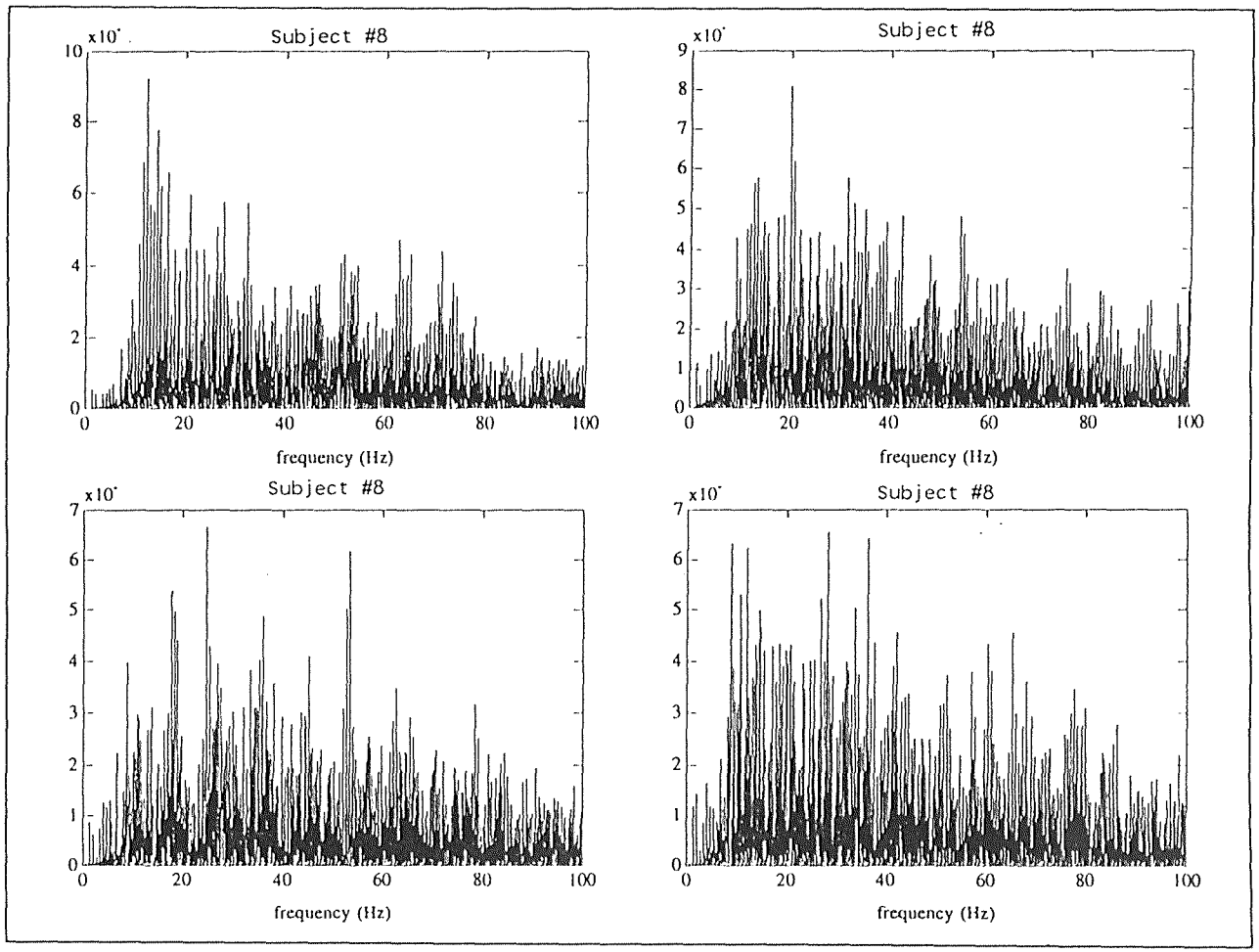

Figure 62 Power Spectra of 25 Second Time Windows for Intervals 5 to 8

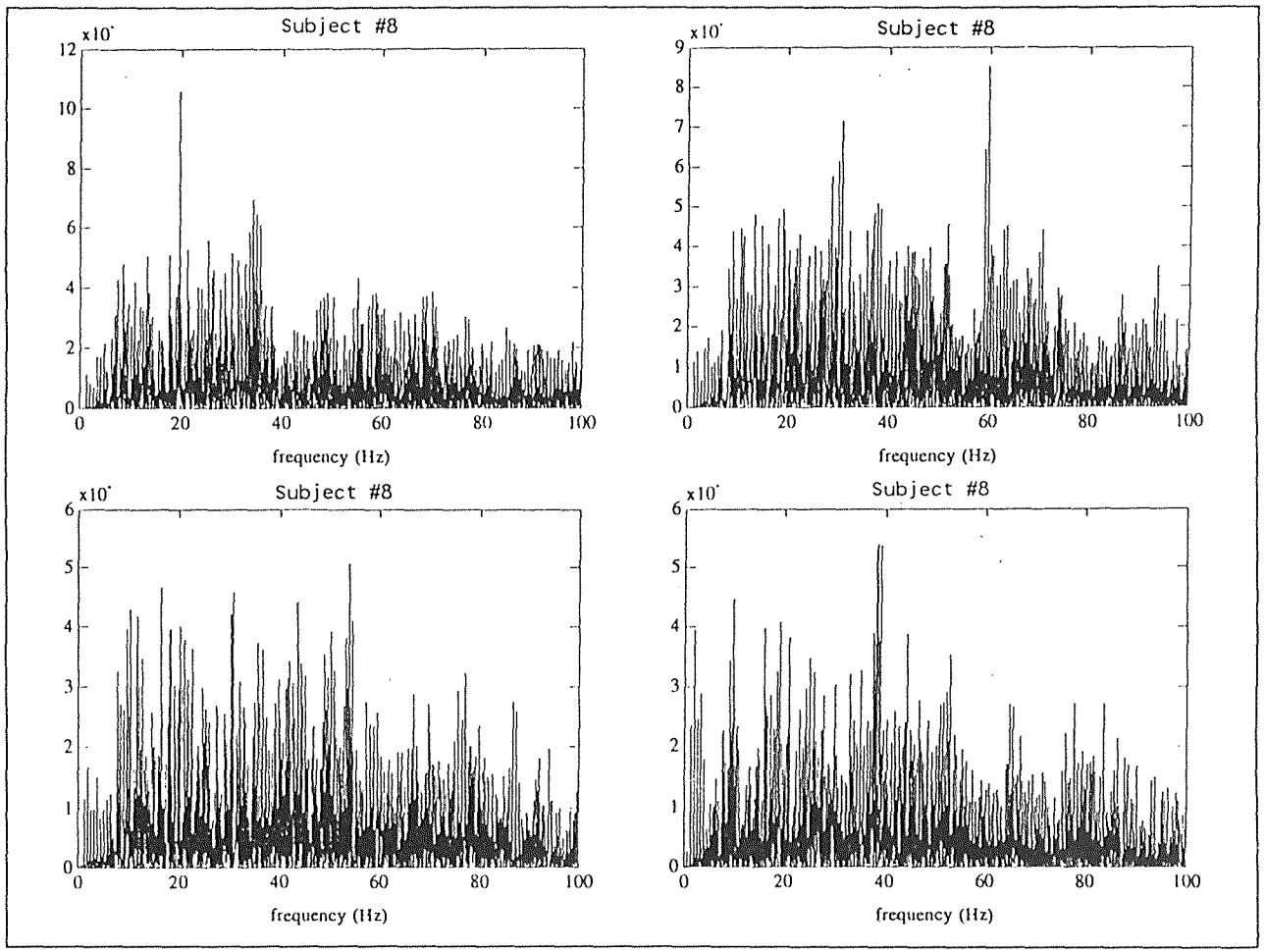

Figure 63 Power Spectra of 25 Second Time Windows for Intervals 9 to 12

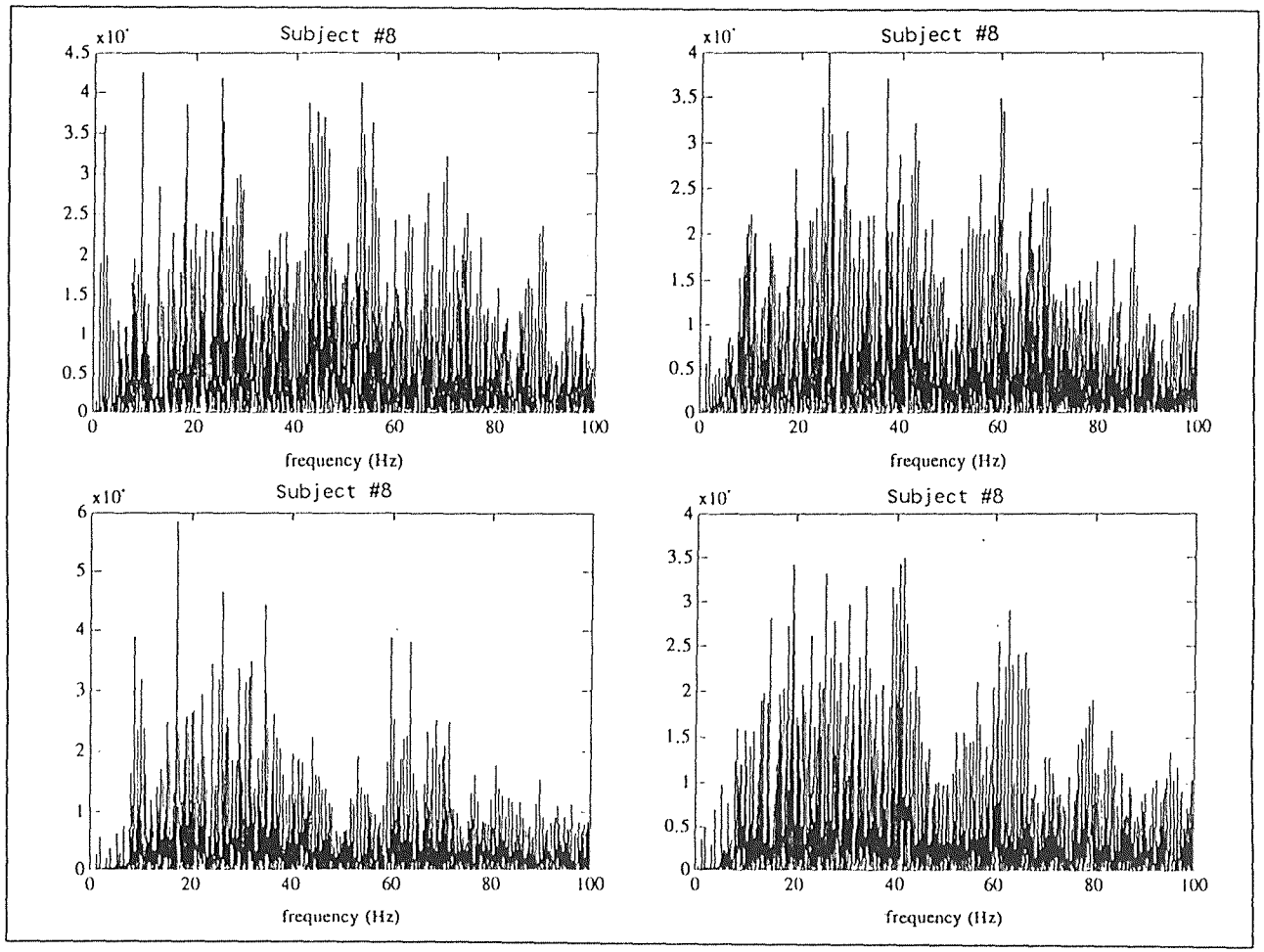

Figure 64 Power Spectra of 25 Second Time Windows for Intervals 13 to 16

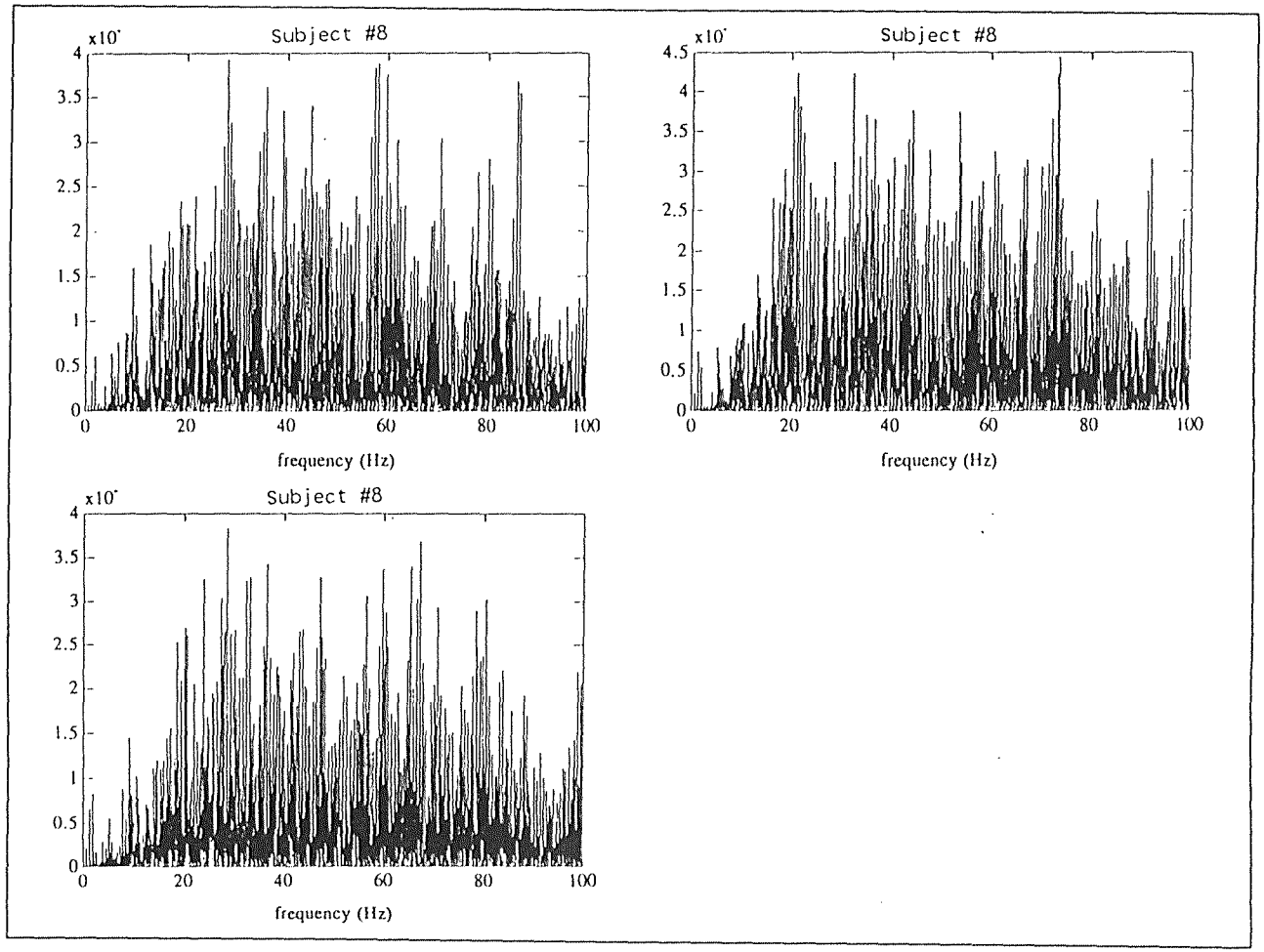

Figure 65 Power Spectra of 25 Second Time Windows for Intervals 17 to 19

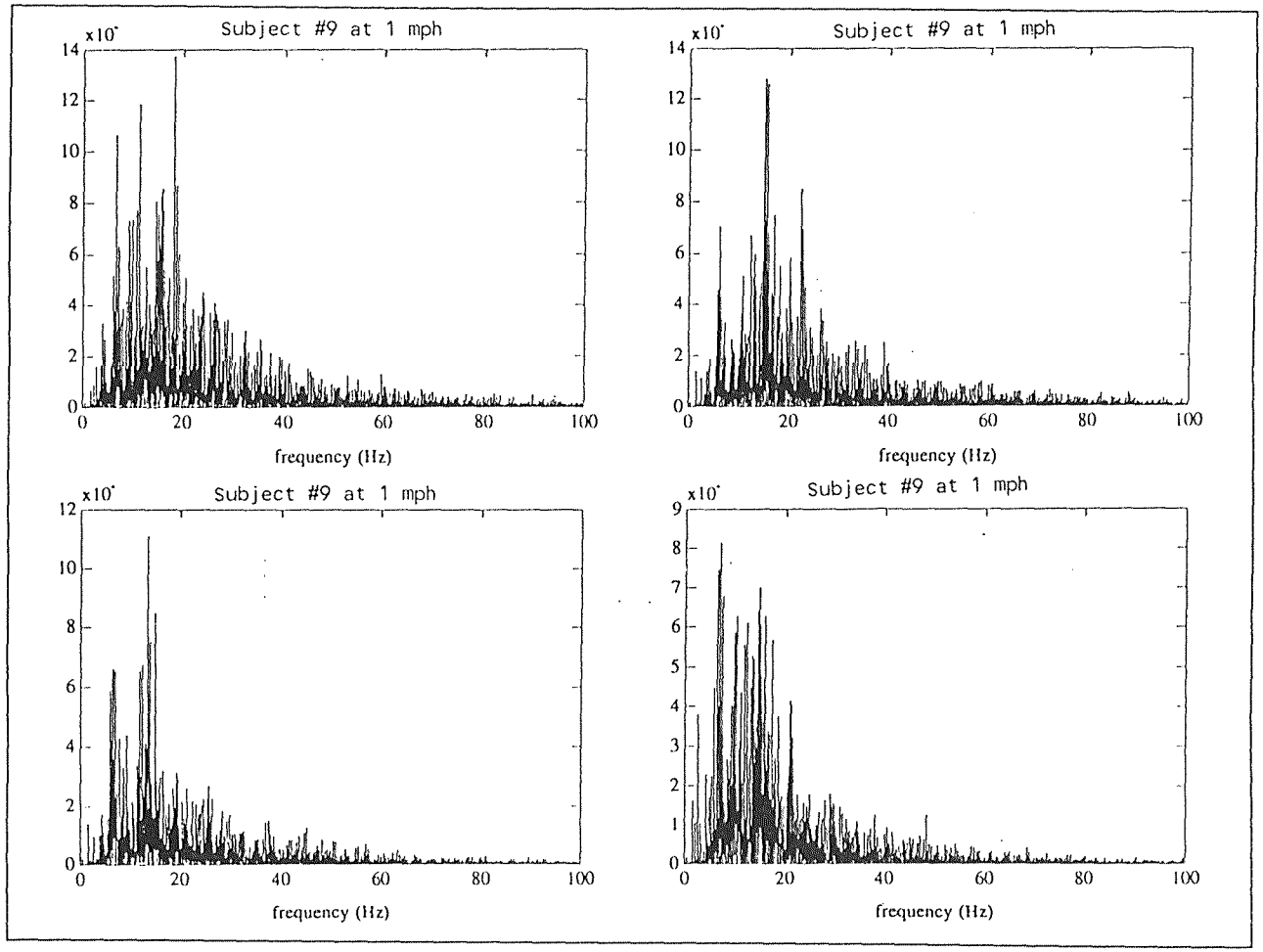

Figure 66 Power Spectra of 25 Second Time Windows for Intervals 1 to 4

APPENDIX D

FREQUENCY PARAMETER PLOTS

The nine frequency parameters were calculated for each consecutive 25 second time window using Programs 1, 2, and 3. Program 7 was written to plot these parameters. The plots are located on the following pages of this appendix. These plots demonstrate how fatigue, adaptation and recruitment expressed through EMG can be quantitized.

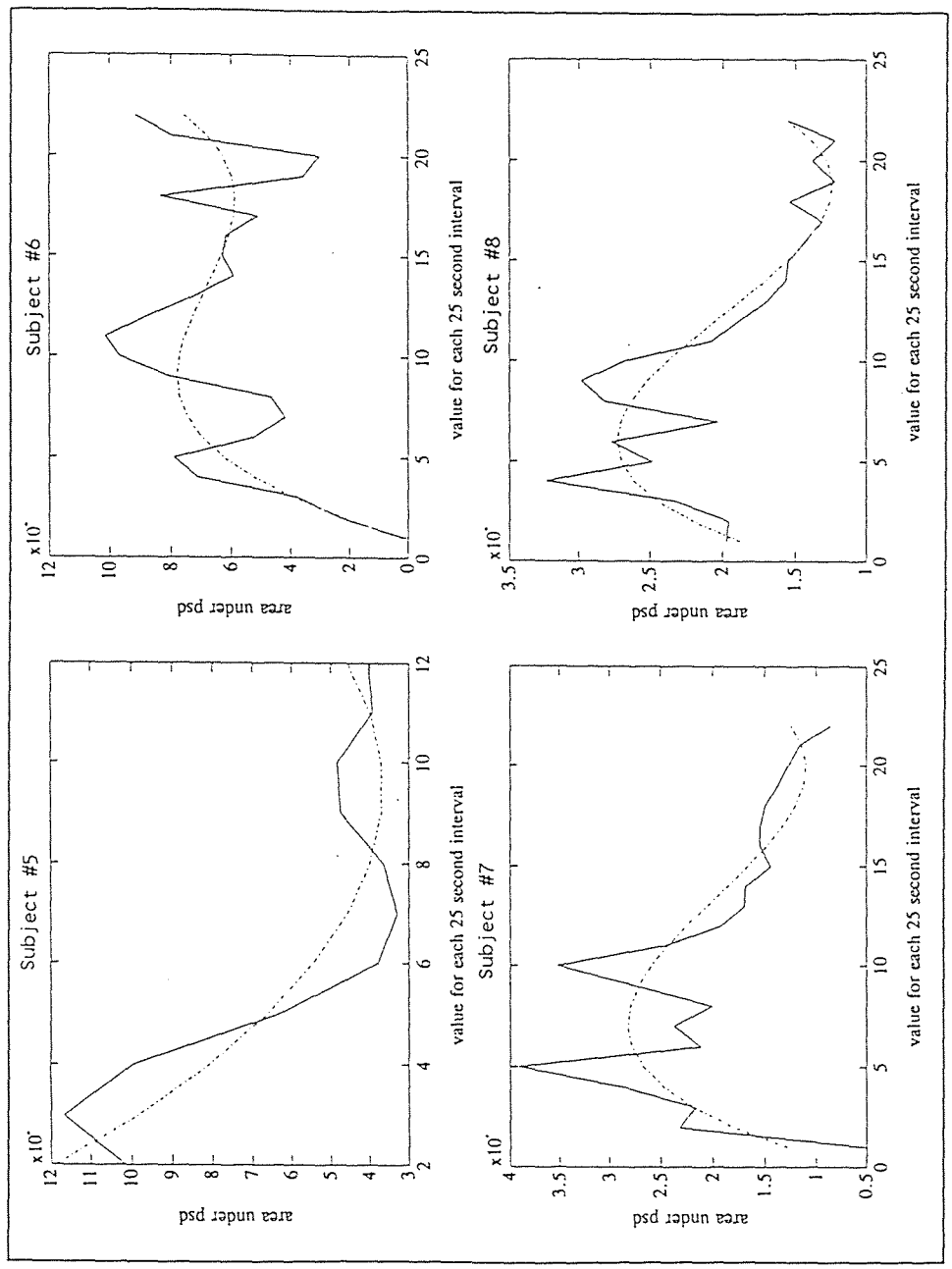

Figure 68 Changes in Area Under the Power Spectra (0 to 35 Hz) Over Time

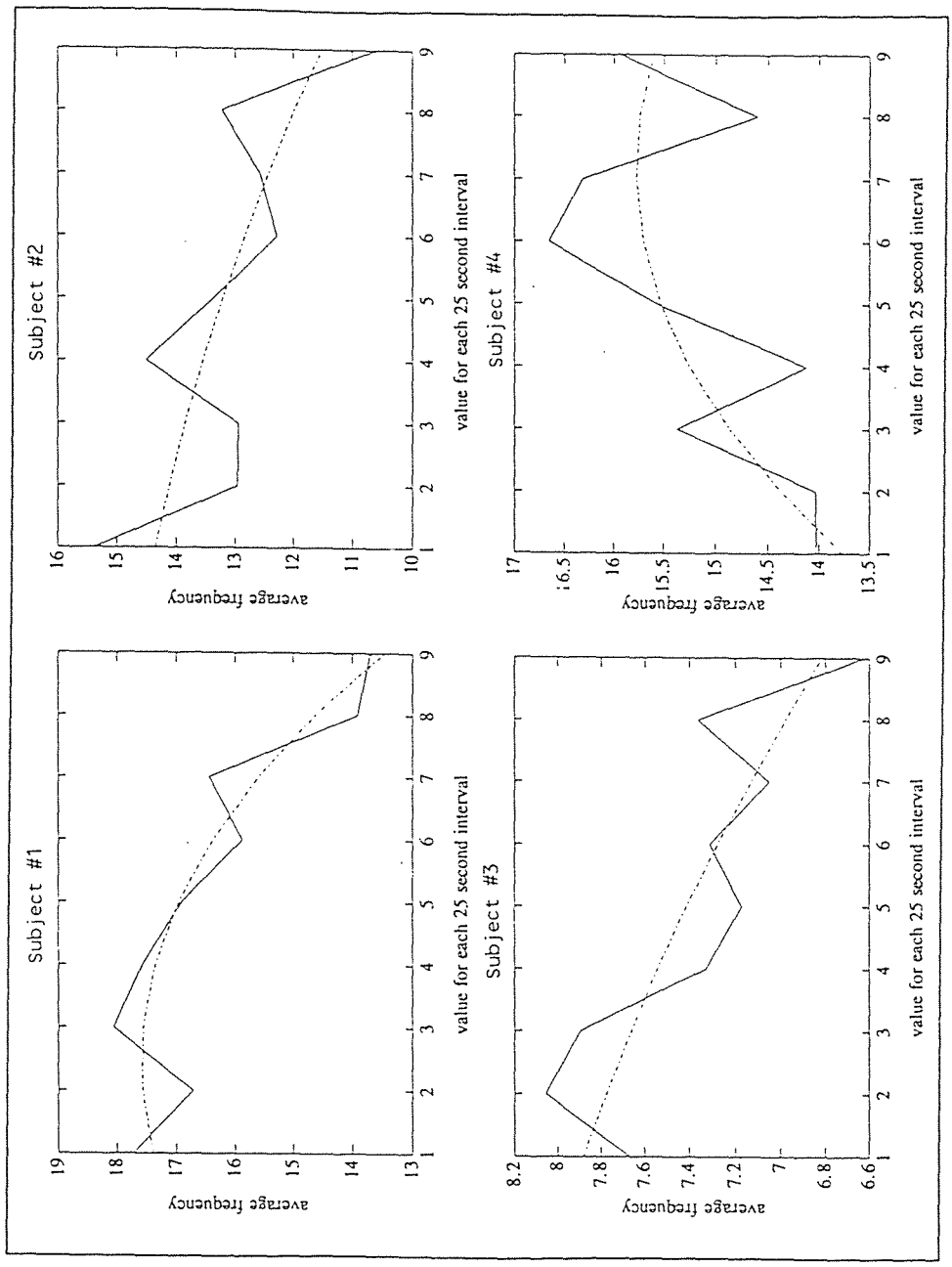

Figure 69 Changes in Average Frequency (0 to 35 Hz) Over Time

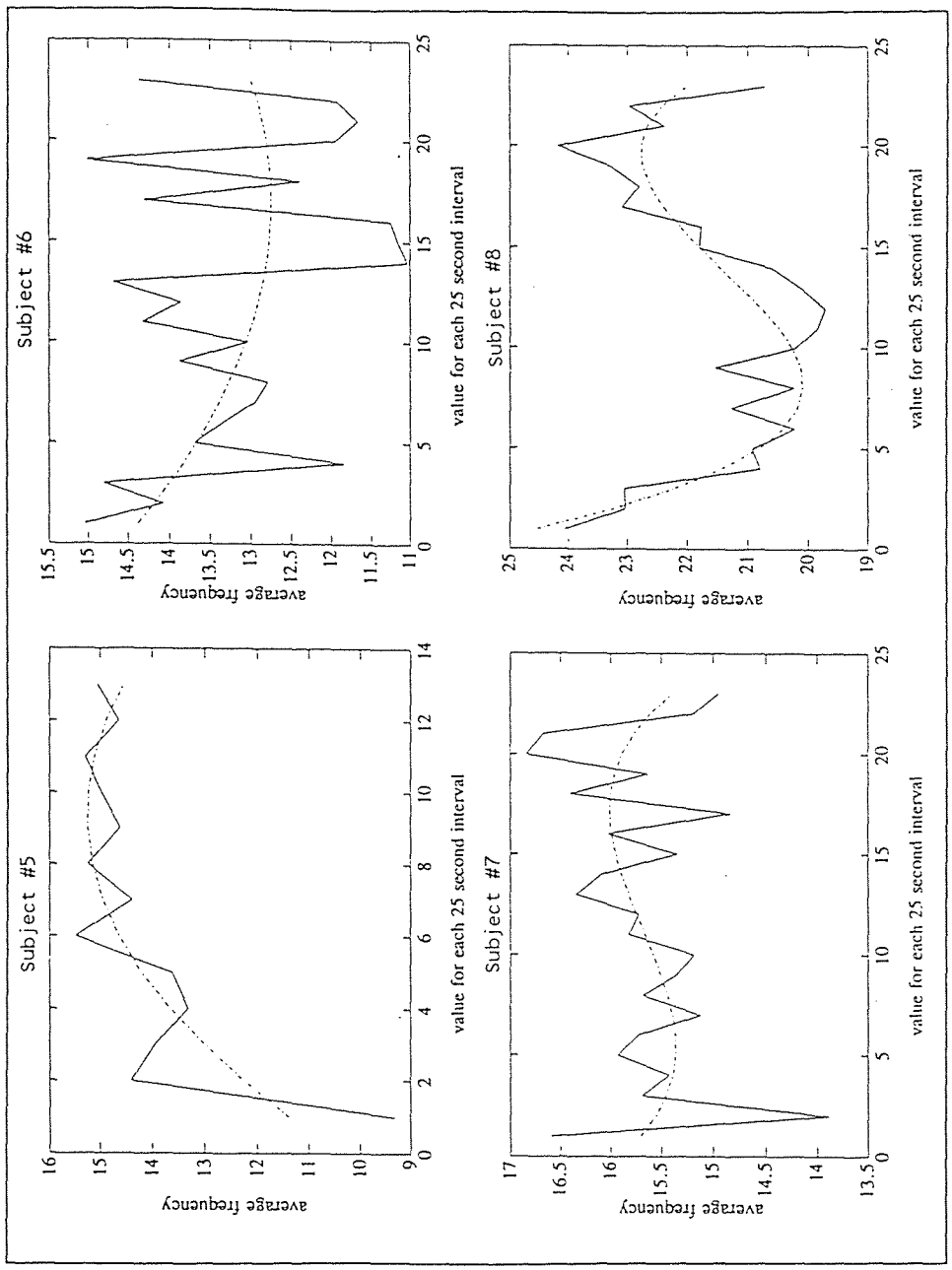

Figure 70 Changes in Average Frequency (0 to 35 Hz) Over Time

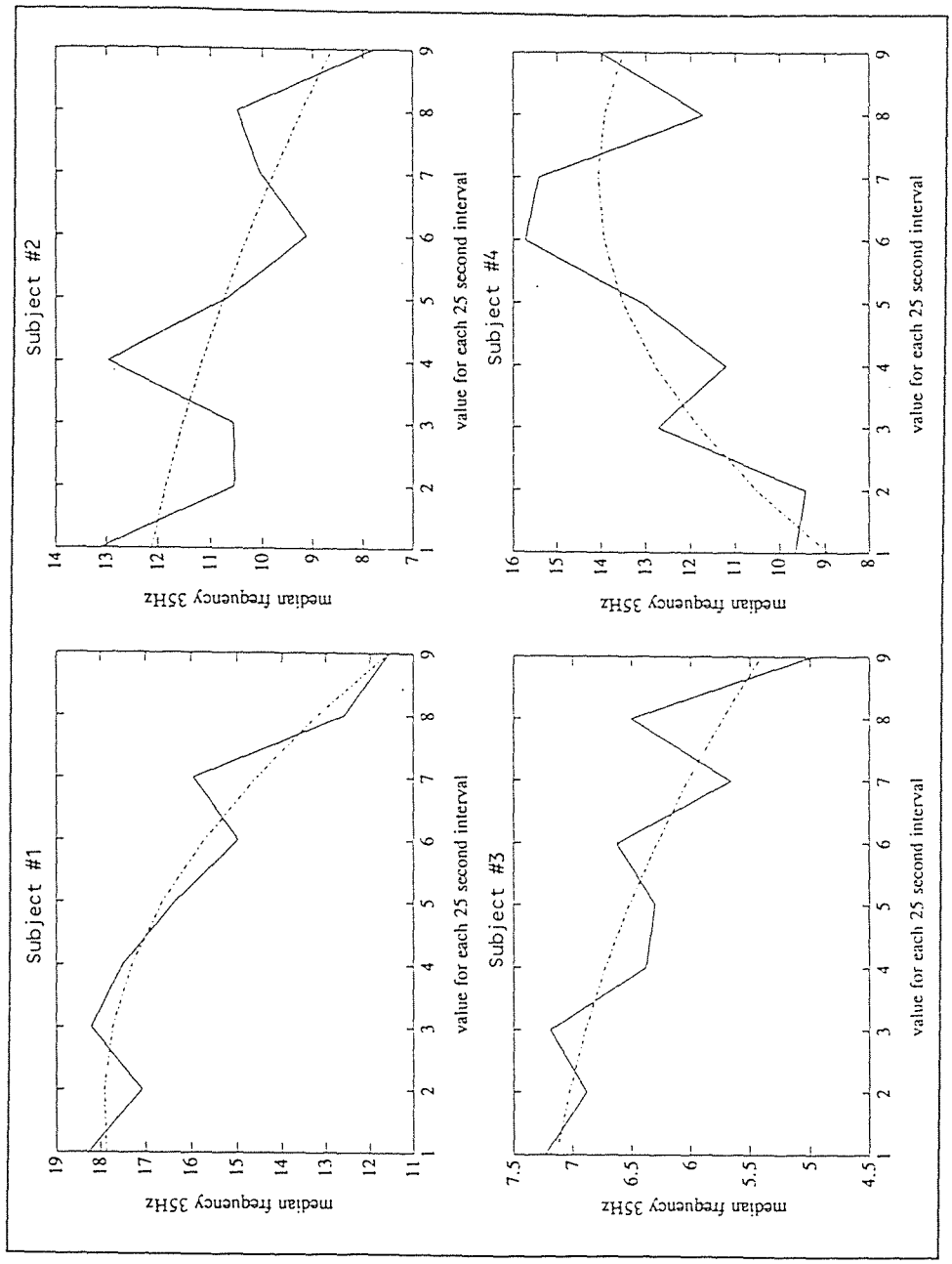

Figure 71 Changes in Median Frequency (0 to 35 Hz) Over Time

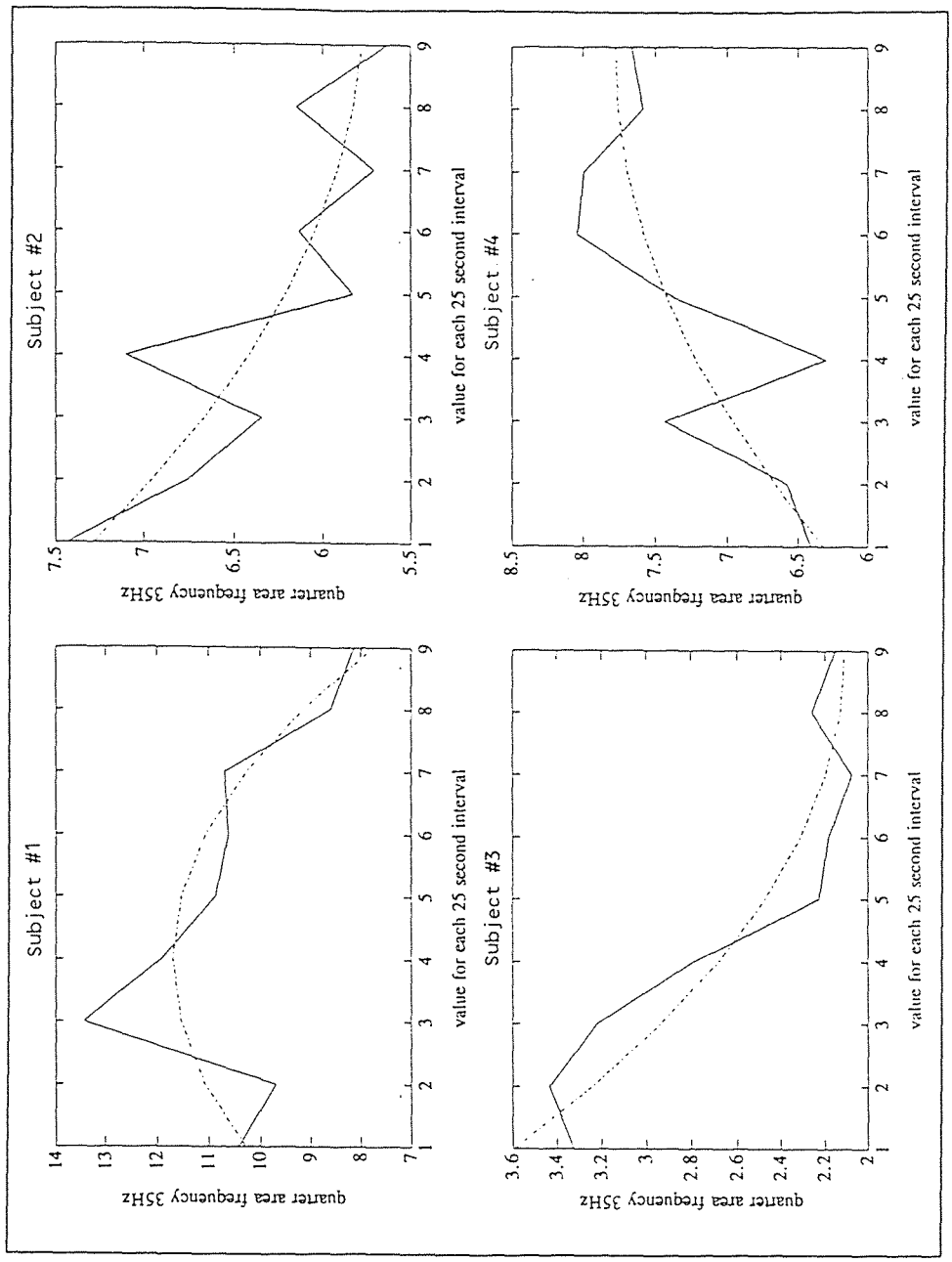

Figure 73 Changes in Quarter Area Frequency (0 to 35 Hz) Over Time

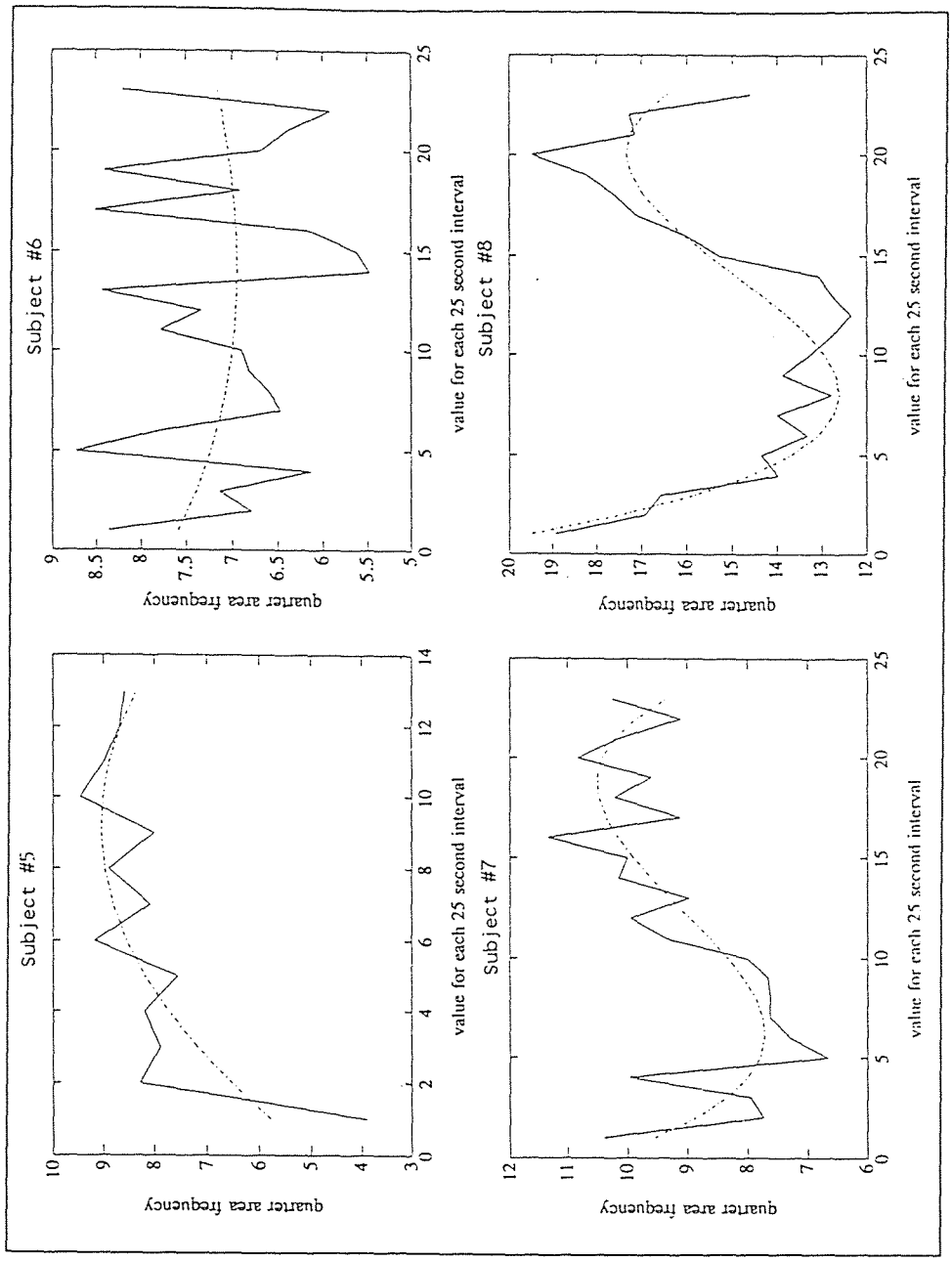

Figure 74 Changes in Quarter Area Frequency (0 to 35 Hz) Over Time

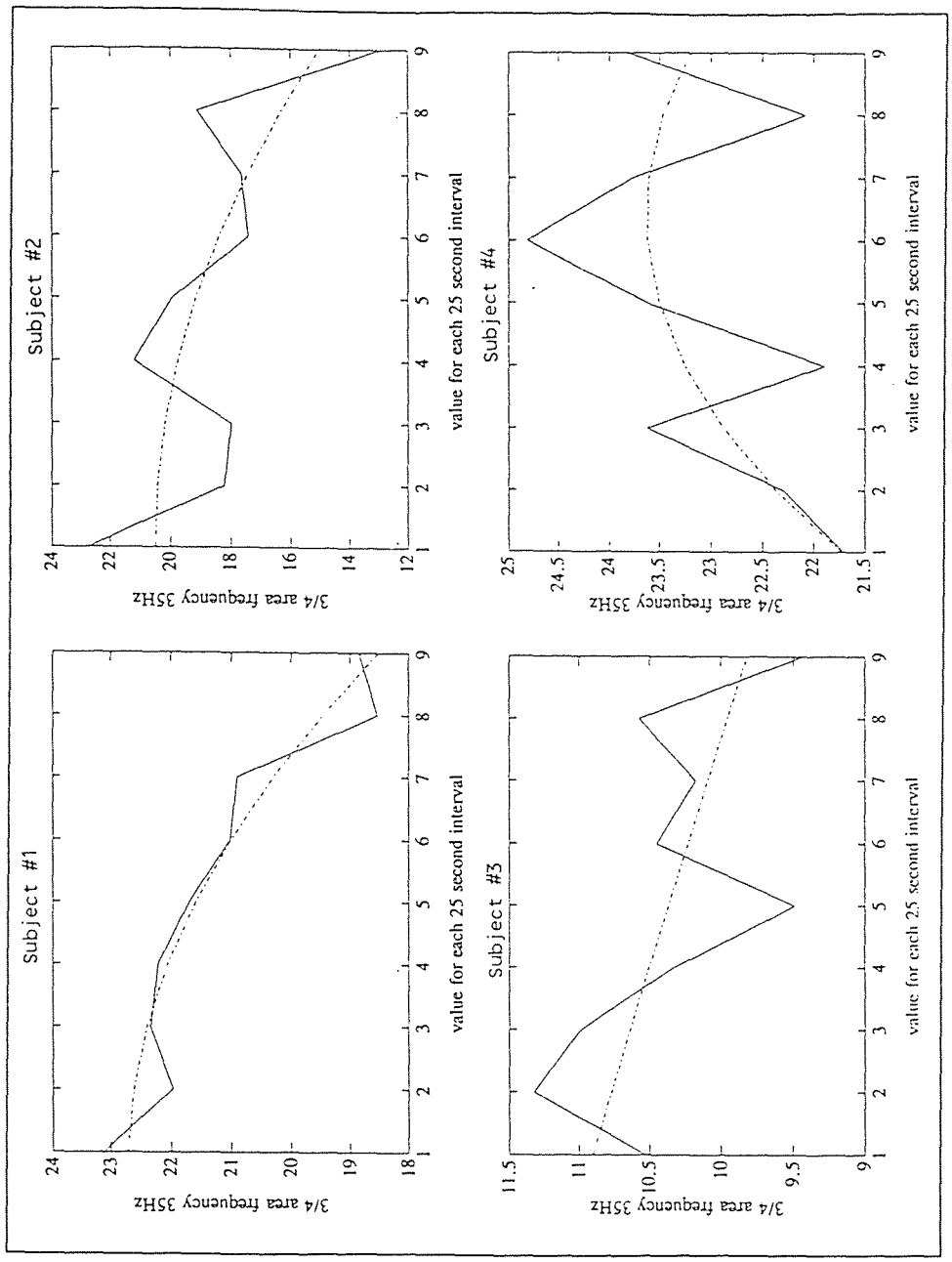

Figure 75 Changes in Three Quarter Area Frequency (0 to 35 Hz) Over Time

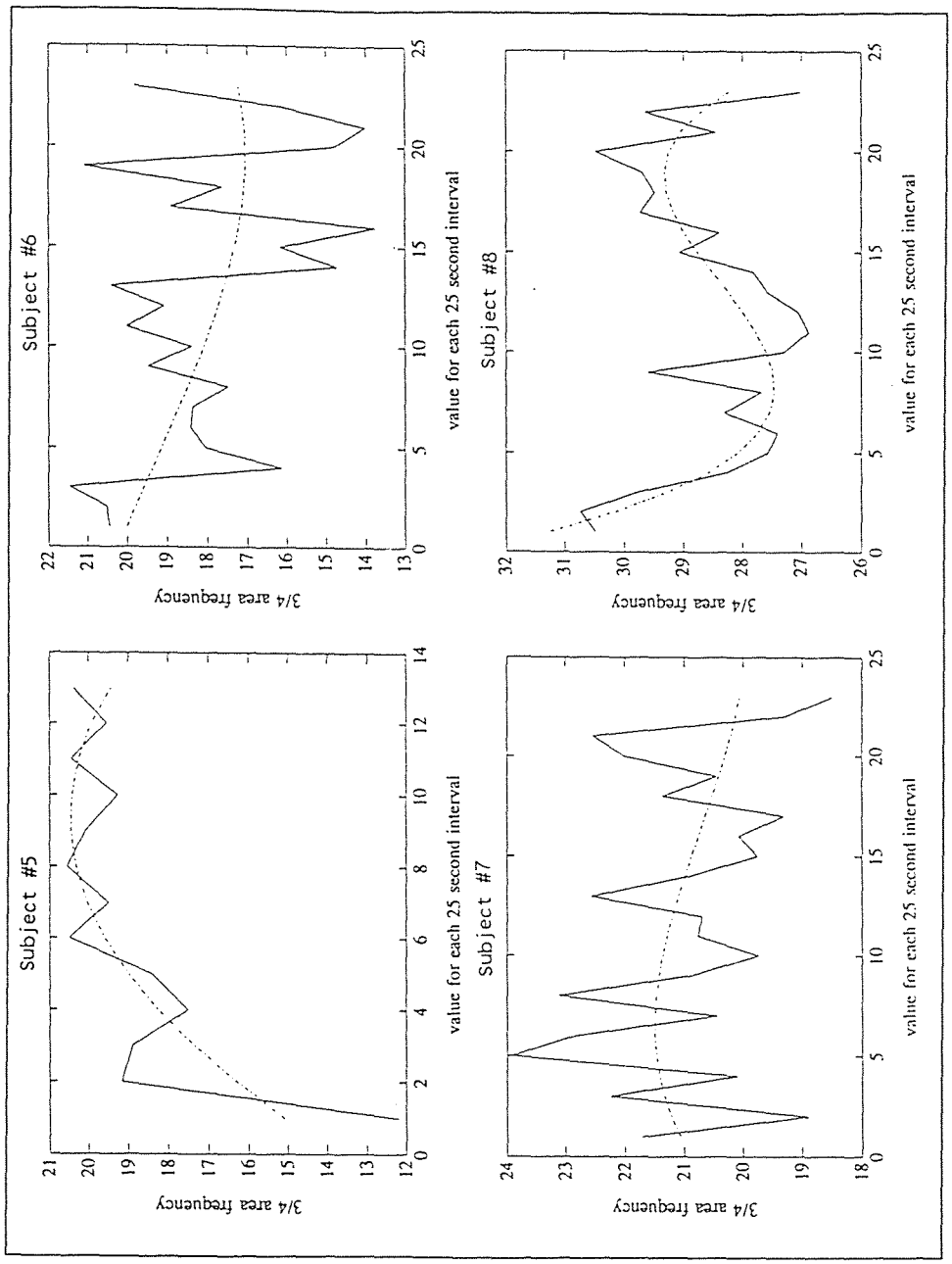

Figure 76 Changes in Three Quarter Area Frequency (0 to 35 Hz) Over Time

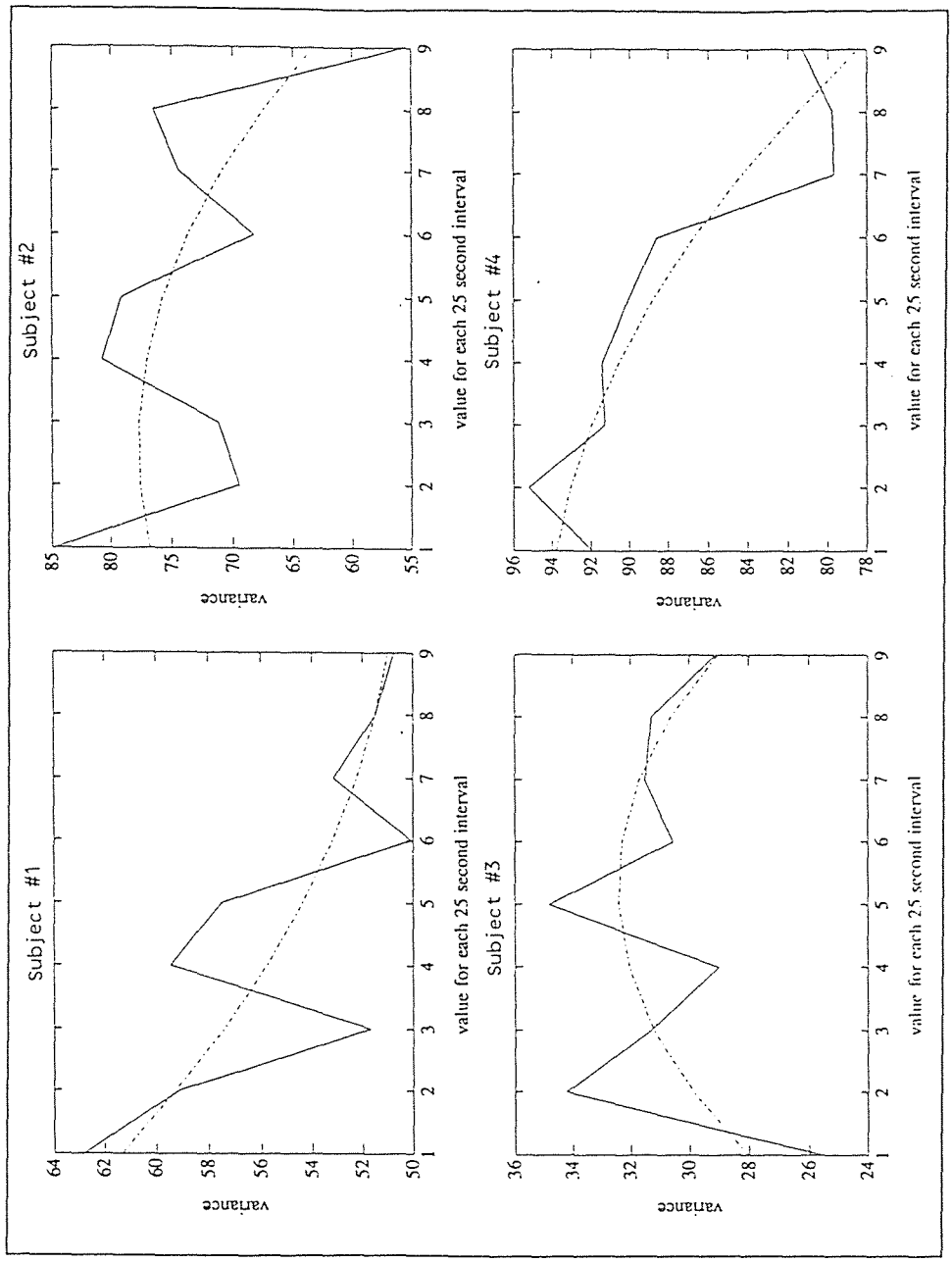

Figure 77 Changes in Variance (0 to 35 Hz) Over Time

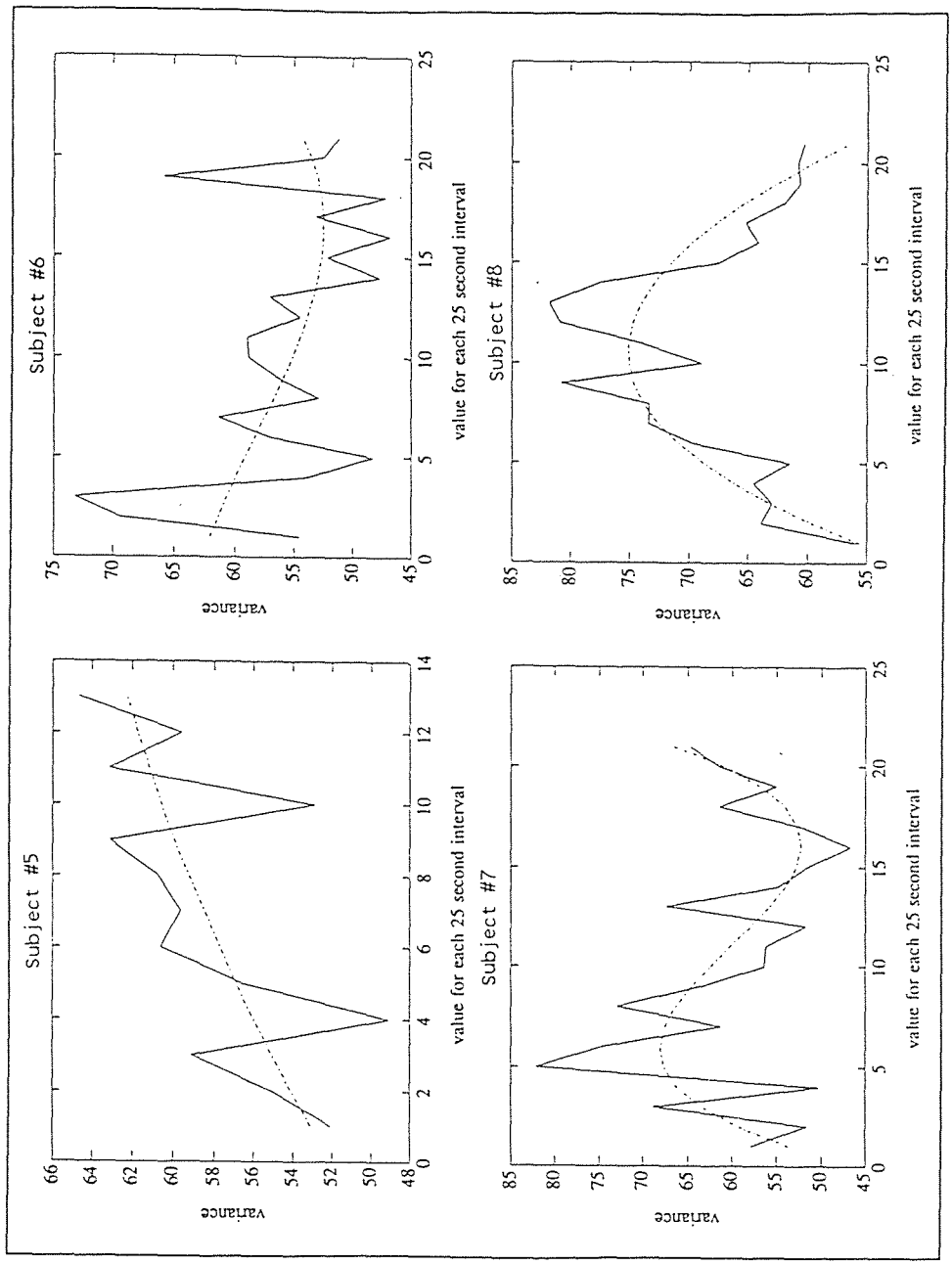

Figure 78 Changes in Variance (0 to 35 Hz) Over Time

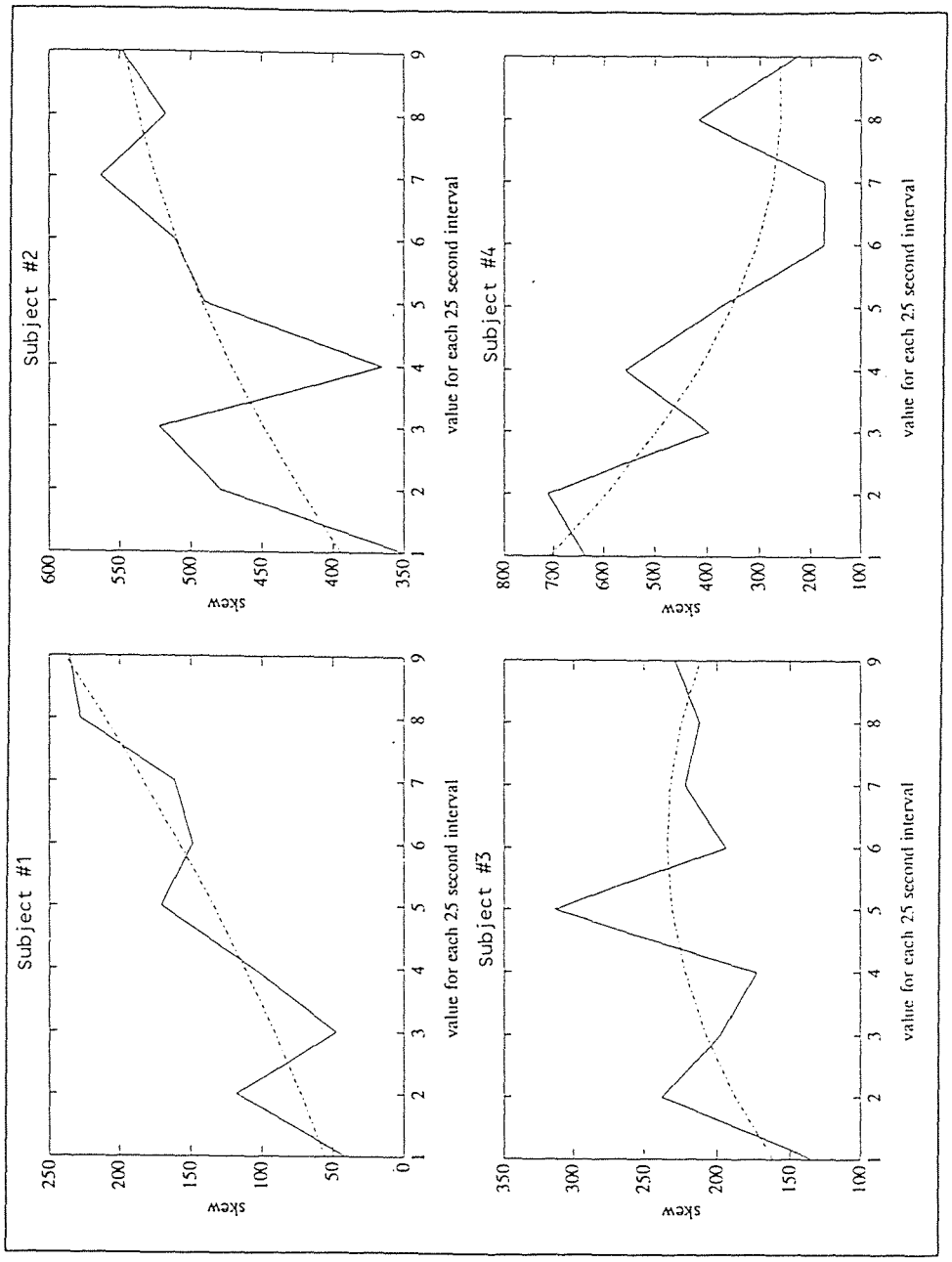

Figure 79 Changes in Skew (0 to 35 Hz) Over Time

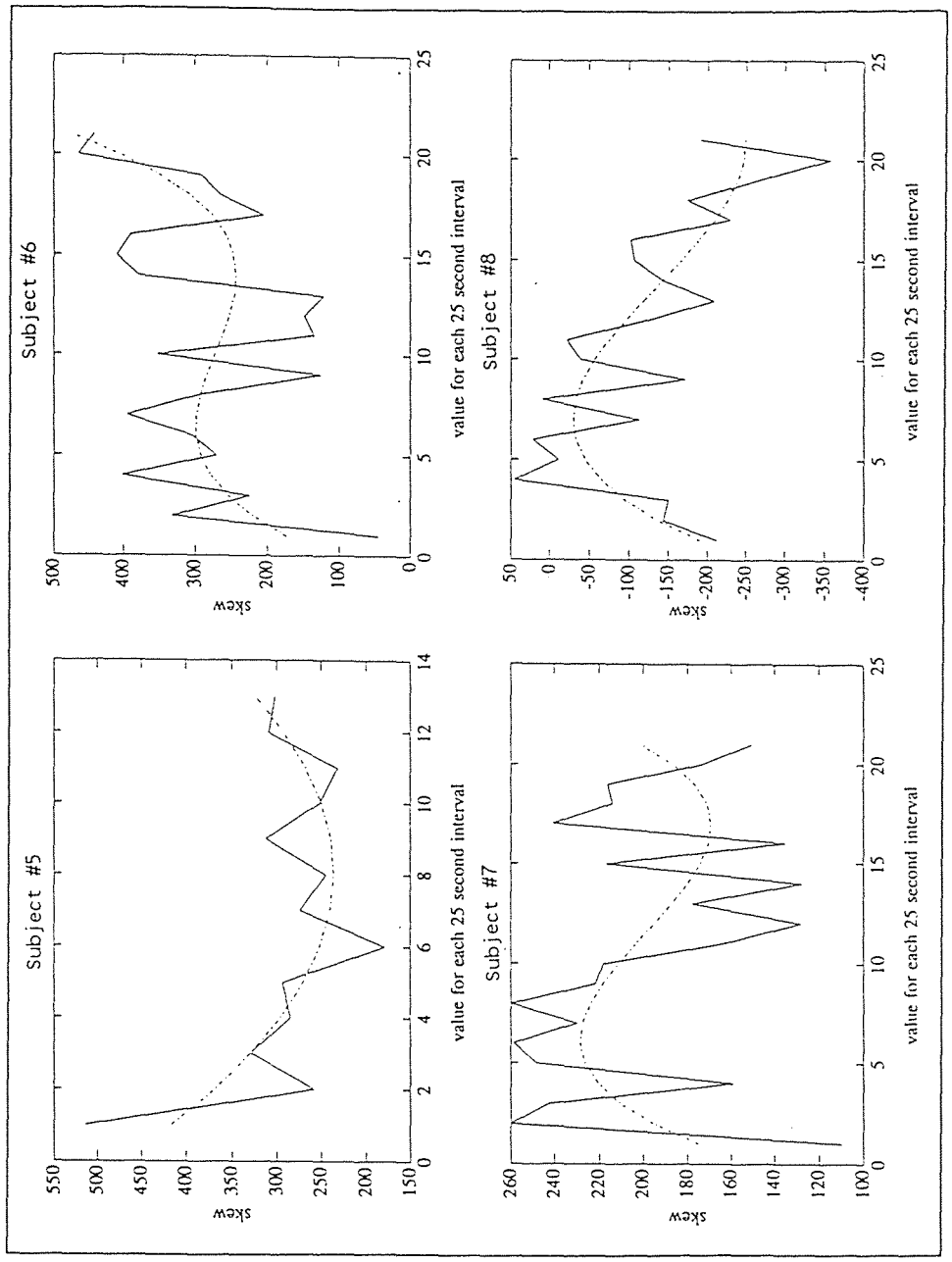

Figure 80 Changes in Skew (0 to 35 Hz) Over Time

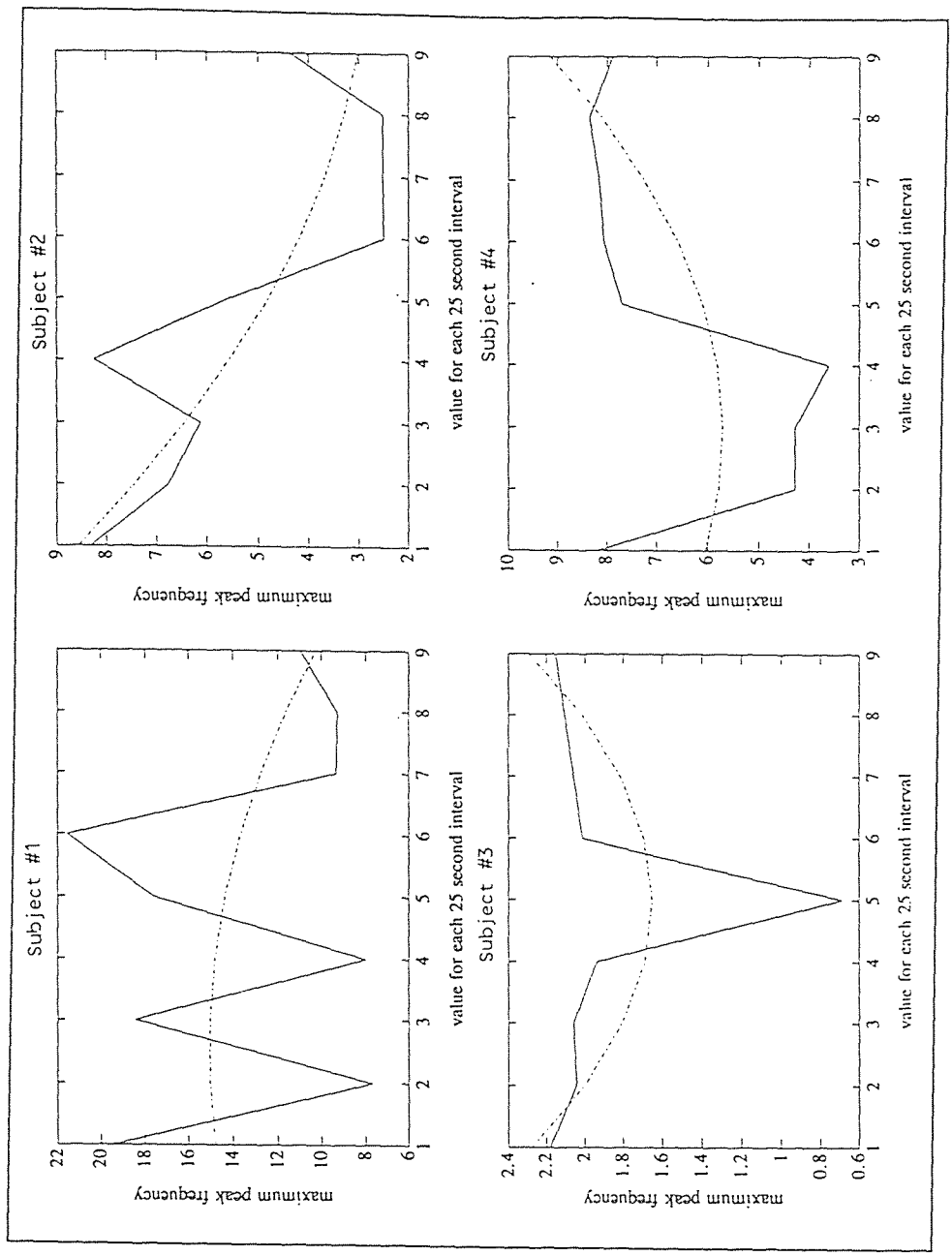

Figure 81 Changes in Maximum Peak Frequency Over Time

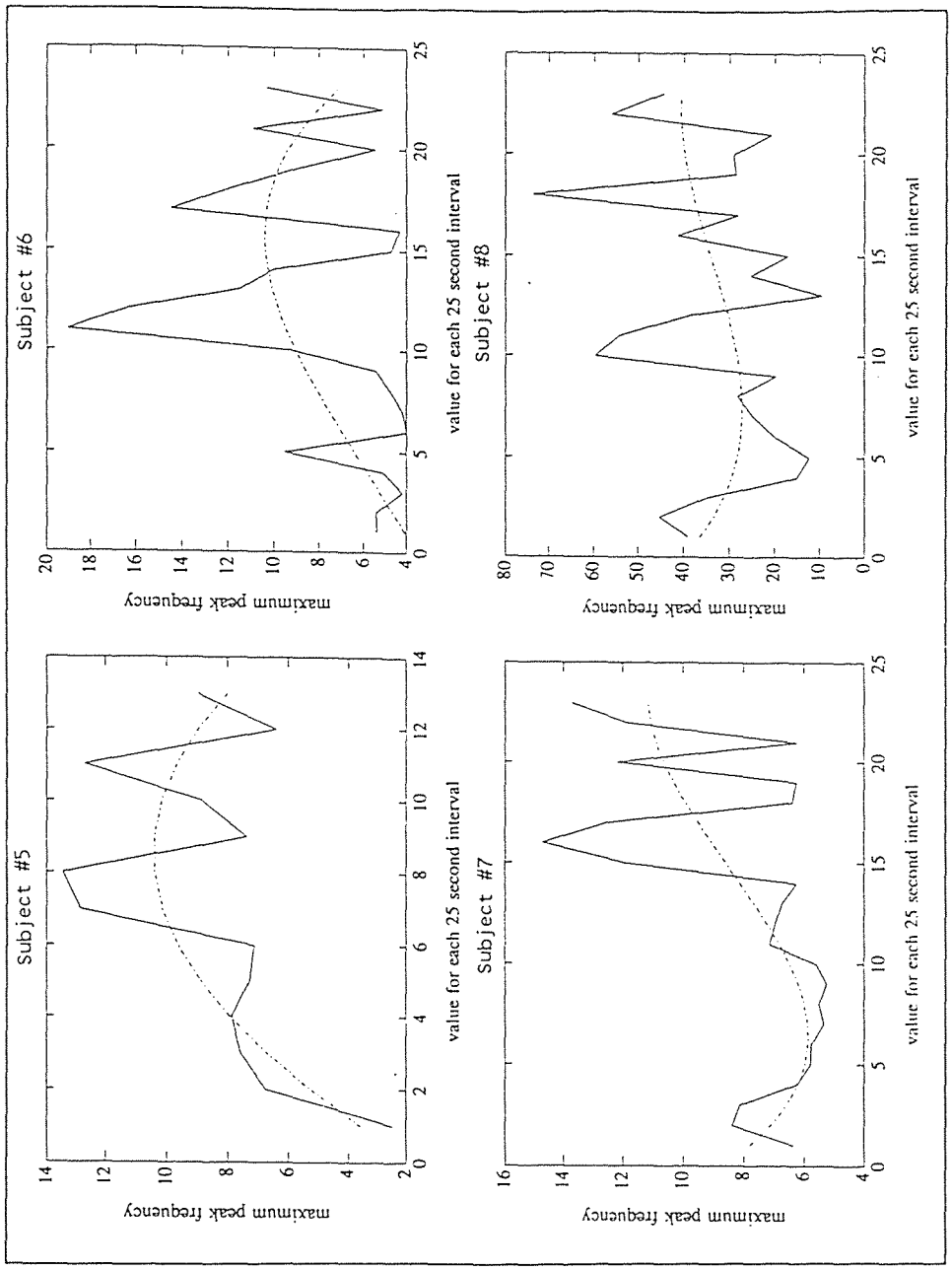

Figure 82 Changes in Maximum Peak Frequency Over Time

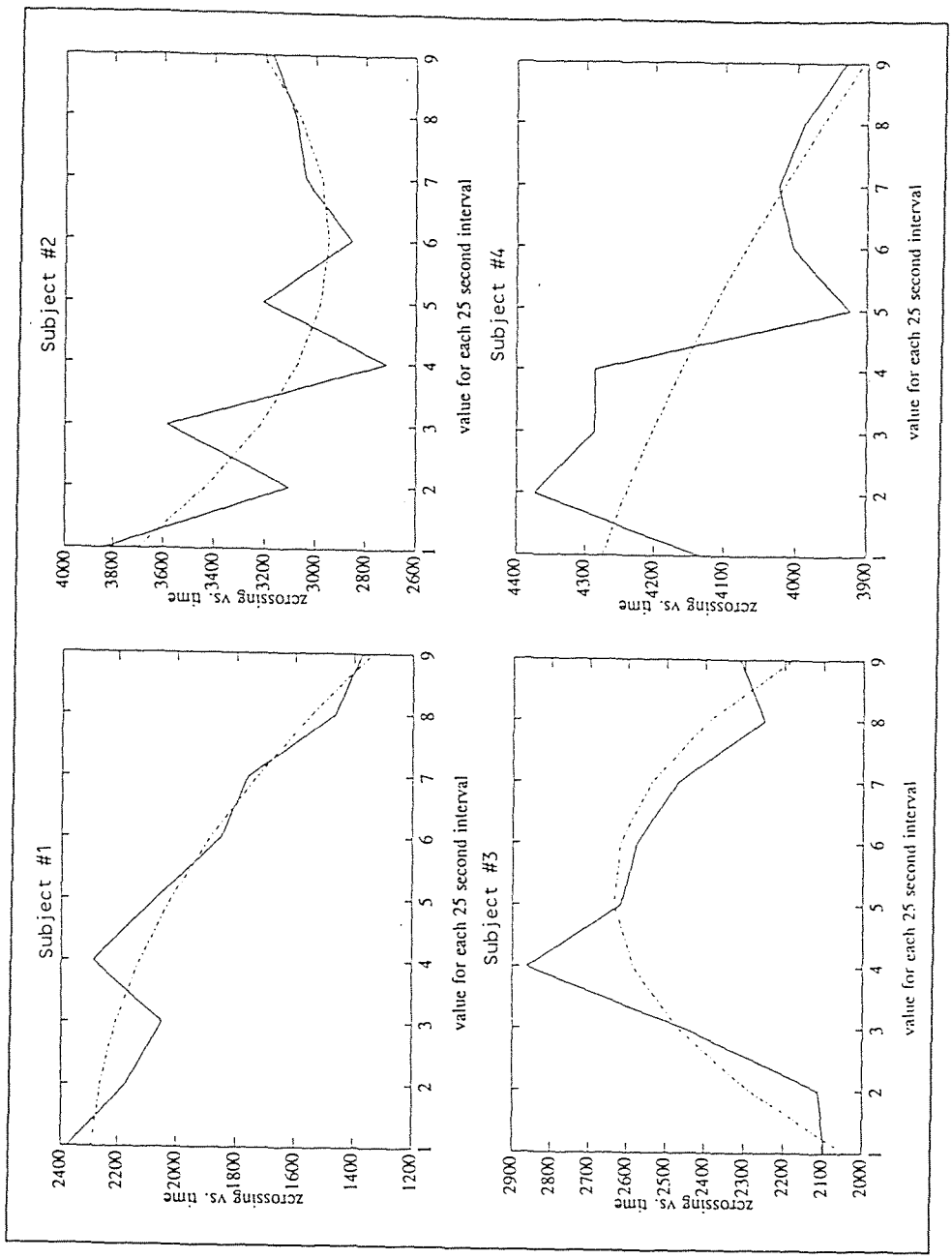

Figure 83 Changes in Zero Crossings Over Time

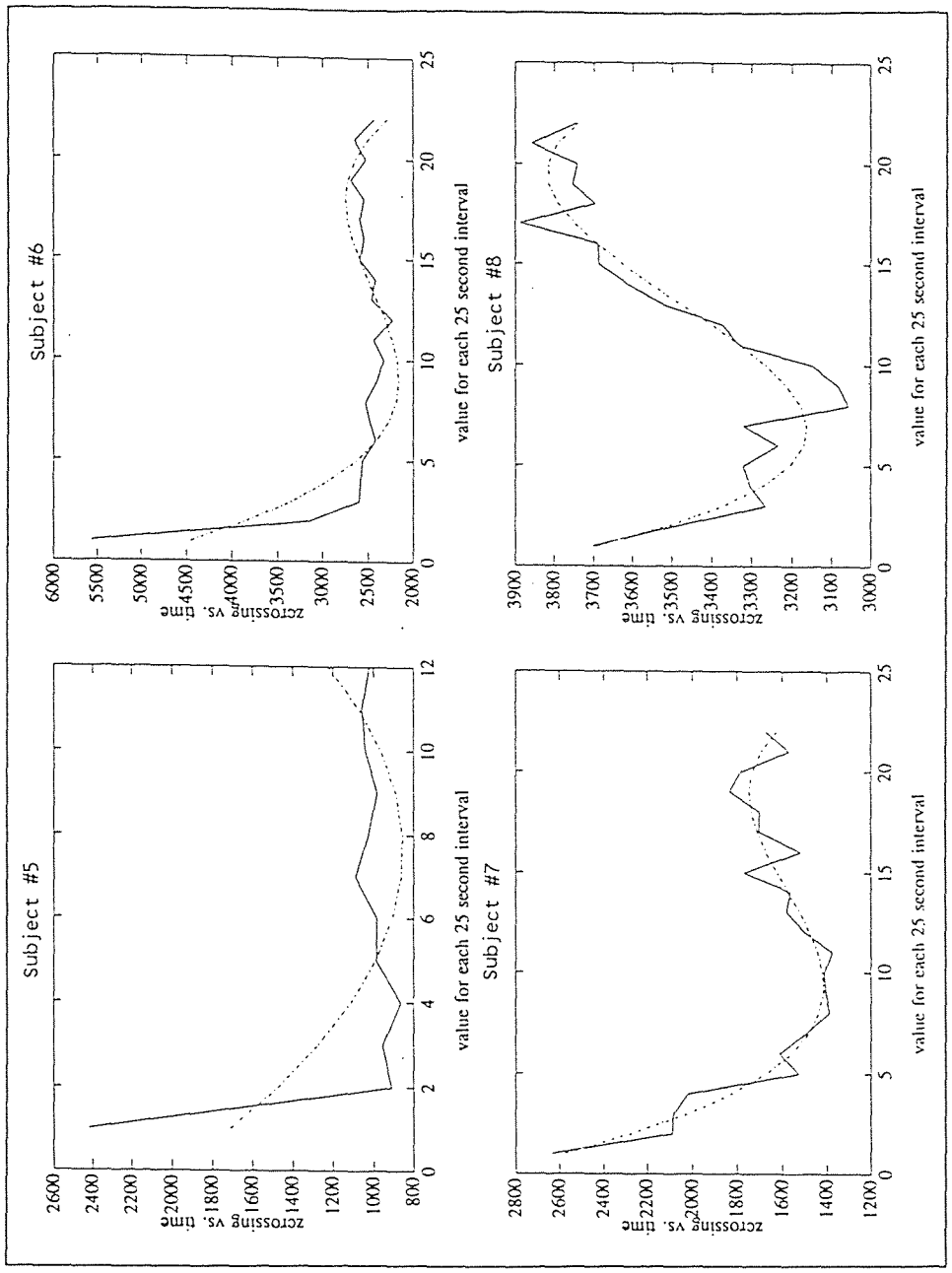

Figure 84 Changes in Zero Crossings Over Time

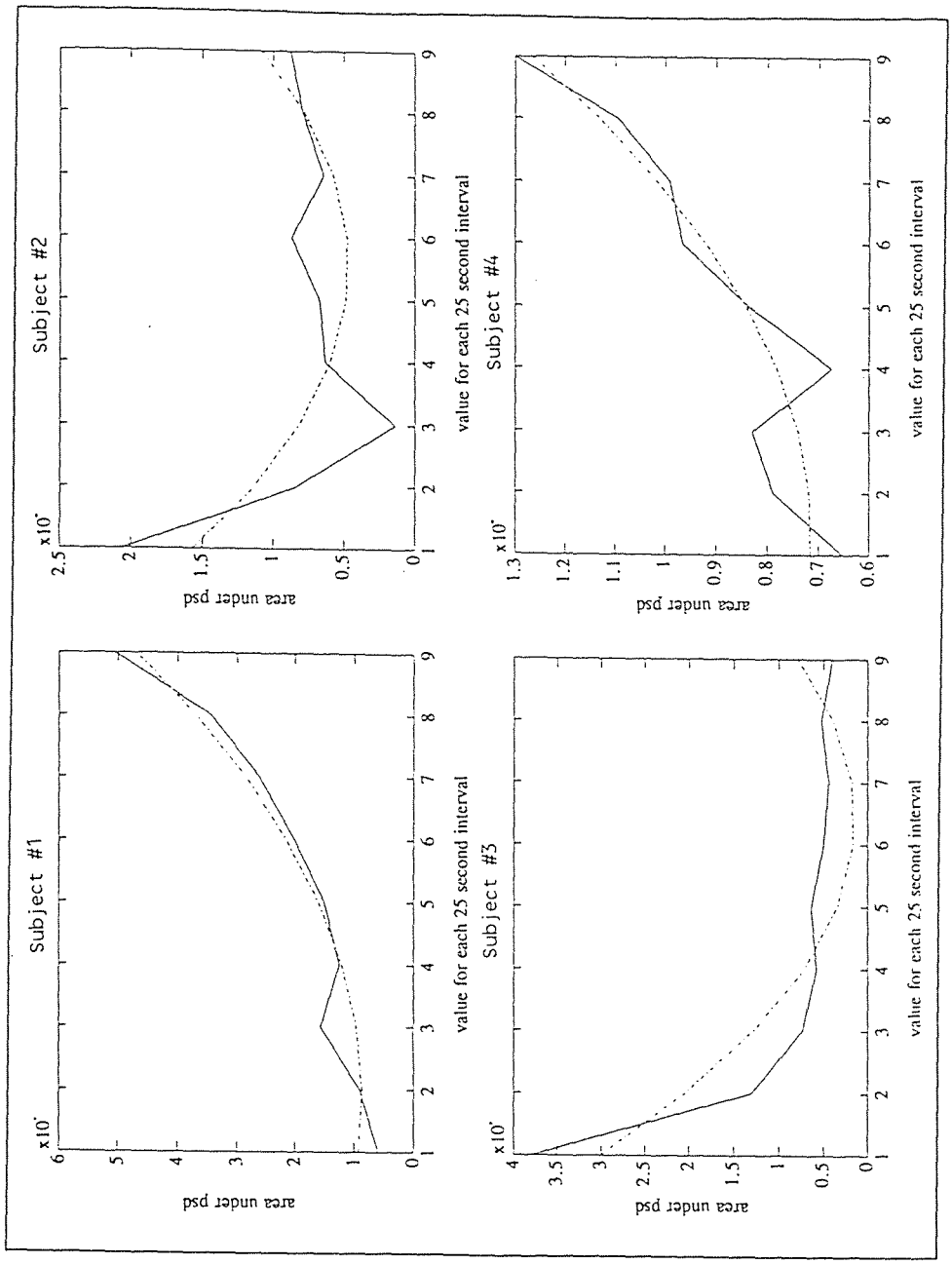

Figure 85 Changes in Area Under the Power Spectra Over Time

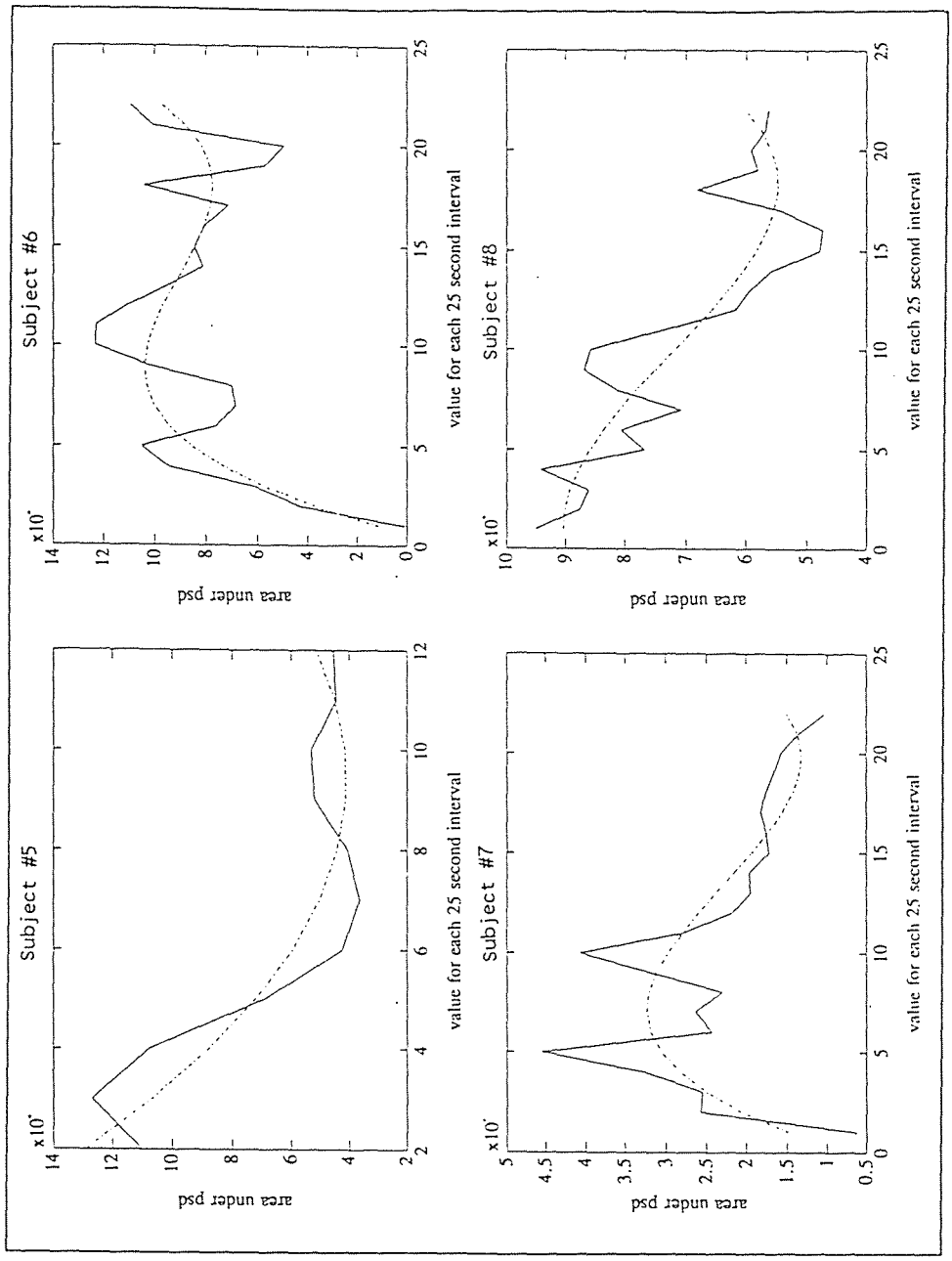

Figure 86 Changes in Area Under the Power Spectra Over Time

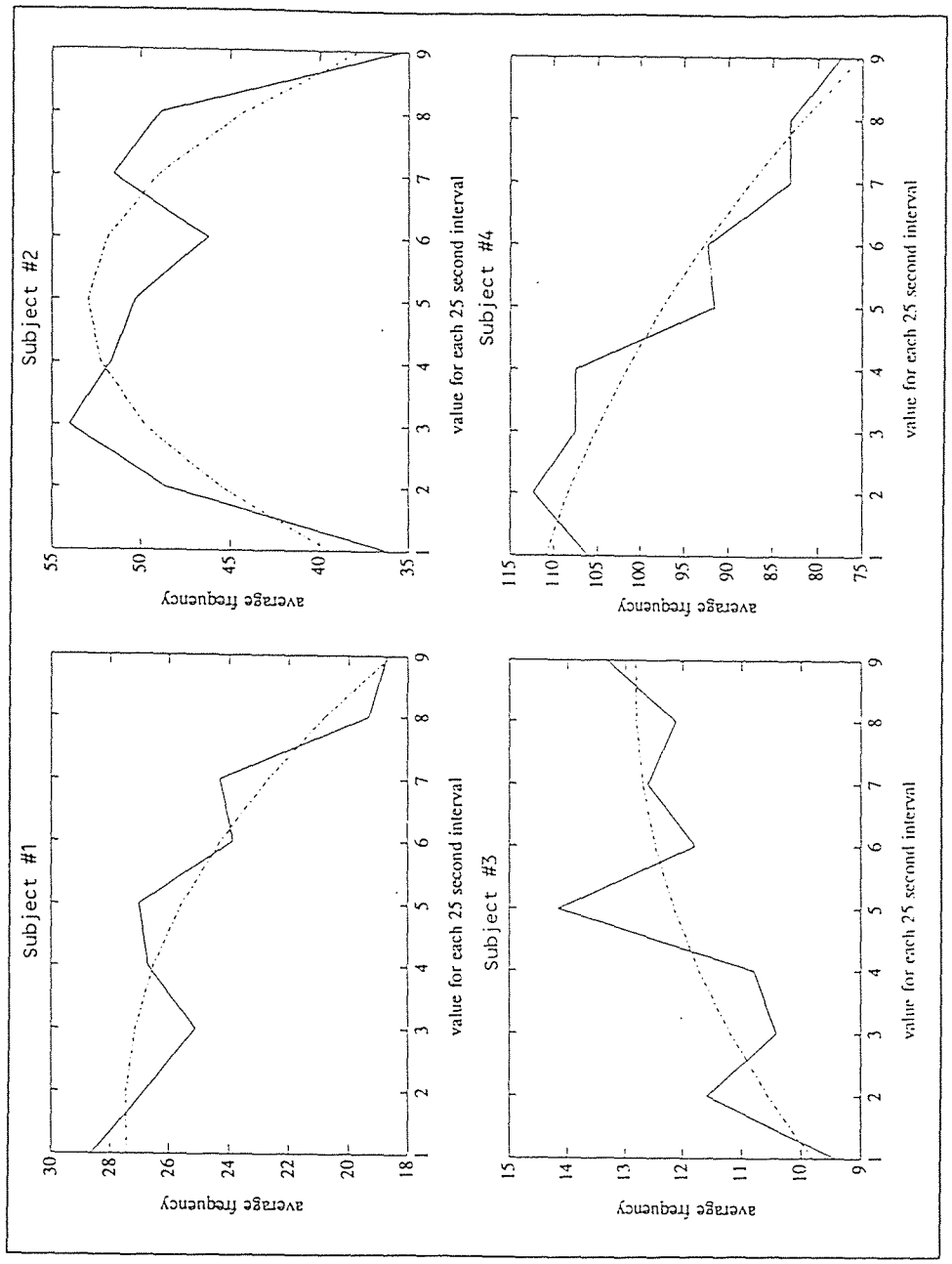

Figure 87 Changes in Average Frequency Over Time

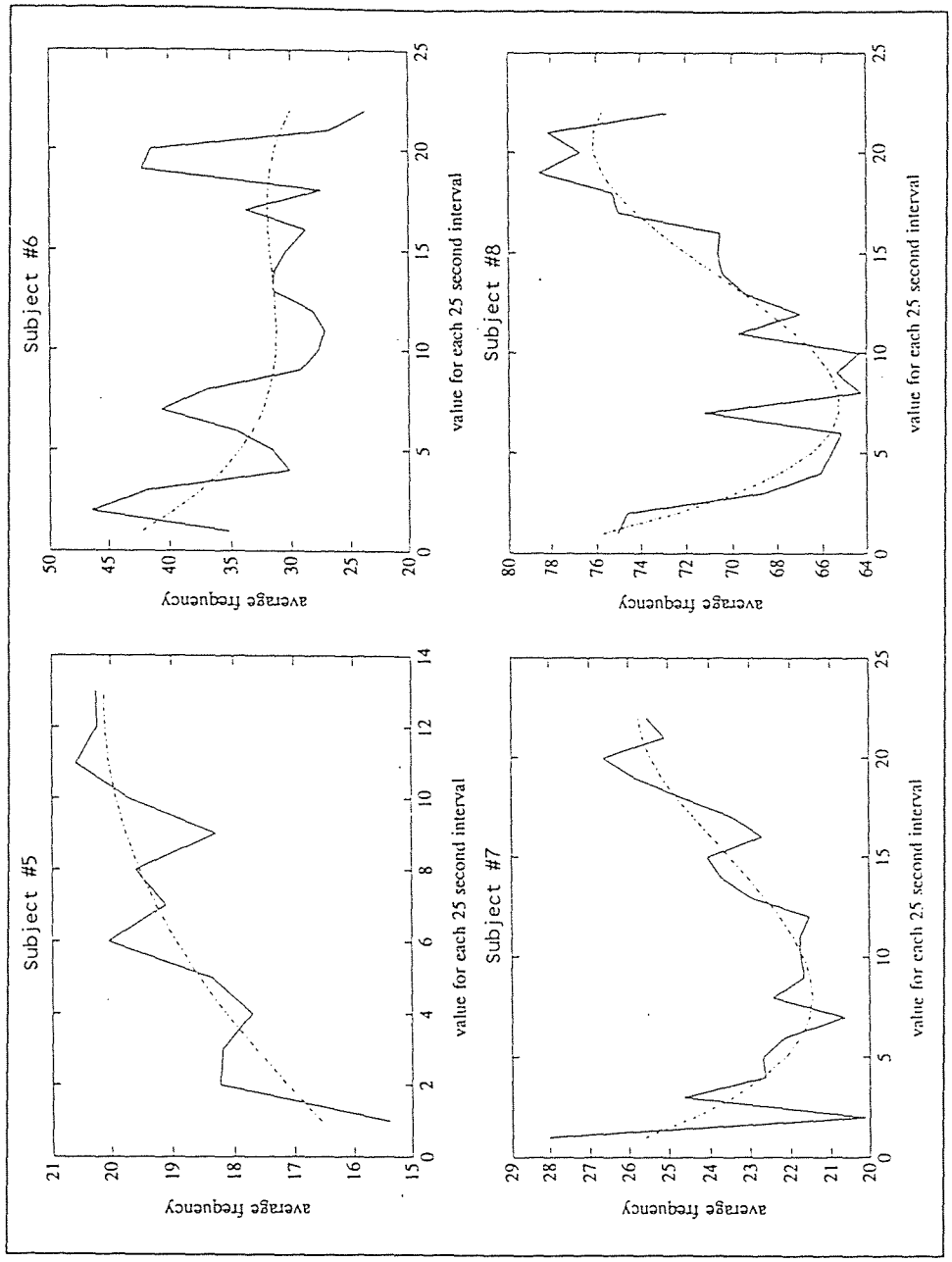

Figure 88 Changes in Average Frequency Over Time

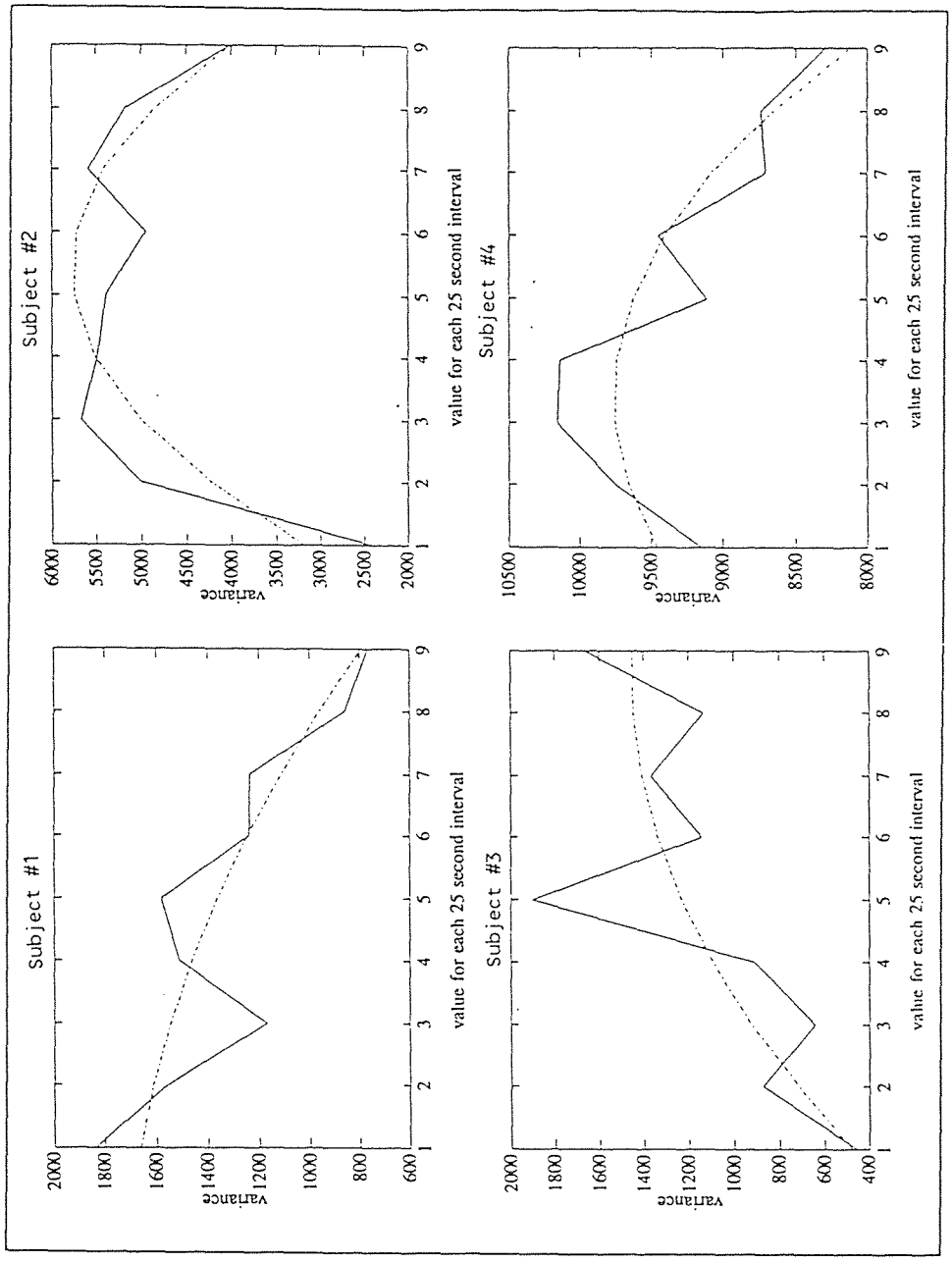

Figure 89 Changes in Variance Over Time

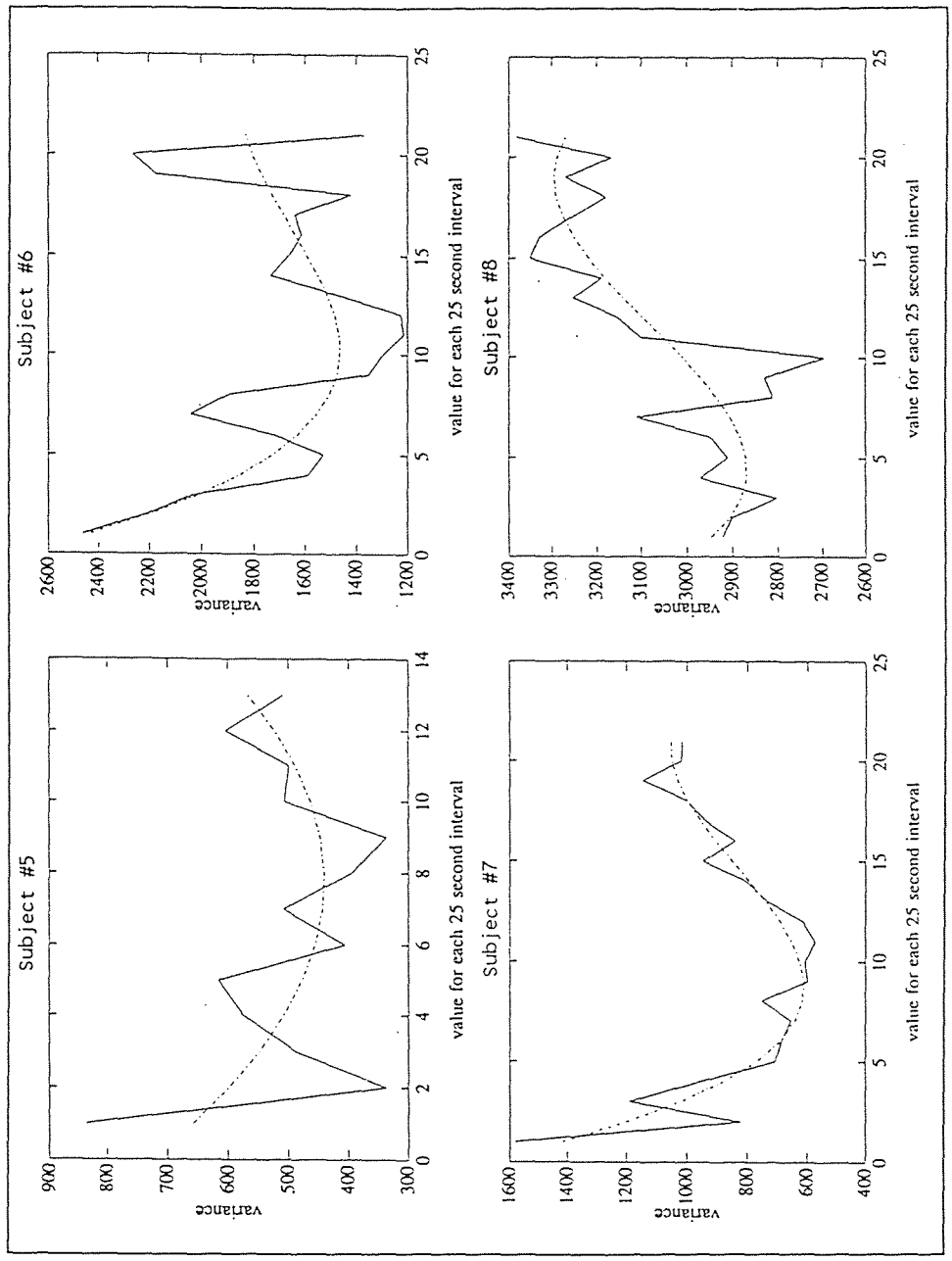

Figure 90 Changes in Variance Over Time

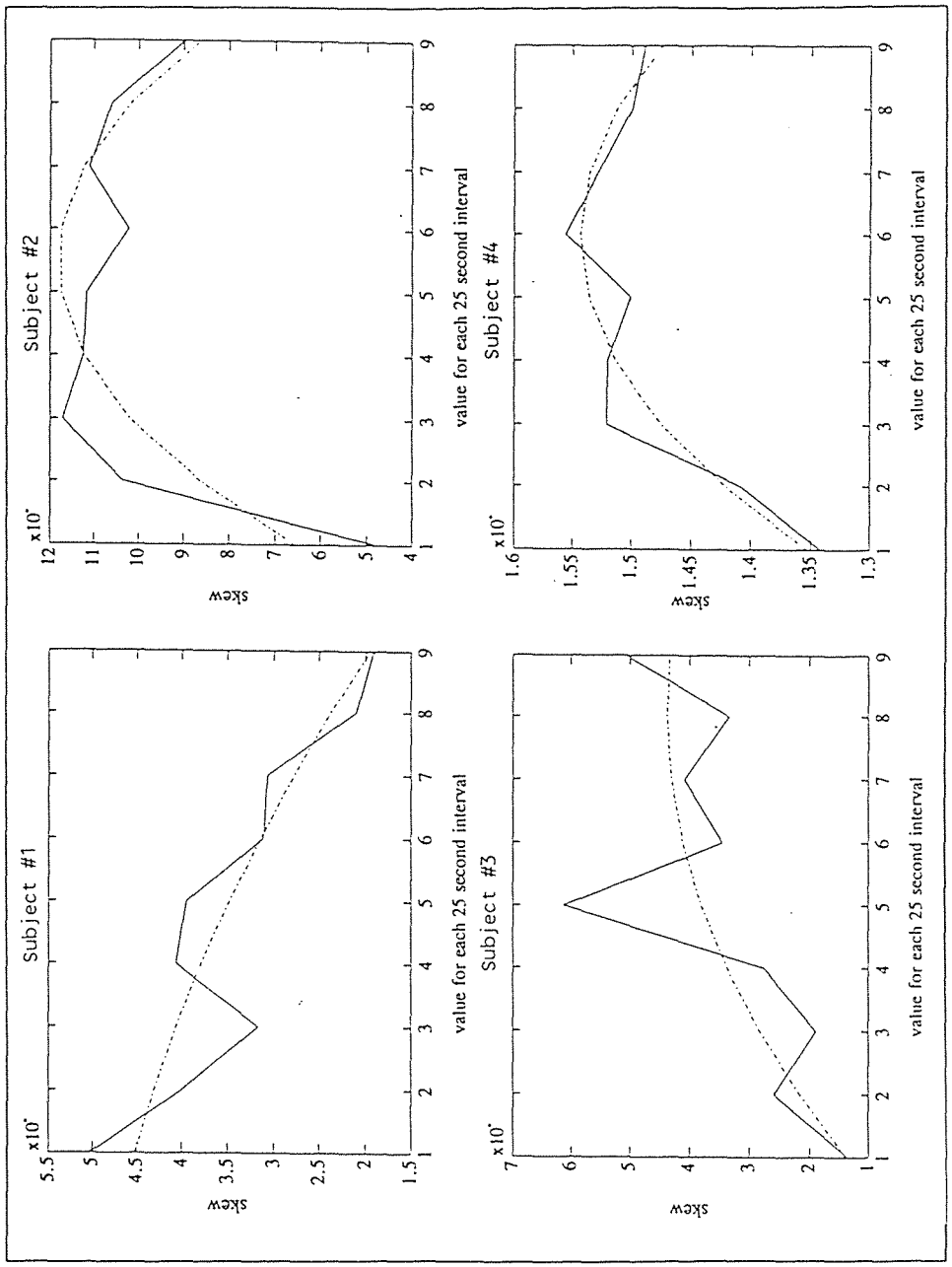

Figure 91 Changes in Skew Over Time

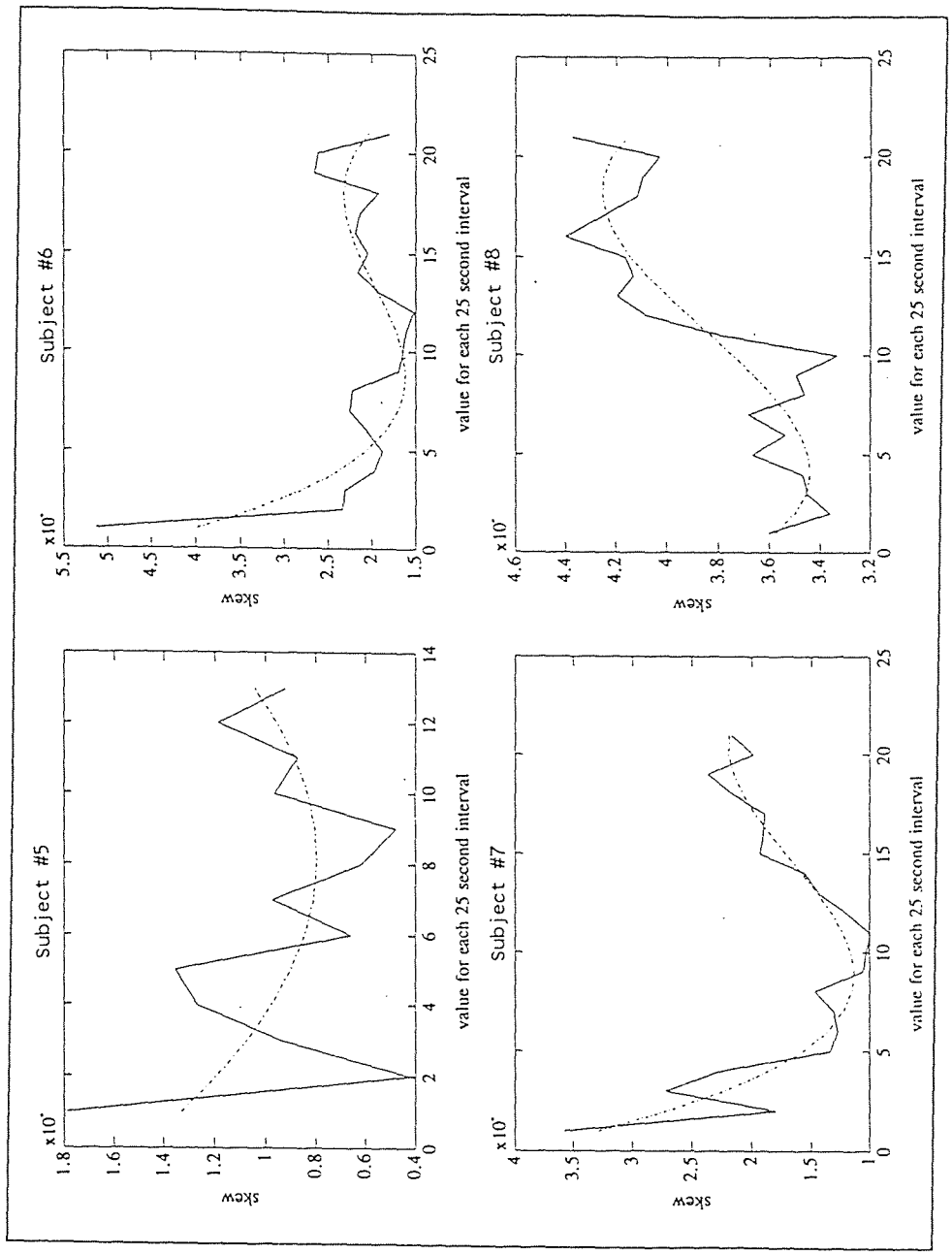

Figure 92 Changes in Skew Over Time

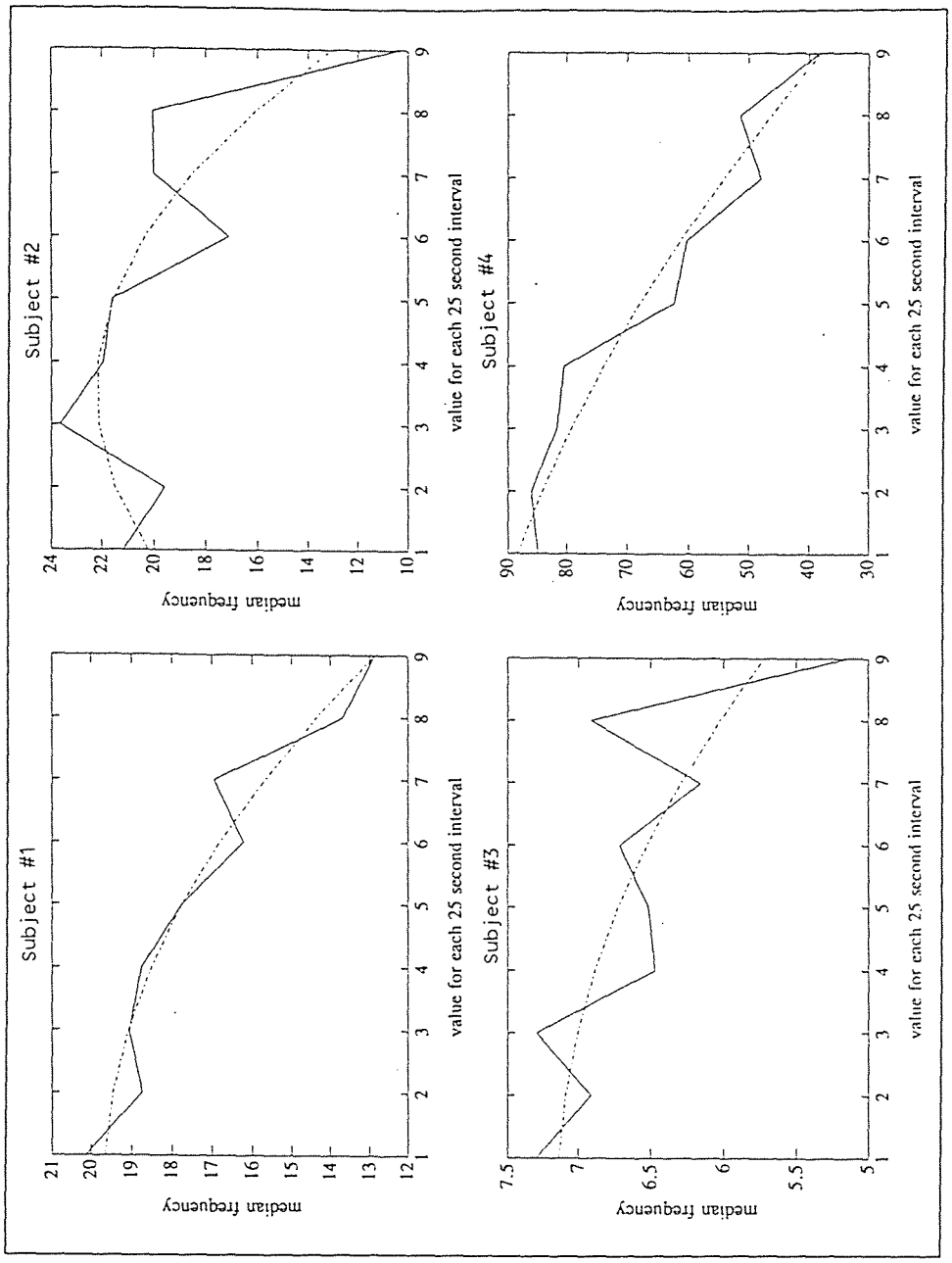

Figure 93 Changes in Median Frequency Over Time

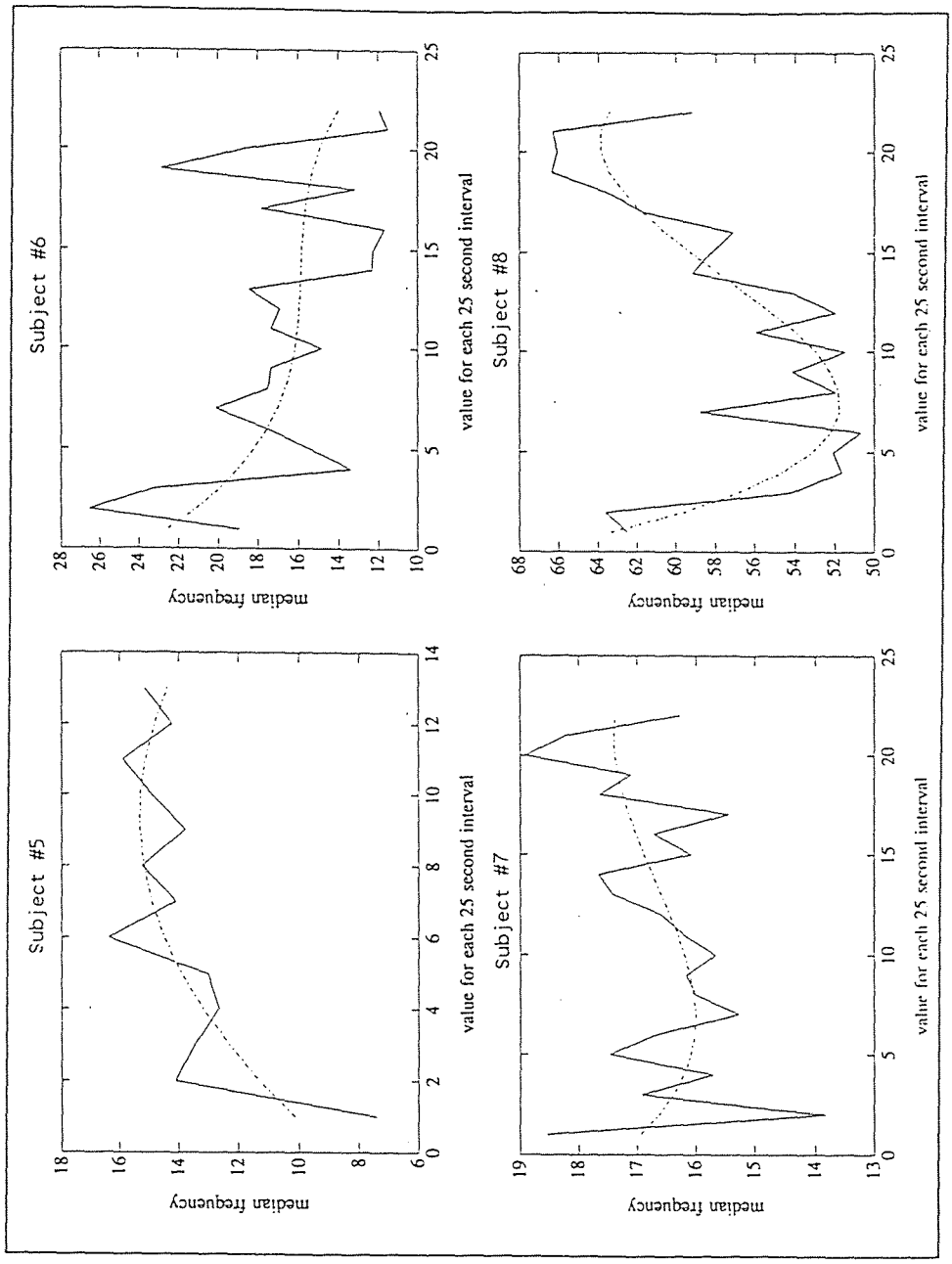

Figure 94 Changes in Median Frequency Over Time

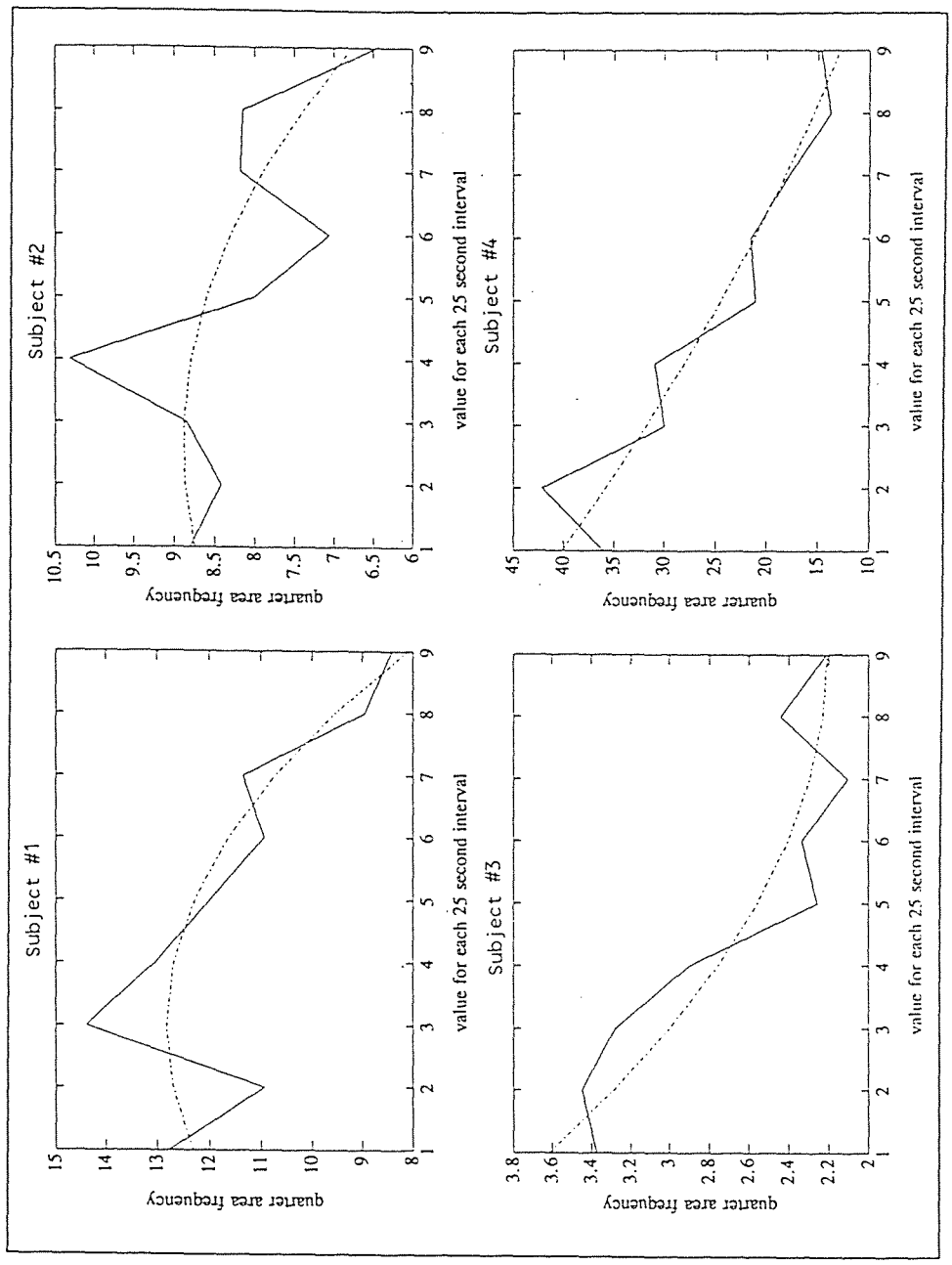

Figure 95 Changes in Quarter Area Frequency Over Time

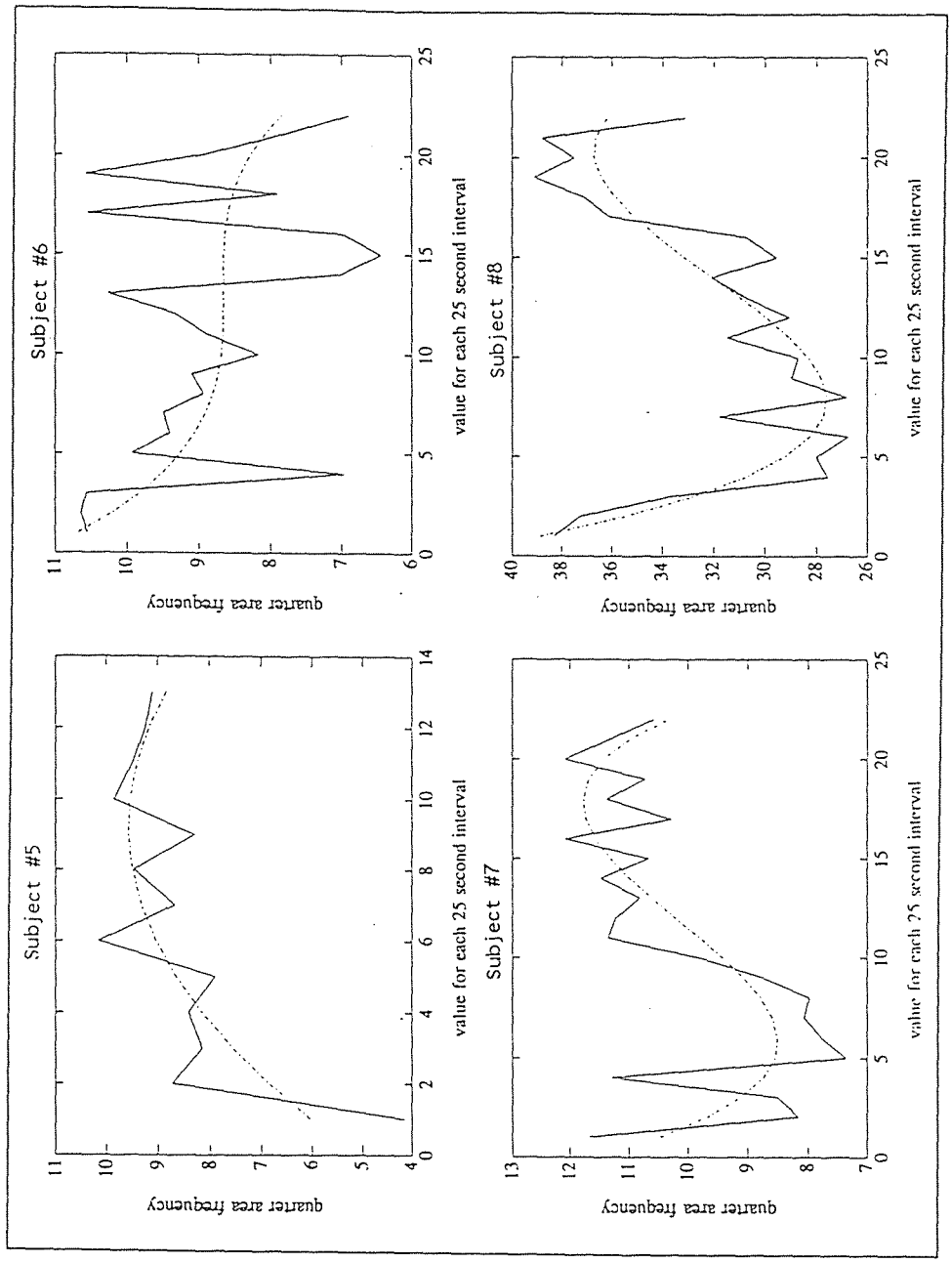

Figure 96 Changes in Quarter Area Frequency Over Time

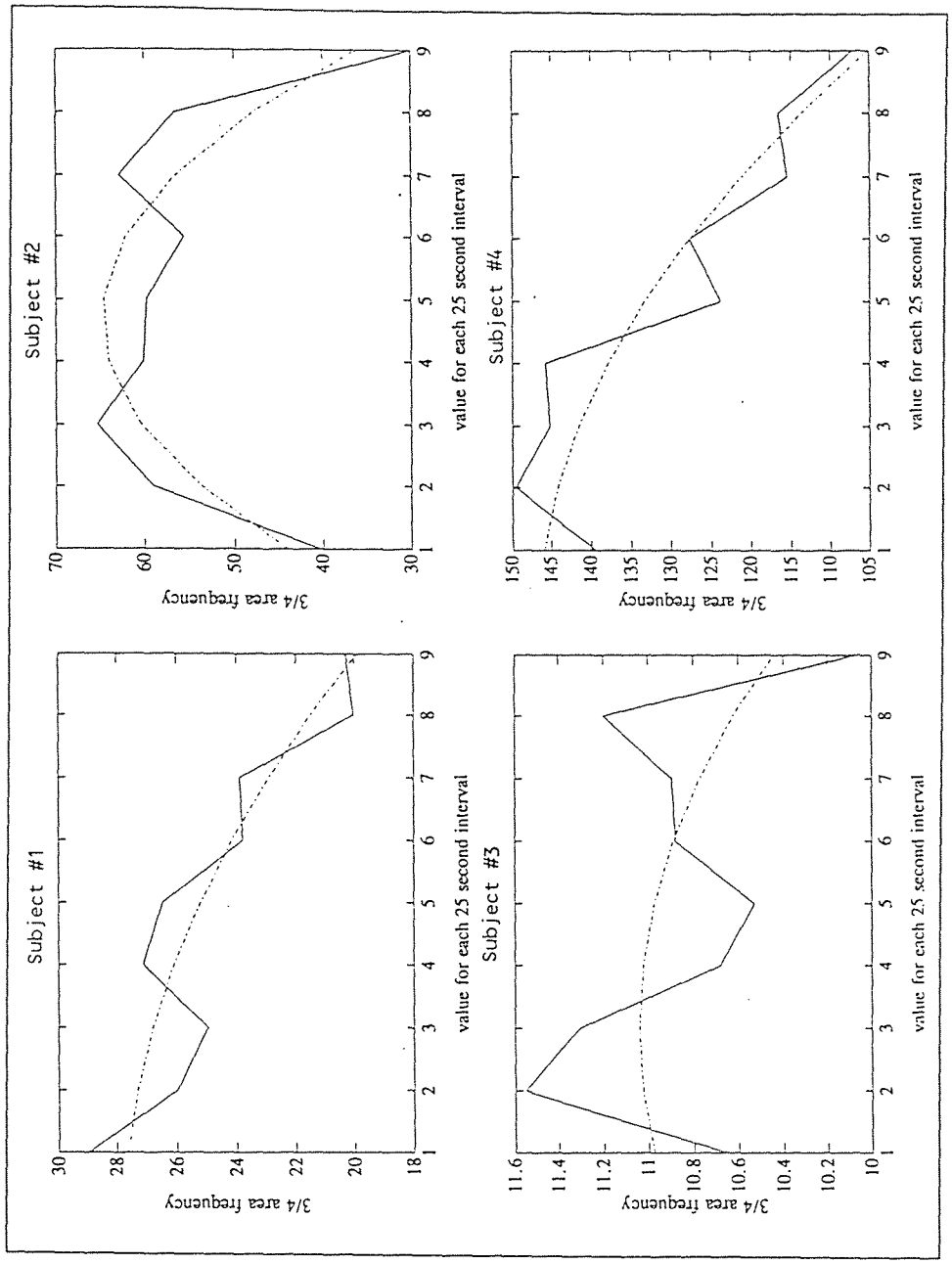

Figure 97 Changes in Three Quarter Area Frequency Over Time

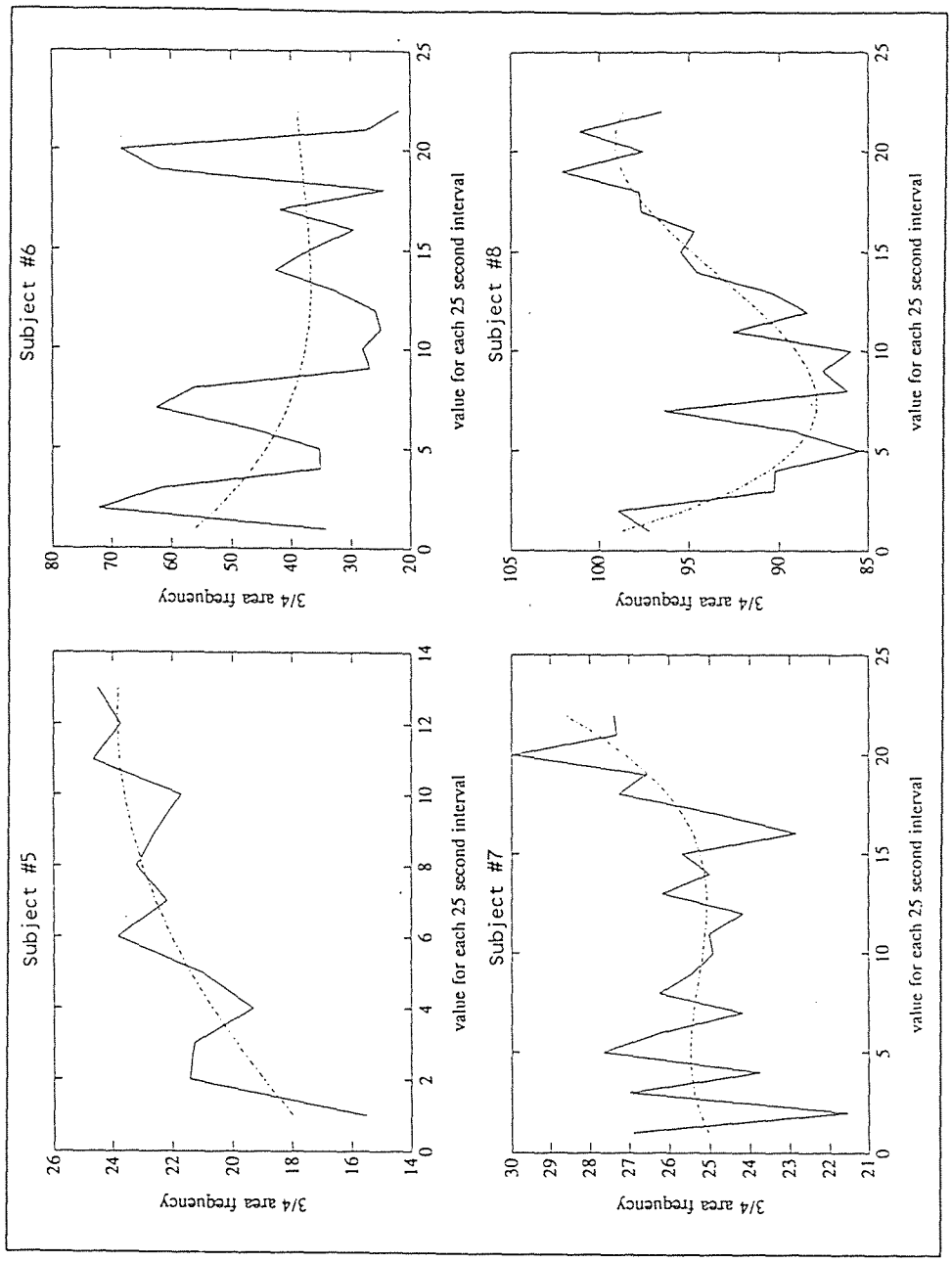

Figure 98 Changes in Three Quarter Area Frequency Over Time

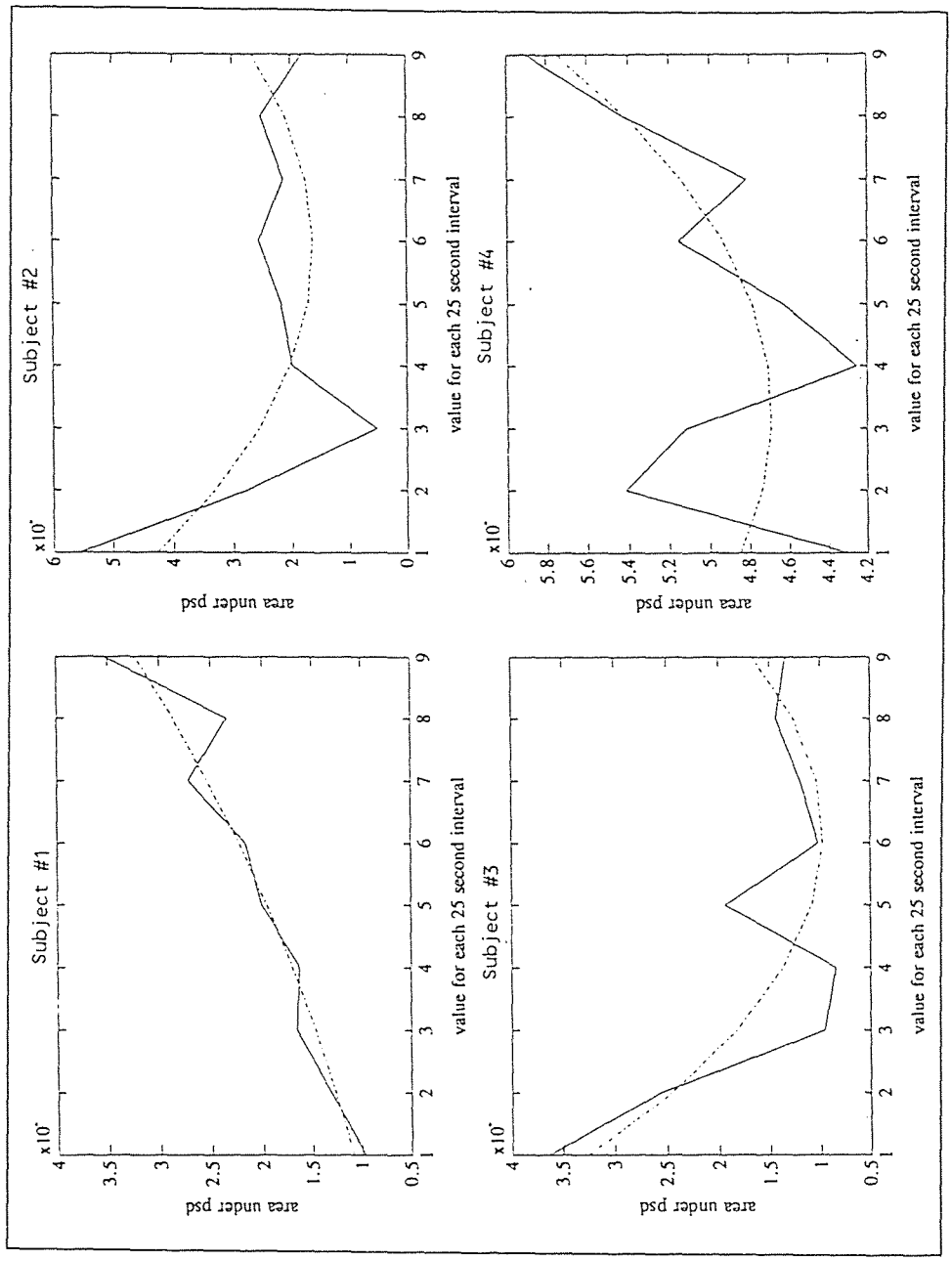

Figure 99 Changes in Area Under the Power Spectra (35 to 250 Hz) Over Time

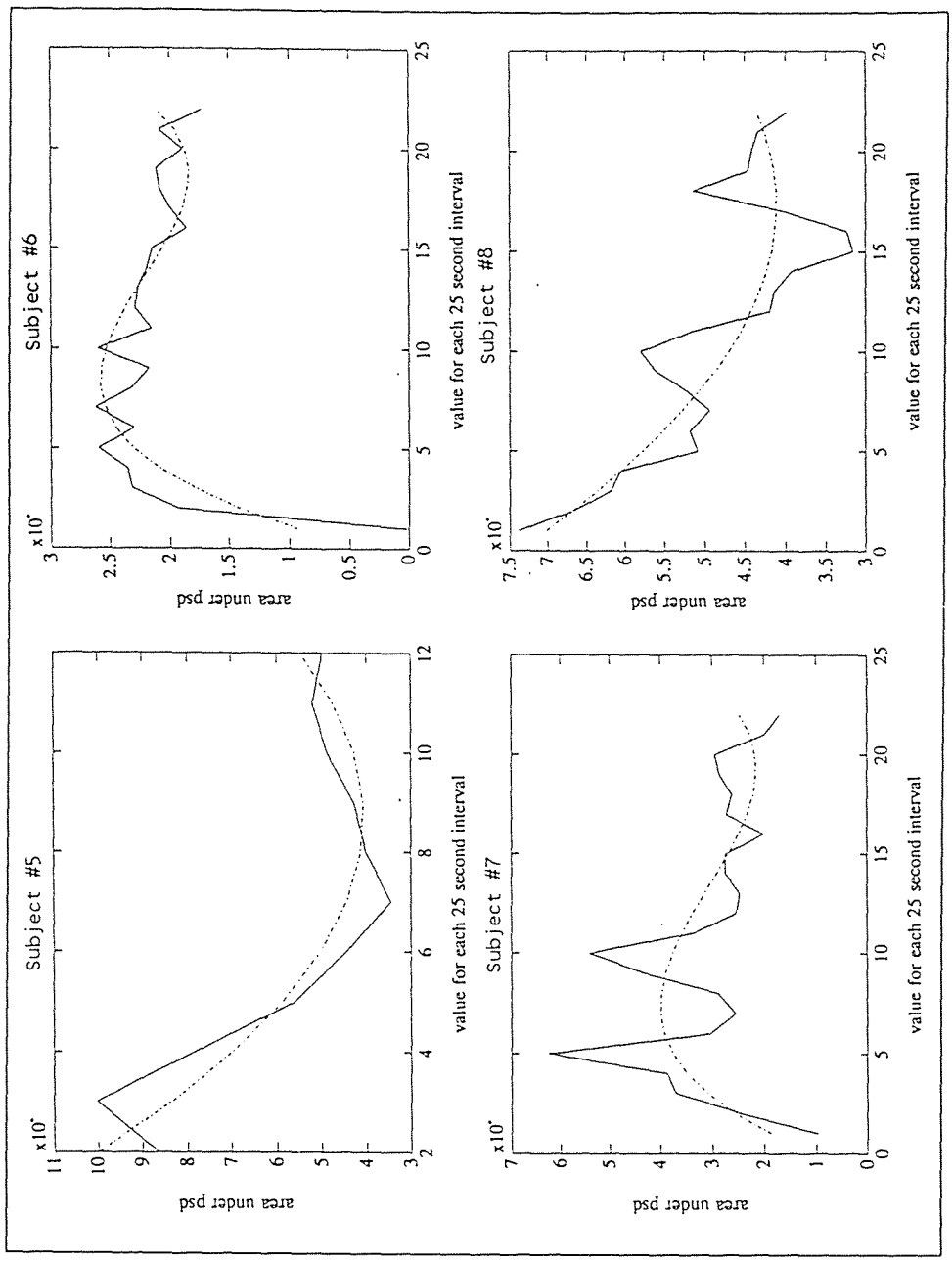

Figure 100 Changes in Area Under the Power Spectra (35 to 250 Hz) Over Time

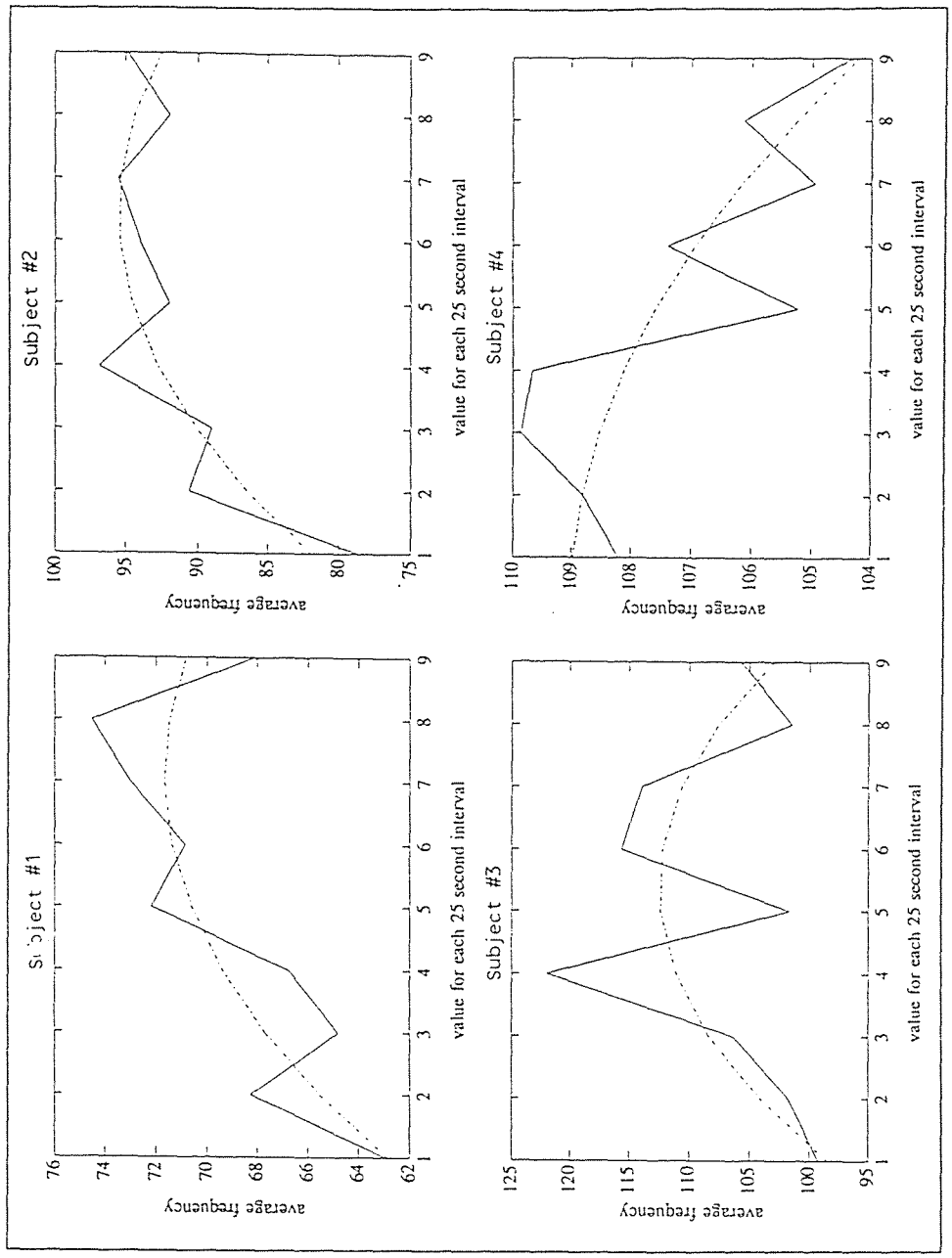

Figure 101 Changes in Average Frequency (35 to 250 Hz) Over Time

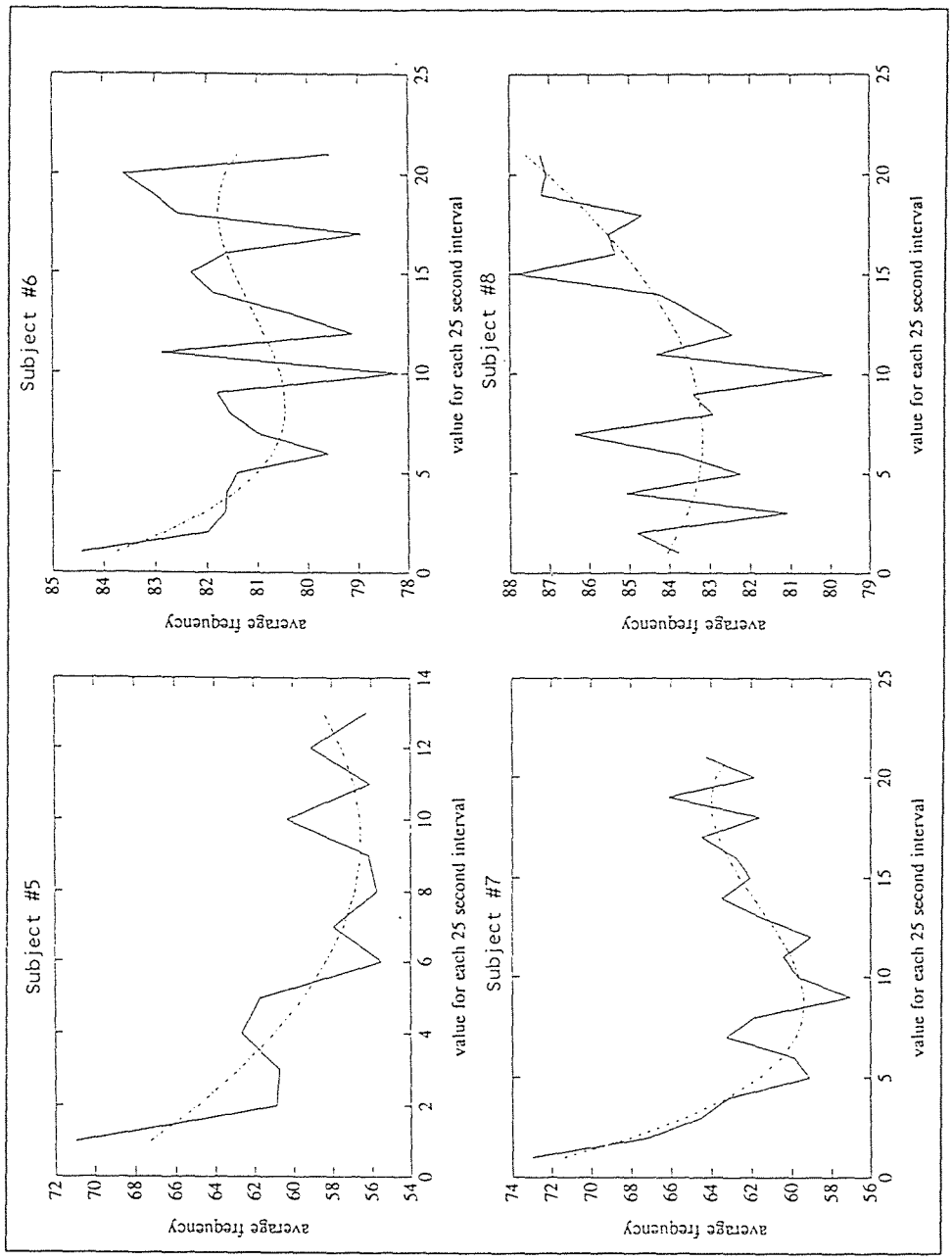

Figure 102 Changes in Average Frequency (35 to 250 Hz) Over Time

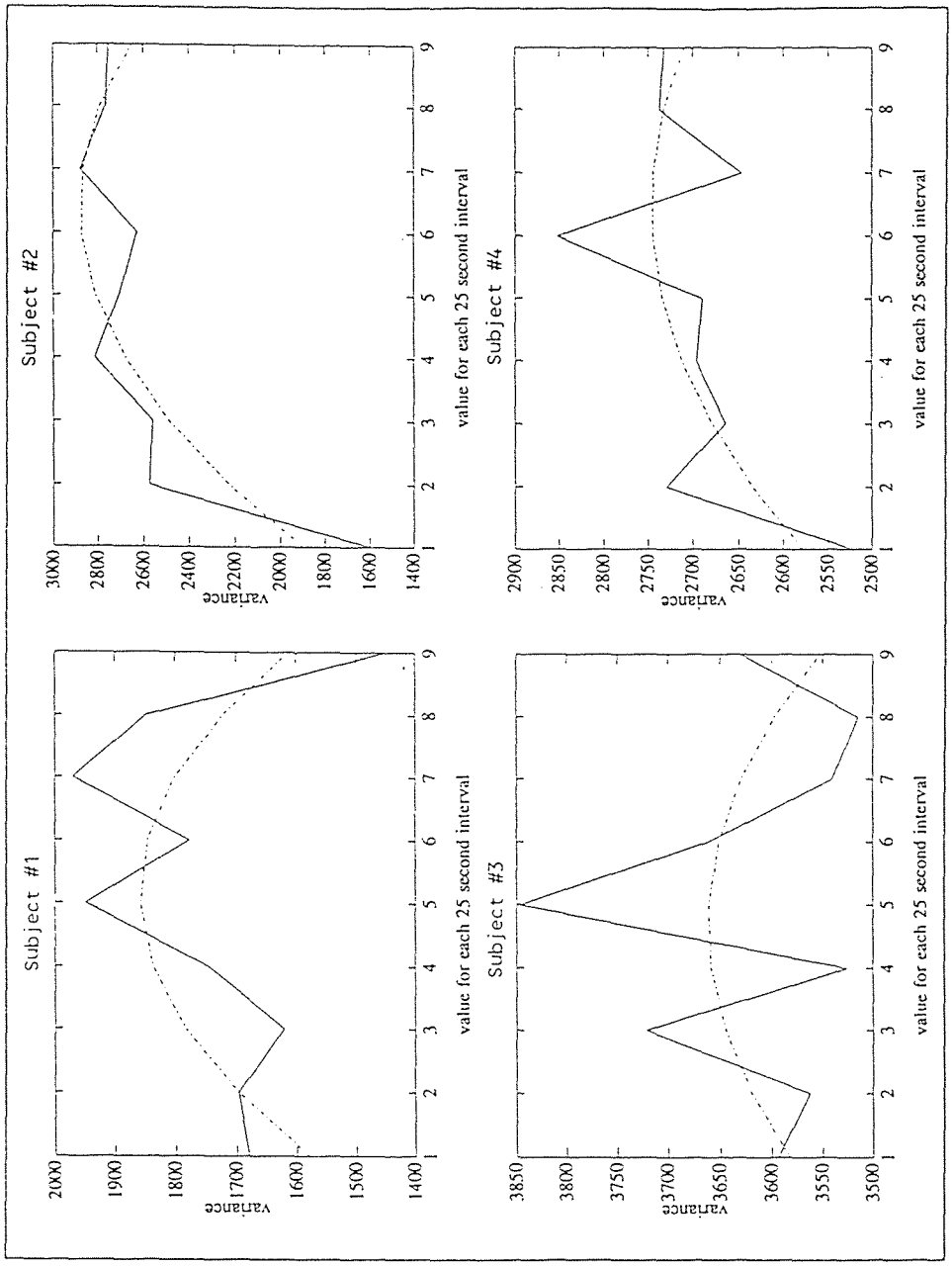

Figure 103 Changes in Variance (35 to 250 Hz) Over Time

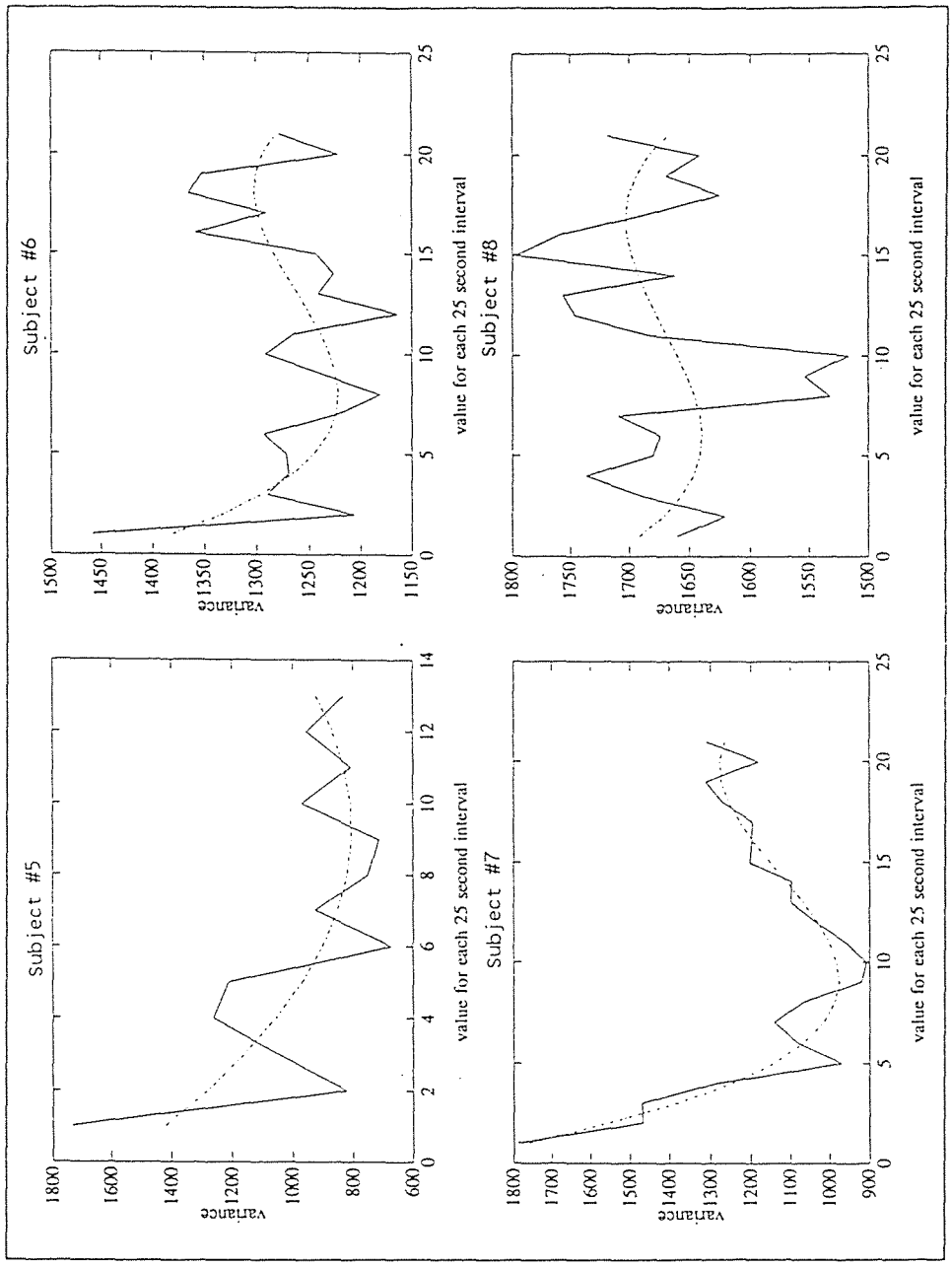

Figure 104 Changes in Variance (35 to 250 Hz) Over Time

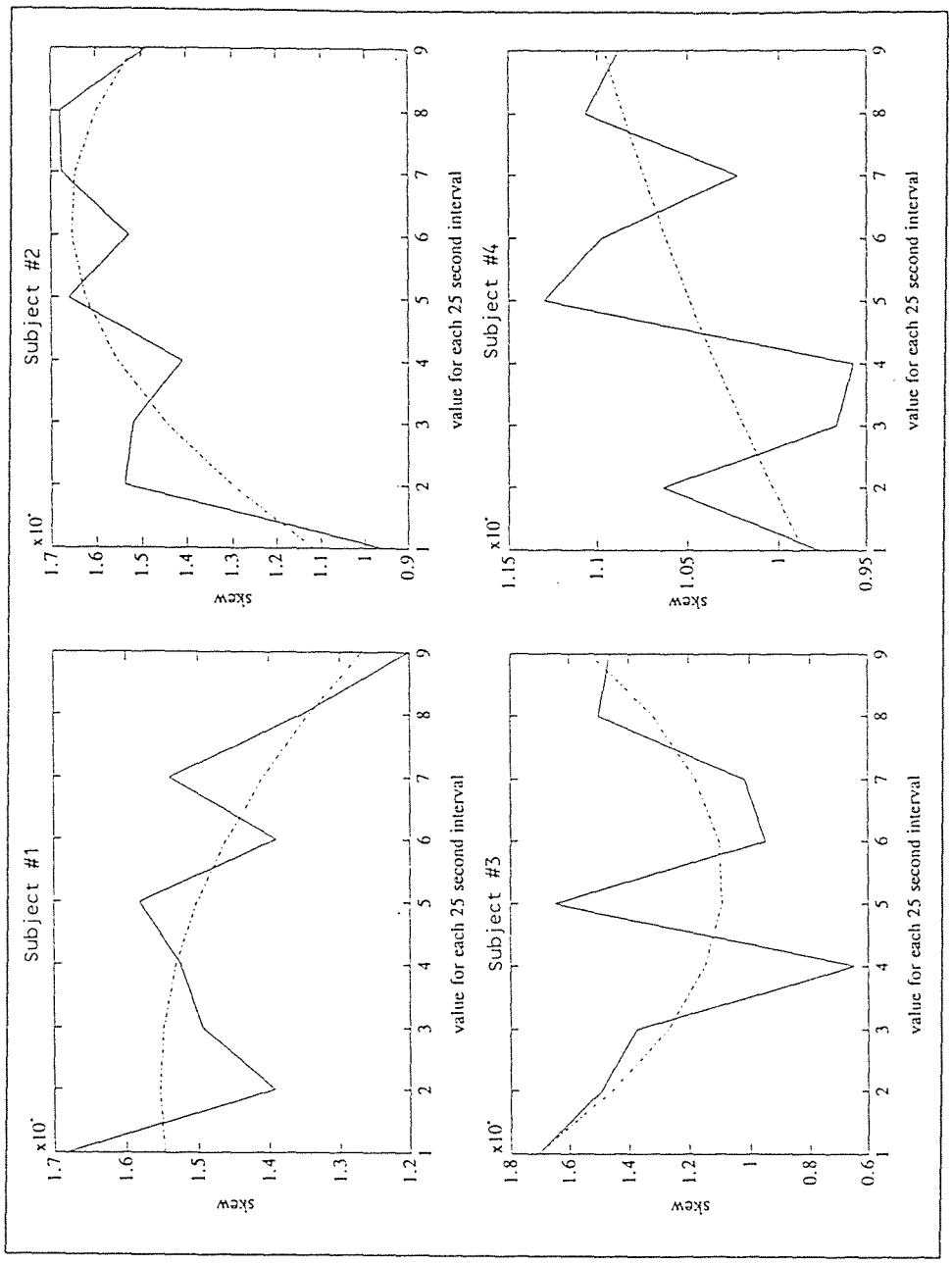

Figure 105 Changes in Skew (35 to 250 Hz) Over Time

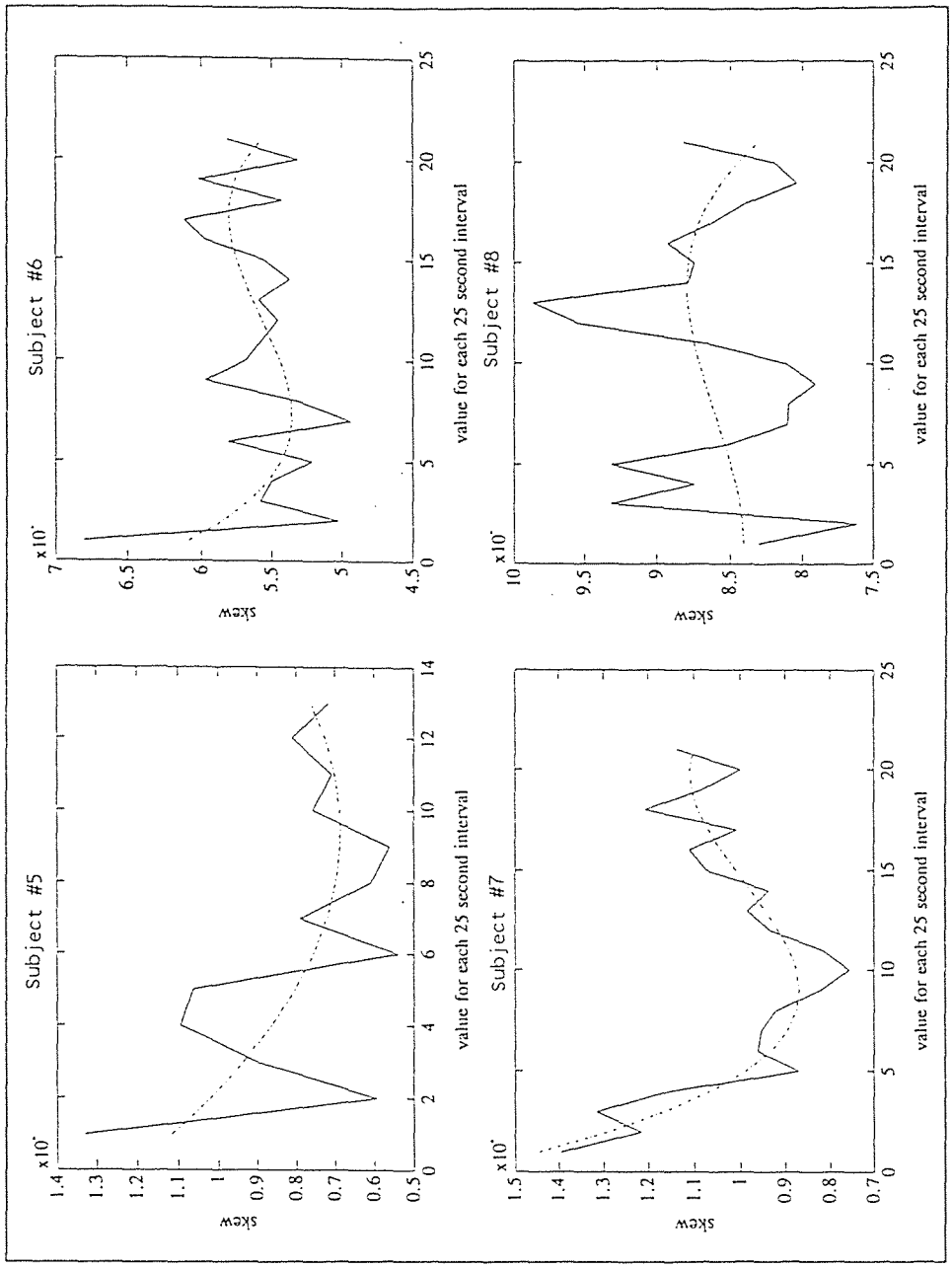

Figure 106 Changes in Skew (35 to 250 Hz) Over Time

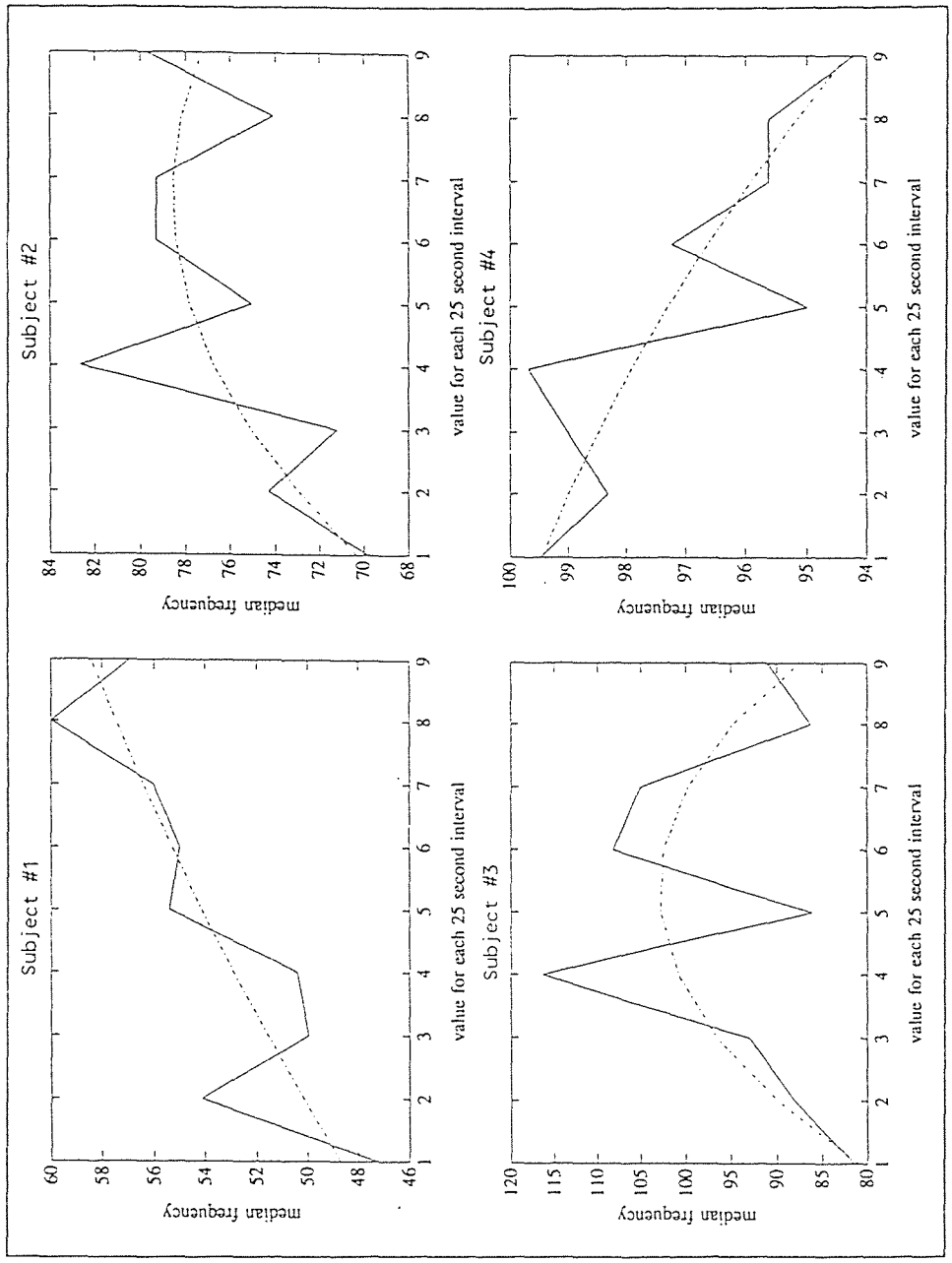

Figure 107 Changes in Median Frequency (35 to 250 Hz) Over Time

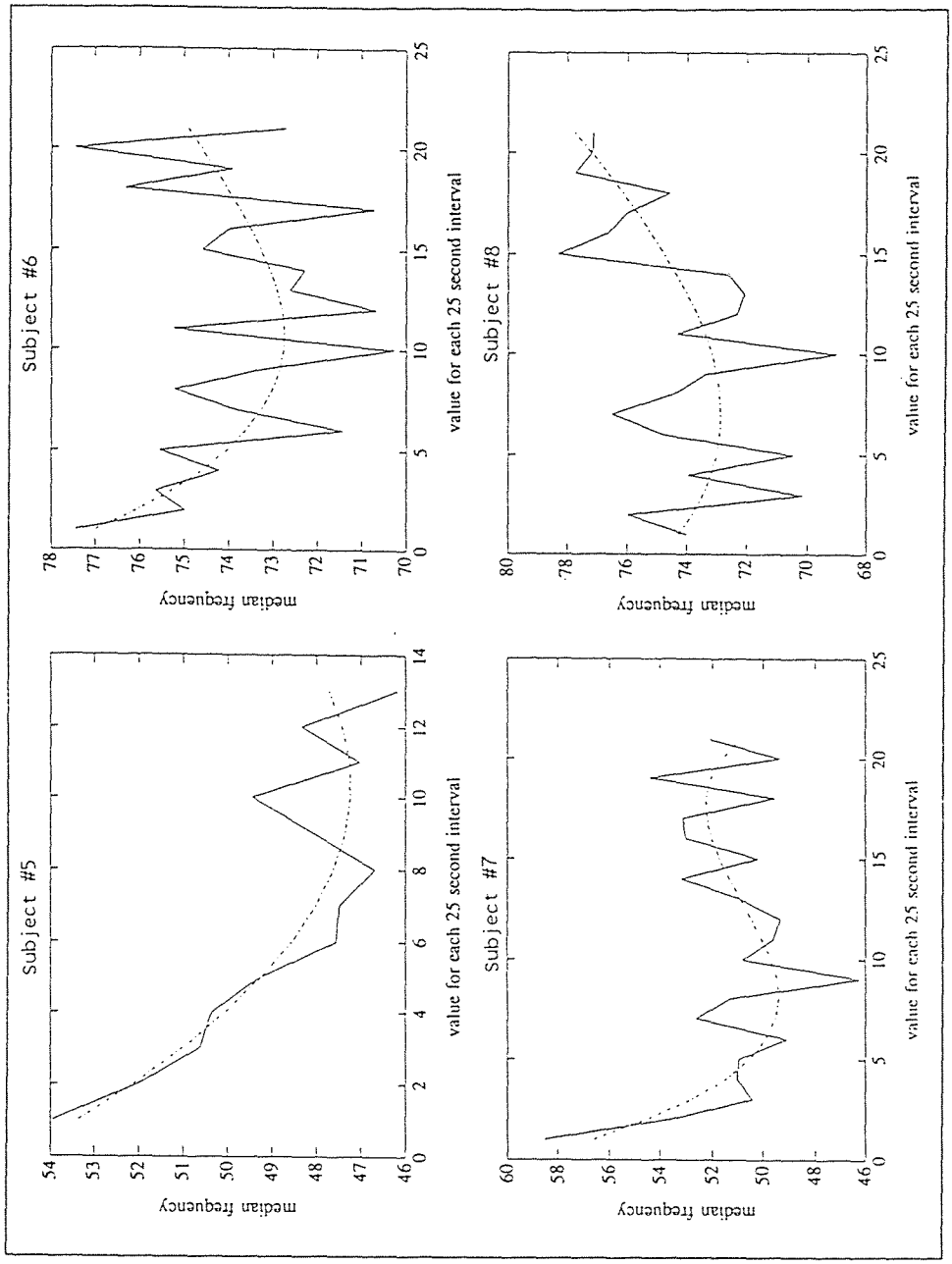

Figure 108 Changes in Median Frequency (35 to 250 Hz) Over Time

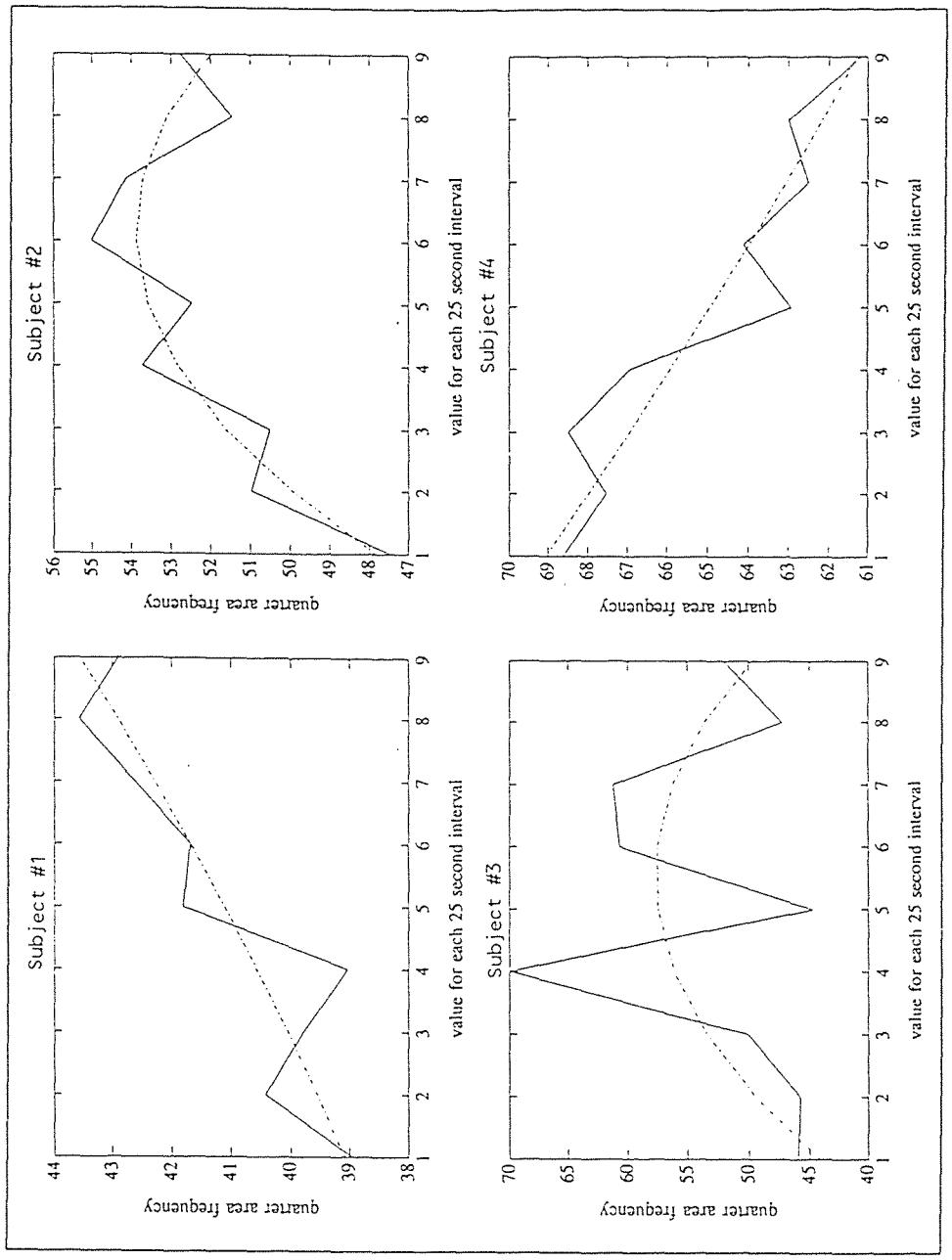

Figure 109 Changes in Quarter Area Frequency (35 to 250 Hz) Over Time

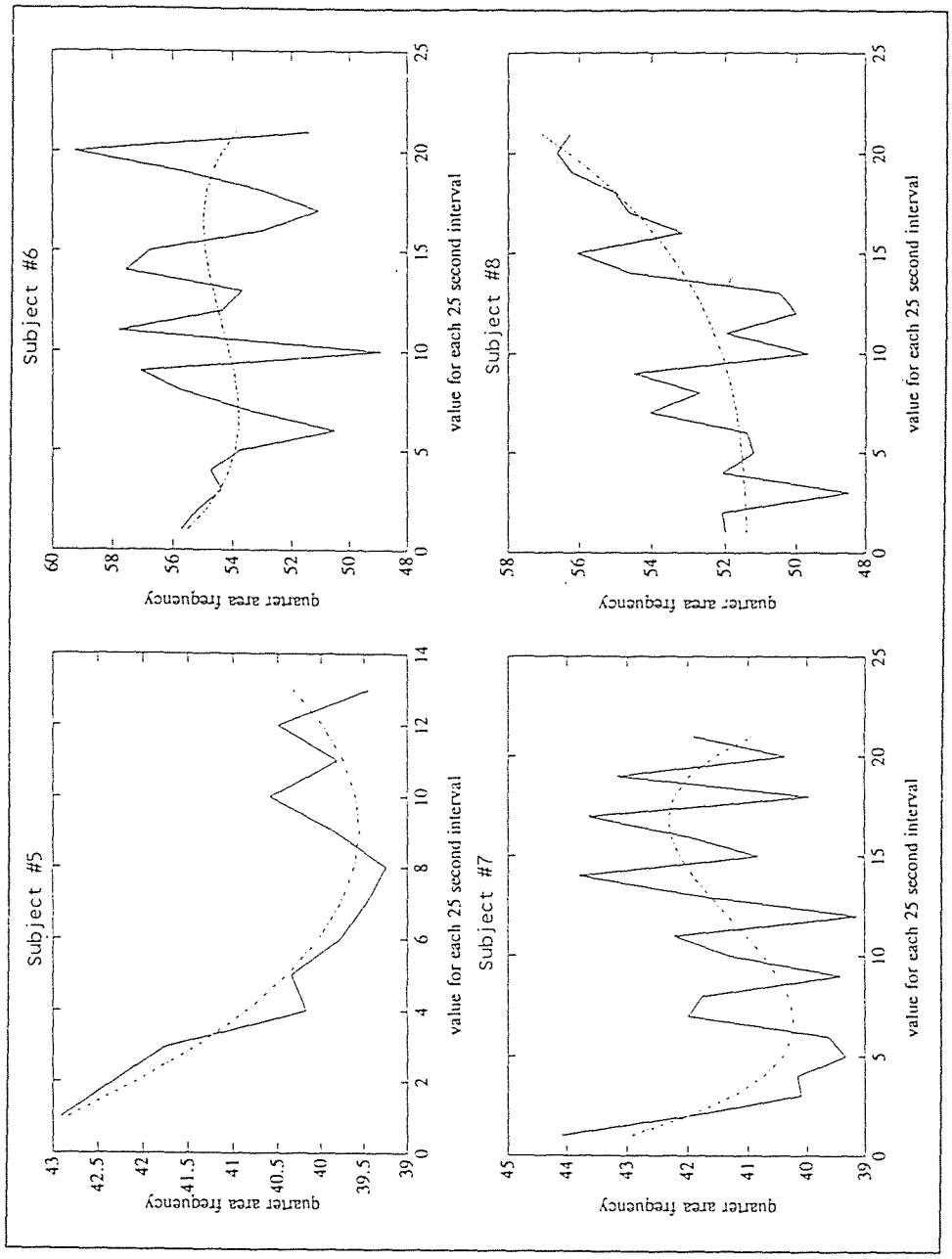

Figure 110 Changes in Quarter Area Frequency (35 to 250 Hz) Over Time

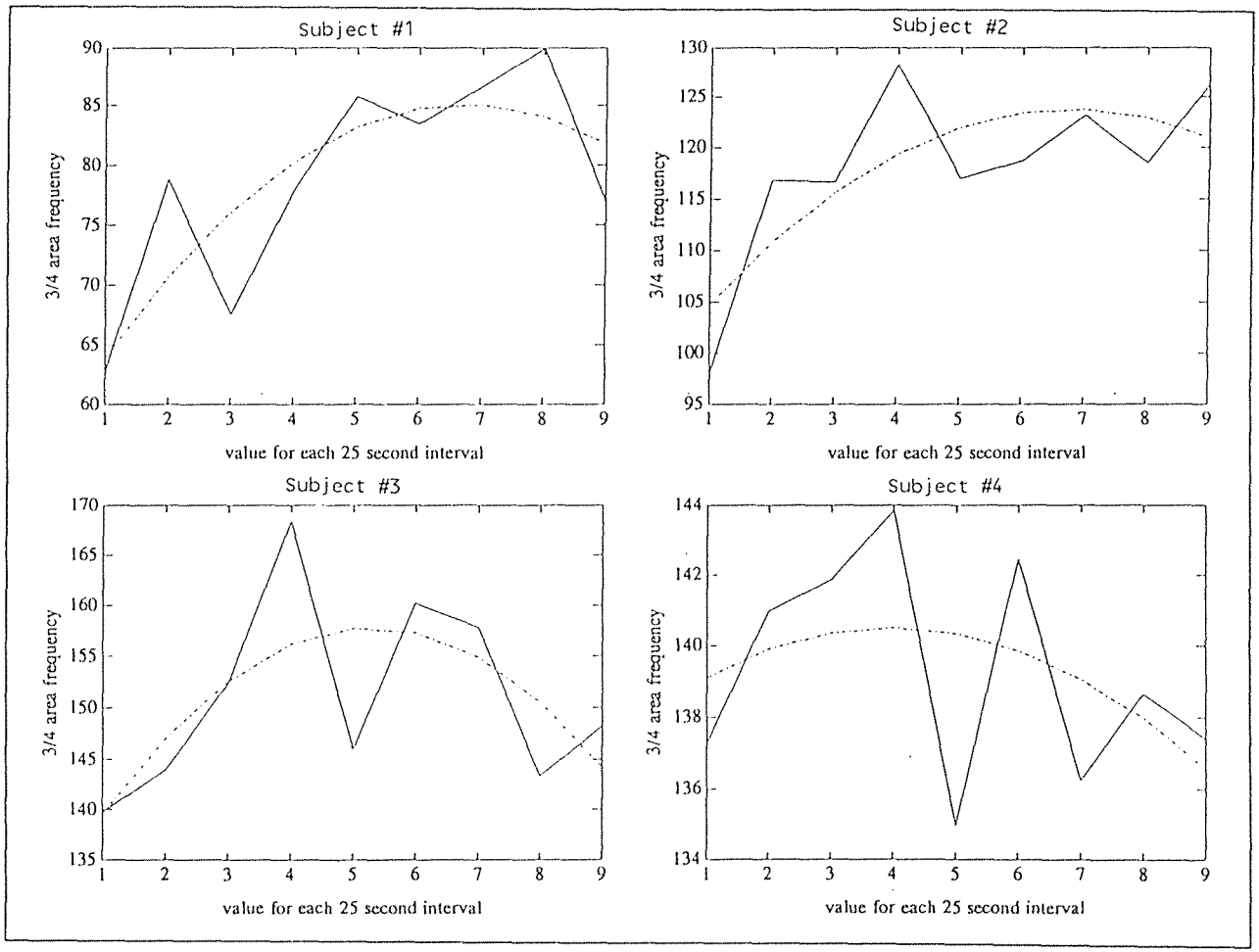

Figure 111 Changes in Three Quarter Area Frequency (35 to 250 Hz) Over Time

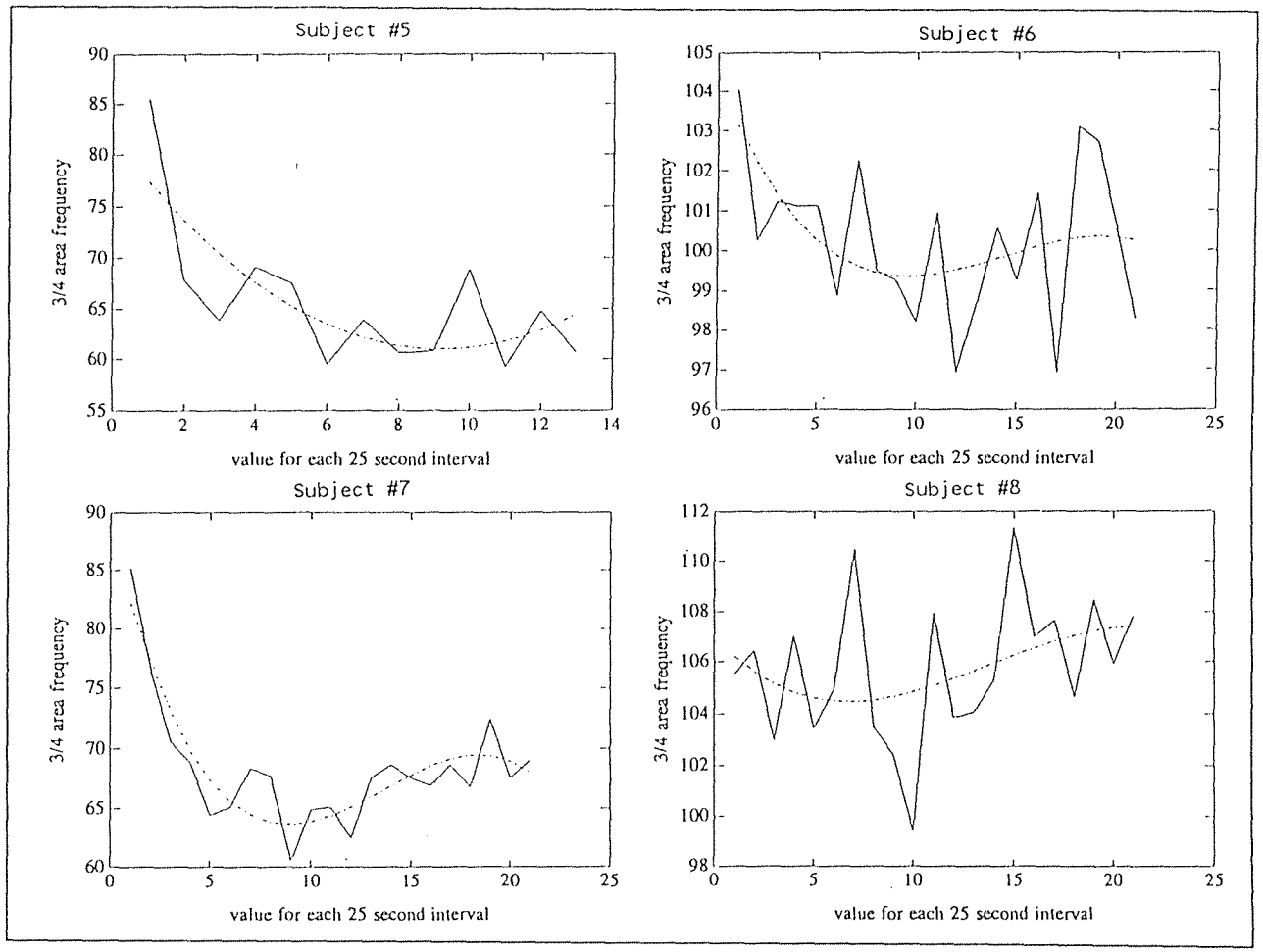

Figure 112 Changes in Three Quarter Area Frequency (35 to 250 Hz) Over Time

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