VIBRATION TRANSMISSION TO BICYCLE AND RIDER: A FIELD AND A LABORATORY STUDY

A THESIS SUBMITTED TO
THE GRADUATE SCHOOL OF SOCIAL SCIENCE
OF
MIDDLE EAST TECHNICAL UNIVERSITY

BY

PINAR ARPINAR-AVŞAR

IN PARTIAL FULFILLMENT OF THE REQUIREMENTS
FOR
THE DEGREE OF DOCTOR OF PHILOSOPHY
IN
THE DEPARTMENT OF PHYSICAL EDUCATION AND SPORT

AUGUST 2009

Approval of the Graduate School of Social Sciences.

Prof.Dr. Sencer Ayata
Director

I certify that this thesis satisfy all the requirements as a thesis for the degree of Doctor of Philosophy.

Assoc.Prof.Dr. M.Settar Koçak
Head of Department

This is to certify that we have read this thesis and that in our opinion it is fully adequate, in scope and quality, as thesis for the degree of Doctor of Philosophy.

Prof.Dr. Gülin Birlik
Co-Supervisor

Prof.Dr. Feza Korkusuz
Supervisor

Examining Committee Members

Prof. Dr. Gülin Birlik	(METU,ES)	____________________
Prof. Dr. Feza Korkusuz	(METU,PES)	____________________
Assist. Prof. Dr. Serdar Arıtan	(HU,SBT)	____________________
Assist. Prof. Dr. Sadettin Kirazcı	(METU,PES)	____________________
Dr. Önder Cem Sezgin	(METU,MC)	____________________

I hereby declare that all information in this document has been obtained and presented in accordance with academic rules and ethical conduct. I also declare that, as required by these rules and conduct, I have fully cited and referenced all material and results that are not original to this work.

Name, Surname: Pınar Arpınar-Avşar

Signature:

ABSTRACT

VIBRATION TRANSMISSION TO BICYCLE AND RIDER:
A FIELD AND A LABORATORY STUDY

Arpınar-Avsar, Pınar
Ph.D.,Department of Physical Education and Sport
Supervisor: Prof.Dr.Feza Korkusuz
Co-Supervisor: Prof.Dr. Gülin Birlik

August 2009, 166 pages

The purpose of this study is to investigate the frequency and amplitude characteristics of vibration exposed to the bicycle and the rider as well as the features of the vibration transmission to the riders' body. The findings showed that, vibration transmission to the bicycle and the rider is effective in x-and z axis. As a result of increased roughness, effective frequency range shifted to lower frequencies between 15-30Hz at both saddle and stem. The severity of transmitted vibration to the bicycle was found to be considerably higher in road bike trials (up to 25 ms^{-2}). The frequency range of the vibration exposure of the body parts were in between 0-30Hz and independent of the level of vibration transmission the peak values were within the range of 3-12Hz. As the acceleration magnitude increased depending on road roughness, normalized rms EMG values also increased up to 50% in forearm extensor muscles during MTB trials and in the flexor muscles during road bike trials. With respect to no vibration trials, rms EMG values increased in order to maintain the same force output. Vibration transmission to the body tends to be amplified with increased force production. Transmission values were found to be higher at lower frequencies. Since the magnitude and frequency of vibration is known to have some adverse effects on body functions such as impaired breathing pattern and increased muscle tone, vibration transmitted to the body might be considered to influence the riding comfort, controllability and overall health of the cyclist.

Key Words: Vibration Transmission, Acceleration, EMG, Bicycle, Rider

ÖZ

BİSİKLET VE SÜRÜCÜ ÜZERİNE TİTREŞİM İLETİMİ:
ALAN VE LABORATUVAR ÇALIŞMASI

Arpınar-Avşar, Pınar
Doktora,Beden Eğitimi ve Spor Bölümü
Danışman: Prof.Dr. Feza Korkusuz
Yardımcı Danışman: Prof.Dr. Gülin Birlik

Ağustos 2009, 166 sayfa

Araştırmanın amacı, bisiklet ve sürücünün maruz kaldığı titreşimin frekans ve büyüklüğü ile vücuda iletilen titreşimin iletim özelliklerinin araştırılmasıdır. Araştırmanın bulguları, bisiklet ve sürücüye titreşim iletiminin x ve z eksenlerinde etkin olduğunu göstermiştir. Yol bozukluğunun artmasıyla, sele ve gidon üzerinde ölçülen titreşimin etkin olduğu frekans aralığı yol ve dağ bisikleti için 15-30 Hz gibi daha düşük frekaslara gerilemiştir. Bisiklet üzerine iletilen titreşim düzeyi yol bisikletinde çok daha yüksek değerlere ulaşmıştır (25 $m.s^{-2}$ rms'e kadar). Farklı vücut noktaları üzerinde ölçülen iletim değerlerinin 0-30 Hz arasında etkin olduğu ve iletilen titreşim düzeyine bağlı olmaksızın 3-12 Hz arasında maksimum değerlere ulaştığı gözlenmiştir. Yol bozukluğuna bağlı olarak ivme değerleri artarken, önkola ait rmsEMG değerleri MTB ölçümlerinde ekstensör kaslarda, yol bisikletinde ise fleksör kaslarda %50 düzeyinde bir artış göstermiştir. Titreşim uyaranının olmadığı ölçümler ile karşılaştırıldığında, titreşim uyarı sı altında aynı kuvvet çıktısını sürdürebilmek için rms EMG değerleri artmıştır.Vücuda iletilen titreşim artan kuvvet üretimi ile birlikte artma eğilimindedir. İletim değerleri alçak frekaslarda yüksek değerlere ulaşmıştır. Titreşim büyüklük ve frekansının bozulan solunum paterni, artan kas tonusu gibi

vücut fonksiyonları üzerine bilinen bazı olumsuz etkileri sebebiyle, bisiklet ile sürüş esnasında vücuda iletilen titreşimin sürüş konforunu, bisikletin kontrolünü ve bisikletçinin genel olarak sağlığını etkileyebileceği düşünülmelidir.

Anahtar Kelimeler: Titreşim İletimi, İvme, EMG, Bisiklet, Bisikletçi

ACKNOWLEDGEMENTS

I would like to express my sincere gratitude to my advisors Prof.Dr.Feza Korkusuz and Prof.Dr.Gülin Birlik for their guidance, and support throughout this study. I am grateful to Professor Birlik not only for critically evaluating this dissertation work, but also for allowing me to work in her laboratory.

I would like to thank TÜBİTAK, The Scientific and Technical Research Council of Turkey, for providing financial support to this study (Project number: 128 MAG 122).

I also want to thank Dr.Önder Cem Sezgin for his support during the challenging field measurements. I am grateful to Dr.Abdullah Ruhi Soylu for providing me valuable insights into signal acquisition and processing during my doctoral studies.

I would like to thank my past and present colleagues Leyla Saraç Yılmaz, Serap Sevimli and Deniz Hünük for their help and the constant moral support. Also, I would like to acknowledge the support and patience of all of the participants.

Finally, I am greatly indebted to my parents and my husband for their constant encouragement and support.

ACKNOWLEDGEMENTS

I would like to express my sincere gratitude to my advisors Prof.Dr.Feza Korkusuz and Prof.Dr.Gülin Birlik for their guidance, and support throughout this study. I am grateful to Professor Birlik not only for critically evaluating this dissertation work, but also for allowing me to work in her laboratory.

I would like to thank TÜBİTAK, The Scientific and Technical Research Council of Turkey, for providing financial support to this study (Project number:107M223).

I also want to thank Dr.Önder Cem Sezgin for his support during the challenging field measurements. I am grateful to Dr.Abdullah Ruhi Soylu for providing me valuable insights into signal acquisition and processing during my doctoral studies.

I also like to thank my past and present colleagues Leyla Saraç Yılmaz, Serap Sevimli and Deniz Hünük for their help and the constant moral support. I would like to acknowledge the support and patience of all of the participants.

Finally, I am greatly indebted to my parents and my husband, Çağatay Avşar, for their constant encouragement and support.

TABLE OF CONTENTS

LIST OF FIGURES

FIGURES

LIST OF TABLES

TABLES

DEFINITIONS OF TERMS

Acceleration: time rate of change of velocity which is a vector quantity. Acceleration is expressed in ms^{-2}.

Acceleration level: the ratio of a measured acceleration level to reference acceleration level.

Accelerometer: a transducer which produces an output (usually electrical), which is proportional to the acceleration in some specific axis, along a specified direction.

Acceleration amplitude: the maximal value of a sinusoidal acceleration.

Axis: one of the three mutually orthogonal straight lines passing through the origin of a Cartesian co-ordinate system (i.e., translational axis, x-axis, y-axis, z-axis).

Band pass filter: a filter which removes unwanted low- and high- frequency oscillations.

Basicentric co-ordinate system: co-ordinate system suggested by ISO 2631-1. Origin is taken at a point on the interface with the human body or on a contact surface from which the vibration is considered to enter the human body.

Bio-dynamics: science dealing with the changes, in the physical, biological and mechanical properties or responses of the human body, its tissues, organs, parts and systems, with respect to time.

Carpal tunnel syndrome: Compression of the median nerve as it passes through the carpal tunnel formed by the carpal bones on the bottom of the wrist and the transverse carpal ligament across the top of the wrist.

Electrodynamic vibrator: a vibration generator which derives its vibratory force from the interaction of a constant magnetic field with a coil of wire.

Electromyography (EMG): a technique of recording the activation signal of muscles

Extensor: is a muscle that straighten a limb with increasing joint angle

Feedback: the return of a portion of the output of any process or system to the input

Flexor: is a muscle that tends to bend a limb by muscular contraction

Fourier spectrum: Frequency spectrum of the motion of a vehicle or a human body or its parts.

Fourier transform: A mathematical operation for decomposing a non-periodic function of time into its frequency components

Frequency: is the number of complete cycles per second. Frequency is expressed in Hertz (Hz).

Frequency weightings: A frequency varying curve of accelerations suggested by ISO 2631-1 to be applied to a measured response acceleration curve. Frequency weightings reflect the human sensitivity to vibration.

Hand-arm-system: the human forelimb.

Hand-transmitted vibration: vibration that enters the body through the hands or fingers.

Isometric contraction: a muscular contraction in which the tension is the same throughout the movement.

Random vibration: is a non-deterministic excitation.

Resonance: Resonance of the human body system occurs when any change, however small, in the frequency of the excitation causes a decrease in the response of the vibration exposed human body.

Resonance frequency: a frequency at which resonance of the human body occurs.

Roughness: a term which indicates the presence of irregularities existent on the surface

Spectrum: description of acceleration as a function of frequency

Standards: documented agreements containing technical specifications or other suggested criteria to be used consistently as rules, guidelines, or definitions of the characteristics to ensure that, materials, products are manufactured to fit for the purposes and measurements are done accordingly.

Transmissibility ratio: the non dimensional ratio of accelerations at a location on the human body to the accelerations on a contact surface with the body.

Vibration: Fluctuation of a body about an equilibrium position

Vibration severity: generic term designating any hazardous effect to the health, comfort and perception of a human body when exposed to vibration.

Weighted acceleration: an acceleration waveform after it has been frequency-weighted using the weightings given in ISO 2631-1.

Whole-body-vibration: mechanical vibration when transmitted to the body affects it as a whole.

CHAPTER I

1. INTRODUCTION

1.1. Rationale of the Study

Human beings are exposed to vibration in many daily activities such as riding in vehicles or working with vibrating machines. Similarly, people are also exposed to vibration through various types of sport activities such as snow skiing, water skiing, cycling, motor sports, tennis and golf. Therefore, the topic of vibration has been studied in the fields of Ergonomics, Sports Engineering, Occupational Health and Medicine by focusing on the adverse effects on the human body. The injury potential and perceived discomfort are the common interests of studies on vibration in sport with respect to level of vibration transmitted to the athlete's body. For example, transmission of vibration to the body, particularly to the hand and arm, has been investigated in tennis (Hennig et al, 1992; Stroede et al, 1999) and golf (Robert et al, 2005). In addition, this topic has also attracted interest in its beneficial effects on body as a training tool, as well as a massage tool, in exercise science and in rehabilitation (Zatsiorsky and Kraemer, 2006; Cardinale and Wakeling, 2005).

The effects of vibration on the body in both seated and standing positions have been widely reported by many researches. During travelling with motor vehicles, it is well known that increased magnitude or duration of the vibration exposure may result in undesired changes in different physiological systems of the human body. In contrast, there is very limited knowledge of vibration transmission to the human body while riding on a bicycle. Lewis and Paddan (1990) investigated vibration transmission to the cyclist's head and concluded that vibration transmission to a cyclist's body is dependent on the posture maintained by the cyclist. Even if the both postures studied in the study resulted in almost the same level of vibration transmission, different frequency response was observed for each posture. The transmission path between the head and the source of the vibration (i.e. saddle or handlebar), was also reported as not having a significant effect on the level of vibration transmitted to the body.

On the other hand, Torbic et al (2003) have investigated the subjective comfort level for various body parts of the cyclists who are exposed to vibration on different bicycles. In their study, as a result of the vibration exposure, the body parts that are likely to induce a feeling of discomfort were listed as wrist, elbows, shoulder, neck, seat area, knees, ankles and feet. Although our knowledge on vibration transmitted to the riders' body is limited to the head vibrations (Lewis and Paddan, 1990), subjective ratings of discomfort and the anecdotal evidences provided by the cyclists suggest that the head is not the only body part of a cyclist affected by the vibration exposure. Therefore, the level of vibration transmission to the different parts of the bicycle-rider system has been examined in the present study. When cyclists are riding on uneven surfaces that result in continuous vibration exposure and repeated shocks, it can be observed that they stop pedalling and stand up from the saddle when it reaches intolerable levels (Burke, 1996). However, it is not usual for them to remove their hands from the handlebar under the vibration exposure on such a high level. Therefore, in accordance with the research questions of the present study, the body parts were selected as cyclist's head, shoulder and elbow by considering their role in controlling handlebar movements.

While riding a bicycle, the muscles of trunk, the neck, lower and upper extremities are actively involved in motion while applying force to the pedals and maintaining the body in a static position. Due to the unbalanced nature of bicycle and vibration exposure, the arm muscles have an important role in controlling handlebar movements. While the cyclist generates propulsive forces on pedals and keeps the posture, arm muscles actively participate in maintaining balance on the bicycle by contracting isometrically. However, it is known that while being exposed to vibration, the response of the system may affect the function of the tissues involved in force production. Therefore, bicycle-rider hand-arm-vibration transmission has been decided to be the core of this study considering the importance of the maintenance of controlled muscle contraction during this activity, and it has been hypothesized that the magnitude and input spectra of the vibration exposure associated with road surface conditions would be the factors that affect controlled force exertion of the arm muscles.

Being exposed to prolonged and excessive vibration or repeated mechanical shocks might give rise to various health related problems. To illustrate, it has been reported that the adverse affects of vibration transmission to the human hand-arm system will cause functional disorders that can be observed in peripheral disturbance of blood circulation, peripheral nerve conduction and musculoskeletal system, and therefore, can be the cause of the impairment in the execution of motor skills performed by the hand (Goglia et al, 2006; Cui, 2001; ISO,5349, 2001; McDowell, 2006; Starck et al, 1990; Kihlberg and Hagberg, 1997; Griffin and Bovenzi, 2001).

Furthermore, the amount of vibration transmission to the hand-arm system has been shown to be related with the hand coupling forces measured at the contact with the source of vibration, where coupling force was defined as the sum of grip and push forces (Radwin et al, 1987; Riedel, 1995; Kaulbars, 1996). While riding a bicycle, some of the body weight is transferred to the handle through the arms while coupling forces are also applied by the hands. On the other hand, hand transmitted vibration exposure together with repetitive shocks and prolonged pressure on the median and ulnar nerves applied over years are known to be the main cause of peripheral nerve damage occurring at the hand and wrist (Capitani and Beer, 2002, Stewart, 1993). This neurological disorder, known as Cyclist's Palsy, is postulated to occur from high-frequency repetitive compression of the deep motor branch at the hand in prolonged biking or from single, short exposition and can appear in mountain biking (Capitani and Beer, 2002; Akuthota et al, 2005). Although the mechanisms of the hand-arm vibration syndrome (HAV) have not been exactly identified, prolonged contact of the hand with the vibrating surface and hand transmitted vibration might result in vibration trauma in this region when it is combined with forced and repetitive hand movements, similar to that in bicycle riding (Cannon et al, 1981; Silverstein et al, 1987).

It has been suggested that it is important to quantify mechanical effects of vibration in understanding the relationship between the mechanical inputs of hand transmitted vibration and the syndrome (Dong, 2006).

Bio dynamics of the hand-arm system is among the leading topics occupying researchers in order to establish the foundation for understanding hand transmitted vibration and its effects on health. Methods for evaluating hand-arm vibration and dose-response relationship have been set by the International Standard (ISO, 5349-1 and -2, 2001). According to relevant knowledge, the parameters affecting the degree of biological effect of hand transmitted vibration are shown to be related to source, direction, frequency, amplitude and duration of the vibration and also the position of the hand and the body.

It has been reported that neurological disorders induced by bicycle riding might be triggered by the differences in hand position and the increased amount of body weight transferred to the handlebar through the hand-arm system depending on sitting posture and slope of the road (Capitani and Beer, 2002). Researches have also indicated that in addition to evaluation of vibration characteristics, measurements should also include the evaluation of the forces applied by the hand in respect to anatomical position of the hand (McDowell, 2006). However, there is a lack of knowledge on forces applied by the hand while vibration is transmitted to the hand-arm region during bicycle riding.

1.2. Research Questions

- What are the magnitude and the frequency range of the transmitted vibration to the bicycle-rider system?

- And are these values influenced by different road surfaces and bicycle types?

- Are the vibration transmission values for different body postures influenced by vibration characteristics?

- Does the vibration transmission to hand-arm-system affect forearm muscle activity during a bicycle ride?

- Do the slope of the rode and the vibration frequency affect vibration amplitude transmitted to the hand-arm system during submaximal force production?

- Does the vibration frequency affect the muscle activity level in the forearm during sustained submaximal contractions?

1.3. Limitations

There are three noteworthy limitations that need to be acknowledged regarding this study, namely; exposure time (i), sample size and characteristics of the subjects (ii), and simulated conditions (iii). Firstly, measurements were performed for short durations up to 15 seconds to eliminate possible cumulative effects of fatigue which may be caused by a series of consecutive trials that corresponds approximately 40-min total exposure times for both field and laboratory trials, and to fulfil the time limit requirements of the battery powered equipment in the field settings. Therefore, the measurement durations both in the field and in the laboratory limit the ability to compare the conditions of longer exposure durations. Although it is well known that extended periods of vibration trigger adverse effects on the human body (Griffin, 1990), it is important to note that this study aimed to investigate the frequency and amplitude characteristics of vibration exposed to the cyclist as well as its transmission to the body, (specifically to forearm, shoulder and head), and avoids interpreting results of short term exposures and the adverse effects that may be caused. Secondly, the number of participants tested in the field measurements was limited due to the difficulties of reaching experienced cyclist who can handle field measurements in safety. Different group of cyclists were recruited for the road bike and MTB measurements according to their preferences for cycling training. Also, only male subjects were undertaken to the study to avoid any potential effect of gender. Thirdly, it was possible to simulate only vertical vibration in the laboratory conditions because of the limitations of the shaker.

1.4. Significance of the Study

There is very limited knowledge of vibration transmission to the human body while riding on a bicycle. Although the bicycle rider is considered to be the biggest part of the bicycle-rider system, vibration transmitted to the rider has been neglected by previous research which only investigated the level of vibration transmitted to the bicycle itself. Therefore, the level of vibration transmission to the different parts of the bicycle-rider system has been investigated in the present study. The effect of different bicycle types and hand positions have also been examined under different vibration exposure conditions.

Although, vibration exposure on the bicycle comprises both whole body and hand-arm transmitted vibration, in the relevant literature bicycle riding is classified as an example of whole body vibration exposure. Therefore, to the best of our knowledge, there is also a lack of knowledge on combined effects of whole body vibration and hand-arm vibration transmission on the bicycle-rider system, as well as the level of vibration transmission and musculoskeletal dynamics of the system. Since the muscular activity of the upper body in response to vibration exposed on a bicycle has yet to be studied, the data that was gathered in the present study will provide understanding of the potential effects of forces applied by the hands on biodynamic response under vibration conditions. The data can also be used in representing a bicycle-rider hand-arm transmission model.

CHAPTER II

2. LITERATURE REVIEW ON VIBRATION EXPOSURE IN CYCLING

In cycling the human body is exposed to vibration. The studies on vibration exposure during bicycle riding are very limited in the literature and it is possible to categorize them into two main groups. In the first group, vibration transmitted to the bicycle and the rider have been investigated in terms of possible factors affecting vibration exposure on the bicycle (Pivit, 1988; Lewis and Paddan, 1990; Outcald, 2001; Waechter et al, 1998, 2002; Torbic et al, 2003; Faiss et al., 2007), whereas the studies in the other group have focused on the possible effects of vibration exposure on cyclists regarding physiological and psychological responses of the subjects while being exposed to vibration stimulus (Faiss et al, 2007; Berry et al, 2000; Seifert et al, 1997; Titlestad et al, 2006; MacRae et al, 2000; Rambarran and Roy, 2001; Suhr, 2007).

2.1. Possible Factors Affecting Vibration Exposure of Cyclists

The level of vibration experienced by a bicycle rider is likely to be influenced by some factors such as surface conditions, type of the bicycle, riding posture and the riding speed (Torbic et al, 2003). According to the findings of the previous studies, the aforementioned variables have been discussed below as they have the greatest potential to affect the vibration exposure levels.

2.1.1. Surface Conditions

Surface roughness and the modifications on the road surface such as construction of speed reducers (e.g. rumble strips, humps) are known as factors that result in increased vibration exposed on a bicycle. So far, the published studies have investigated the vibration transmitted to the bicycle under different surface conditions (e.g. asphalted surfaces, rough road, cobble stone road, concrete stone pavement, and paved cycle track). The oldest report on vibration exposed on the bicycle that was obtainable through search engines was a study by Pivit in1988 who carried out the acceleration measurements at the handlebar and at the saddle for eleven different surfaces with four different bicycle types. According to their findings, vibration exposed to the cyclist exceeds the limit of health, comfort and capacity of reaction impaired on many surfaces except new asphalt road. Therefore, they recommend cycle-tracks be constructed with higher road quality to reduce the adverse effects on cyclists.

Outcald (2001) hypothesized that a series of depressions or bumps constructed on the pavement of the road to reduce speed of the vehicles, which is called as rumble strips, can cause an unpleasant level of vibration on the bicycle and possible loss of control. In order to test the hypothesis, subjects were asked to ride the various configurations of rumble strips and to rate their comfort and the difficulty of controlling the bicycle according to how they perceived each configuration. Vibration data was also gathered from a test bike with four different riding speeds where it is possible to ride in safety. The type of speed reducer was found to affect the level of vibration and the frequency at which the peak value occurred. Besides, the subjective scores on control and comfort are likely to coincide with the exposed level of vibration.

Waechter et al (2002) measured acceleration at the handlebars and at the saddle of two different bicycles on four different surfaces that are considered to be very common in everyday bicycle traffic. Cobblestone pavement resulted in the highest values for both bicycles when compared with old asphalt layer, concrete pavement or brick pavement.

2.1.2. Type of the Bicycle

The geometry and the material of a bicycle frame, existence of the shock absorption system and its type, wheel size and tyre pressure are the factors that differentiate bicycle types (i.e. Road Bike, Mountain Bike (rigid frame, full suspension or front suspension), and City Bike etc).

Tyre pressure (Torbic et al, 2003) as well as the type of shock absorption system (Faiss et al, 2007; Ishii et al, 2003; Roy and Robertson, 2000, Rambarran and Roy, 2001) have been shown to influence the level of exposed vibration on a bicycle more than other factors. According to the linear regression model that was developed by Torbic et al (2003) to predict the whole-body vibration levels a cyclist could expect to be exposed to while traversing uneven surfaces, whole-body vibration increases with a unit increase in tyre pressure as a result of increased tyre stiffness.

The studies showed that the type of suspension system results in different dampening characteristics of the MTB s in terms of impact forces and shock attenuation (Roy and Robertson, 2000, Rambarran and Roy, 2001), as well as vertical displacement (Titlestad et al, 2003) under simulated test conditions. To illustrate, it was found that the full suspension bicycle attenuated vertical forces by 21% more compared to front suspension bicycle (Roy and Robertson, 2000).

Rambarran and Roy (2001) reported that MTB s with or without suspension revealed different muscular recruitment levels in both trunk and lower extremity muscles. The average muscle activity of erector spinae muscle was higher in full suspension MTB which may be explained by a reaction to the dampening action of the suspension. However, the lower extremity muscles had greater activity during trials performed with hard tail MTB s which is likely to slow the trunk return to the saddle after being displaced vertically due to initial impact and to stabilize the cyclist while riding a hard tail MTB.

Ishii et al (2003) have pointed out the advantage of full suspension bicycles to absorb more destructive energy than front suspension, which allows riders to remain seated and more relaxed.

2.1.3. Riding Posture

A mathematical model of the bicycle-rider system was developed to predict the vibration stress on the rider depending on the bicycle design (Waechter et al, 2002) and represented the bicycle-rider system by four rigid bodies, e.g. the rider, the front and rear swing arm systems (wheel, derailleur etc.) and the frame, linked together with joints, springs and dampers. Among others, the rider's body is considered to be more important for vibration characteristics of the system as it is the biggest part of it (Waechter et al, 2002), even though, the overall mass of a cyclist has been shown not to affect level of vibration exposed on a bicycle (Torbic et al, 2003). Therefore, it is considered to be more complex structure to include into a model as one rigid body formed by trunk and hand arm system due to the muscular forces acting on numerous articulated structures surrounded by tissues with different viscoelastic properties.

Cyclist's upper body weight is supported on the handlebars via the hands and arms, while the trunk and the lower body weight are supported via the saddle and the pedals, respectively. Depending on the bicycle type and topographic variations as well as the preferences of the cyclist, riding posture may vary among different bicycles. Accordingly, the portion of the bodyweight supported at the contact surfaces may also differ. When cyclists are exposed to continuous shocks and vibrations while riding over rough surfaces, especially when riding downhill, as a strategy to reduce a vibration impact sometimes they stop pedalling and they stand up from the saddle when it exceeds tolerable level (Burke, 1996). However, they do not remove their hands from the handlebar to ensure a secure ride under the same vibration conditions. On the other hand, a cyclist may change his/her posture during even a single ride by shifting hand position. A variety of hand positions available for road cycling has been illustrated elsewhere (Akuthoto, 2005). For example, lower handlebars cause the riders to adopt a more forward leaning posture, even an extreme bending forward posture as seen in road bike rides to ensure aerodynamic riding position by decreasing the drag. In this case, it has been suggested that much of the upper body weight is supported by the arms, and the vibration at the hands may assume a greater importance relative to that at the seat (Lewis and Paddan, 1990). It would be even greater on downhill sections when the portion of the body weight supported by the hand and arm would be higher.

Pivit (1988) speculated that the strain on the hand-arm-system is very critical because the static load would be high in the forward leaning position when the rider is subjected to vibration. It has also been reported that when the arms and wrists of the cyclist are too vertical, they only function as shock absorbers which increase the chance of vibration induced injuries (Mestdagh, 1998). However, the elbow angle will decrease when a cyclist shifts to the bending postures which may affect the level of vibration transmitted through the hand and arm.

On the other hand, Lewis and Paddan (1990) used two handle bar positions on All-Terrain Bicycle (ATB) in their first experiment, i.e. forward leaning posture and more upright sitting posture. Through two separate experiments, Lewis and Paddan (1990) also investigated the effective transmission path to the rider's head through which the vibration travels. They calculated the transfer functions between saddle and the head to evaluate the vibration transmission for different postures. In forward leaning postures as a consequence of lower handlebars, vibration transmission was found to be greater at low frequencies up to 4 Hz, but it was greater in the upright sitting posture at high frequencies. In a forward leaning posture the transmissibility was observed to peak around 4 Hz. Although, the transmissibility was about the same in the upright posture, it occurred at higher frequencies between 5 and 10 Hz. They also concluded that the contribution of the transmission path depends on the posture maintained by the cyclist as well as the vibration frequency. For instance, in the forward leaning posture, at low frequencies, between 2.5 and 5 Hz, a greater portion of the head motion was explained to be caused by vibration transmitted through the hands and arms than through the torso. However, in the upright sitting posture, z-axis head motion was mainly produced by seat vibration at all frequencies and handlebar vibration transmitted through the hands and arms made little contribution at any frequency.

2.1.4. Grip Strength

When exposed to repetitive shocks and vibration, riders make effort to support and keep themselves in balance with arm and leg movements produced by isometrical muscle contractions to handle and stabilize the bicycle against high impact forces (Seifert, 1997). Studies showed that the amount of vibration transmitted to the hand and arm is influenced by the hand coupling forces, the sum of the grip and push forces, at contact with the source of vibration (Radwin et al, 1987; Riedel, 1995; Kaulbars, 1996). Therefore, one might conclude that the level of vibration transmitted to the rider on a bike is affected as a result of the considerable portion of body weight transferred to the handlebar through the arms while coupling forces are applied by the hands.

2.1.5. Riding Speed

Bicycle speed is considered as a significant predictor of whole body vibration (Torbic et al, 2003). In some conditions, especially on downhill sections, bicycle riders may reach to a speed approaching 70kmh^{-1} on both MTB and Road Bike, or even higher speeds.

The bicycle rider model of Torbic et al (2003) suggests that whole-body vibration incrementally increases as a function of bicycle speed up to 19 to 20 kmh^{-1} and then decreases as speeds increase beyond 20 kmh^{-1} .The over all vibration total value, a vector sum of the weighted accelerations in the x-, y-, z-axes, is shown in Figure 2.1 as a function of bicycle speed. According to the model, researchers concluded that bicycle speeds near 19 and 20 kmh^{-1} will cause the highest levels of comfort and control problems for bicyclists. Moreover, the model indicates that the combined effect of vibration magnitude and vibration frequency is greatest at these speeds.

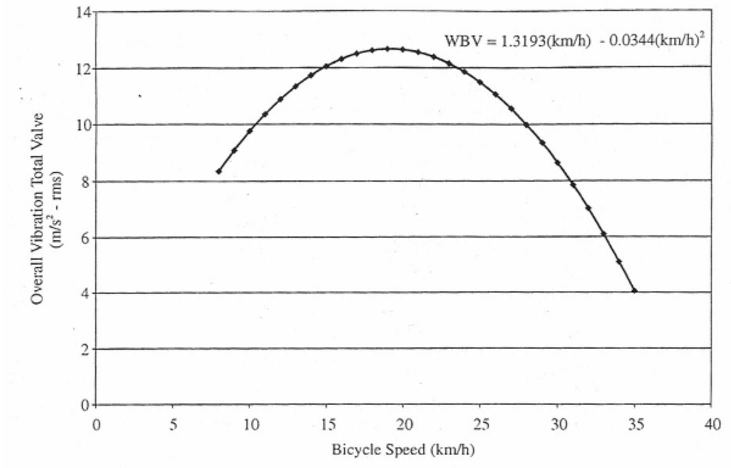

Figure 2.1 Whole-body vibration as a function of bicycle speed
Source:Torbic et al, 2003

As an example of different road surface conditions, Outcald (1991) has investigated the level of vibration and the frequency at which the peak values occurred while riding on ten different speed reducers with different speeds (5, 10, 15 and 20 mph) on a test bike (road bike) and concluded that the frequency of the peak vibration did not necessarily increase with an increase in speed. In that study, it was also reported that the some of the speed reducers did not allow cyclist to ride at high speeds (20 mph) as they felt their bicycles were uncontrollable.

2.2. Possible Effects of Vibration Exposure on Cyclists

2.2.1. Controllability and Comfort

In the literature, the subjective measure of comfort and controllability are widely used methods which are based on the rating of comfort and controllability perceived by the rider. As studies emphasize the high correlation between overall comfort and control ratings, some researchers hypothesized that overall rating of comfort might also be used to explain the relationship between whole-body vibration and perceived controllability of a bicycle (Torbic et al, 2003). The findings of the study conducted by Torbic et al (2003) suggested that the relationship between whole-body vibration and perceived controllability of a bicycle is linear; therefore, as vibration levels increase bicycle seems to become more difficult to control. Similarly, the relationship between whole-body vibration and bicyclists' perceptions of comfort is linear, and as vibration increases comfort decreases. They have also mentioned that, when cyclists experience extremely high level of vibration, ranging from 3.4 ms^{-2} to as high as 28.5 ms^{-2} at the frequency of 10 Hz, it is difficult to assume that the controllability of a bicycle is not affected.

Lewis and Paddan (1990) asked subjects to indicate their perceived level of comfort for both leaning forward and upright sitting postures on a rating scale from 0 to 6, where 0 indicates “not uncomfortable” and 6 was labelled as “extremely uncomfortable”. They found similar subjective ratings of comfort for both postures, around midway between “not uncomfortable” and “extremely uncomfortable” for leaning forward and upright sitting posture, respectively. They also compared the perceived ratings of discomfort with the guidelines (ISO 2631, BS 6841) indicating overall vibration total values which correspond to expected level of discomfort. According to the guidelines, the overall ride value that was found as 1.46 ms^{-2} rms for each exposure during their experiment was expected to be “uncomfortable” or very uncomfortable” as it is in the range between 0.8 and 1.6 ms^{-2} rms.

Torbic et al (2003) also compared the vibration characteristics of different bicycle types (e.g. MTB, Road Bike). They placed the accelerometers on the crossbar of the bicycle near the seat tube. According to the findings, the oscillation centres were not found to be located near the front and rear axles (optimal locations for a good ride), even though it is desirable for good ride quality. Although theoretically the location of the oscillation centre is determined by the factors that include combined mass of the bicycle and the rider, distances between front axle and centre of gravity of the system and stiffness of both front and rear springs, the oscillation centres of the 15 different bicycle and rider systems used in their study are reported not to vary as a function of the characteristics of the bicycle or its rider.

It has also been speculated that the dampening effect which can be achieved by a suspension system would limit visual and vestibular organ disturbance allowing the athlete to better see the trail and maintain better balance while riding a bicycle (Roy and Robertson, 2000).

Under the simulated conditions in which a bump was attached on a roller surface, subjective comfort scores of the subjects were also found to be deteriorates from "fairly comfortable" to "very uncomfortable" between hard tail and full suspension bicycles (Titlestad et al, 2006).

2.2.2. Performance

The human response to vibration in bicycle riding has been investigated by a few studies through its effects on physiological and psychological responses of the body (Faiss et al, 2007; Berry et al, 2000; Seifert et al, 1997; Titlestad et al, 2006; MacRae et al, 2000; Rambarran and Roy, 2001; Suhr, 2007). The studies in this group have mainly focused on the differences of the human response as a result of using bicycles (MTB) with or without suspension system. Most of the studies have used a roller system where bumps were mounted on a roller's surface to stimulate different vertical vibration loads depending on the dimension of bumps and pedalling cadence. Faiss et al (2007), Berry et al (2000) and Titlestad (2003, 2006) have reported the advantages of the suspension system on physiological responses (e.g. oxygen consumption, heart rate). There are also studies which addressed the effect of vibration on biochemical parameters (e.g. angiogenic agents) in normal and hypoxic conditions (Suhr, 2007).

Seifert et al (1997) have also compared the physiological responses (e.g. oxygen consumption, heart rate, HR and creatine kinase, CK, concentration) for three different MTB s (rigid frame, front and full suspension). 24h change in CK, a marker of muscular stress, HR, and oxygen consumption were found to be greater, for the rigid frame MTB during an hour cycling over a bumpy course than that of the front and full suspension MTBs, respectively. Titlestad et al. (2006) have also examined the effects of suspension systems on physiological (heart rate, oxygen consumption) and psychological responses (rates of perceived exertion and comfort) while subjects were being exposed to vibration. Their results indicated that the full suspension bicycle has a significant physiological and psychological advantage over the hard tail bicycle on all selected measures.

Studies performed in field conditions have been conducted by MacRae et al. (2000), Faiss et al (2007), and Rambarran and Roy (2001). MacRea et al (2000) have investigated the effects of different suspension systems (front vs. full suspension) on physiological responses during riding on asphalt road and during climbing on rough road. Despite the significant differences in power output, either a paved or rough road course is reported to have similar results for oxygen consumption or time to complete. Recently, Faiss et al (2007) have simultaneously determined the physiological response of the body and the level of vibration in the field conditions. The authors have mainly focused on the effect of MTB suspensions (full or front suspension) and vibration transmission on off road uphill performance (i.e. oxygen consumption, power output). They concluded that the full suspension bicycle leads to lower energy expenditure, absorbs more high frequency vibration and is more comfortable than a front suspension bicycle.

Ishii et al (2003) conducted an off-road test to observe the effect of different suspension systems in real conditions for comprehensive assessment of a mountain bike suspension system on physiological responses. They found significantly greater average oxygen consumption but lower blood lactate accumulation during trials with full suspension MTB than with front suspension. They emphasized the advantage of full suspension bicycle to absorb much destructive energy which allows the rider to remain seated and more relaxed while putting out a smooth flow of power during a hill climb.

2.2.3. Cycling Injuries Triggered by Vibration Exposure

The dynamic responses of the hand and arm are known to have a great influence on the injury potential of hand-transmitted vibration (Sörensson and Burström, 1997). Cyclists sustain isometric muscle contractions with their arms and legs to stabilize the bicycle against high impact forces in order to support and keep themselves in balance (Seifert, 1997). The combination of high forces and continuous or prolonged gripping has been associated with symptoms of upper extremity disorders (Mogk and Keir, 2003). Hand transmitted vibration exposure together with repetitive shocks and prolonged pressure on the median and ulnar nerves applied over years are known to be the main cause of peripheral nerve damage occurring at the hand and wrist (Capitani and Beer, 2002, Stewart, 1993). This neurological disorder, known as Cyclist's Palsy, is postulated to occur from high-frequency repetitive compression of the deep motor branch at the hand in prolonged biking or from single, short exposition in mountain biking (Capitani and Beer, 2002; Akuthota et al, 2005). Mestdagh (1998) also suggested that riding posture also influences the risk of injury. When arms and wrists are too vertical, they only function as shock absorbers which increase the chance of compression syndromes, characterized by a gradual onset of numbness and unpleasant tingling in the fingers which leads to weakness in the ulnar-innervated intrinsic muscles of the hand (Mestdagh, 1998).

The effects of both long time sitting and the level of vibration transmitted to the cyclist's low back might be the cause of low back pain, another common complaint among bicycle riders. The forward-leaning posture of the cyclist places too much stress on the natural form of the vertebral column by leading to compressive and tensile loads along the spine, in particular around the lumbar part, and may cause low back complaints (Mestdagh, 1998). It has been postulated that sustained awkward seating posture (lordosed or kyphosed, overly arched, or slouched) can result in higher intra discal pressure and may be injurious to spinal postural health (Pynt, 2002). The adverse effects of prolonged sitting will increase significantly when the factors of awkward postures and whole body vibration are combined (Bovenzi, 1997; Lis, 2007). During cycling, surface roughness would affect the level of vibration transmitted to the cyclist body that might in turn affect riding comfort and health. Therefore, it is reasonable to suppose that sustained bending of the spine may provoke pain and discomfort in specific body parts and such symptoms may be aggravated by the additional periodic and transient loads induced by the vibration transmission from the road surface.

CHAPTER III

3. MEASUREMENT AND EVALUATION OF VIBRATION EXPOSURE

The measurement and evaluation of vibration may be required when determining the possible effects of vibration on a person exposed to a vibrating environment. The human body is exposed to localized vibration that usually affects the hand-arm system, or vibration that affects the whole body.

Hand transmitted, or hand arm vibration which is caused by contact of the hand with a vibrating object such as a handlebar is sometimes abbreviated to HTV or HAV. Hand arm vibration is mainly characterized by disorders of the muscles, nerves, bone, joints and circulatory systems. Localized vibration can also occur at other sites of the body, such as at the feet due to pedal vibration, but it is unusual to observe any adverse human response in these situations (Mansfield, 2004). Whole Body Vibration is vibration that affects the whole body and is abbreviated to WBV. It is usually transmitted through seat surface, backrest and through the floor.

3.1. Vibration Characteristics

Since exposure to whole body vibration and hand-transmitted vibration is very complex, the characteristics of the vibration must be defined for quantifying vibration exposure of the bicycle-rider system.

International and national standards specify how whole-body vibration and hand-transmitted vibration should be measured and evaluated. For Whole Body Vibration (WBV) The International Organization for Standardization (ISO) 2631-1:1997, British Standards Institution (BS) 6841 (1987) and European Directive 2002/04/EC; and for Hand Arm Vibration (HAV) ISO 5349-1:2001 and BS 6841 (1987) are two widely used standards for measurement, evaluation and assessment of vibration exposure.

Because of the complexity of evaluating vibration and possible influences of each individual factor on the human response to vibration, the methodology takes into consideration frequency and magnitude of vibration, as well as direction, location and duration of the measurement as independent variables of the vibration evaluation.

3.1.1. Frequency of Vibration

The frequency of vibration, which is expressed in cycle per second (Hertz, Hz), affects the extent to which vibration is transmitted to the body (e.g. surface of a seat or handle of a vibrating tool), the extent to which it is transmitted through the body (e.g. from seat to the head), and the effect of vibration in the body (Griffin, 1990).

The human response to vibration exposure is frequency dependent. The effects of whole-body vibration are usually greatest at the lower end of the range from 0.5 to 100 Hz. Therefore, the recommended frequency range specified in the standard is between 0.5 to 80 Hz (ISO 2631-1, 1997). Although international guidelines recommend reporting up to relatively higher frequencies, in general, people are most sensitive to whole body vibration within the frequency range of 1 to 20 Hz (Mansfield, 2004) since most of the resonance responses of the various human body parts and organs correspond to lower frequencies (Finucane, 2006).

Studies investigating vibration transmission to the bicycle have reported vibration attenuation with increase in frequency after reaching its peak value which generally occurred around 5 to 10 Hz for all measurement points (i.e. saddle, handlebar, bottom bracket and wheel) regardless of the type of bicycle (Lewis and Paddan, 1990; Waechter et al, 2002; Faiss et al, 2007). The spectrum of vibrations also ranges from 0-50 Hz in the studies where it was provided (Waechter et al, 2002; Faiss et al, 2007; De Lorenzo and Hull, 1999).

3.1.2. Magnitude of Vibration

The magnitude of a vibration can be quantified by its displacements, its velocity or its acceleration. For practical convenience, the acceleration is usually measured with accelerometers. The units of acceleration are meters per seconds square (ms^{-2}) and the acceleration due to the Earth's gravity (*g*) is approximately 9.81 ms^{-2}.

The standards require that vibration magnitudes should be expressed in ms^{-2} rather than in g, velocity, and displacement or as peak or peak-to-peak values. ISO 2631-1 (1997) recommends quantifying vibration magnitude in terms of an average measure of the acceleration of the oscillatory motion, the rms acceleration history. The standard requires the measured accelerations, to be expressed as weighted accelerations, a_w, using the below given formula.

$$a_w = \left(\frac{1}{T} \int_0^T a_w^2(t)\,dt \right)^{1/2} \tag{3. 1}$$

Where
$a_w(t)$ = weighted acceleration as a function of time
T = duration of the measurement (s)

Cyclists experience high levels of vibration indicated by the overall vibration total values ranging from 3.4 ms^{-2} to 28.5 ms^{-2} at dominating frequencies between 5 to 10 Hz (Torbic et al, 2003). Lewis and Paddan (1990) calculated overall ride value calculated from frequency weighted (weighting: w_b) z- axis acceleration as 1.46 ms^{-2} rms for the bicycle and the rider being exposed to vibration.

3.1.3. Direction of Measurement

Vibration may take place in three translational directions and three rotational directions. For whole body vibration, complex stimuli may simultaneously move vertically (z-axis), laterally (y-axis), and in the fore-and-aft directions (x-axis).

Two types of biodynamic coordinate systems are available to define the direction of the motion: anatomical and basicentric. Anatomical coordinate systems are defined relative to anatomical features of the body, whereas, basicentric coordinate systems are defined relative to the surfaces that come into contact with the body (Griffin, 1990). In biomechanics, it is usually appropriate and necessary to define the x, y, and z-axes relevant to the coordinate system that is specific to the research (e.g. bicycle locomotion). Therefore, basicentric coordinate systems are more convenient for practical measurement than anatomical coordinate systems (Griffin, 1990). ISO 2631-1 (1997) also recommends measuring the direction of accelerations according to a basicentric coordinate system. The principal relevant basicentric coordinate systems are shown in Figure 3.1.

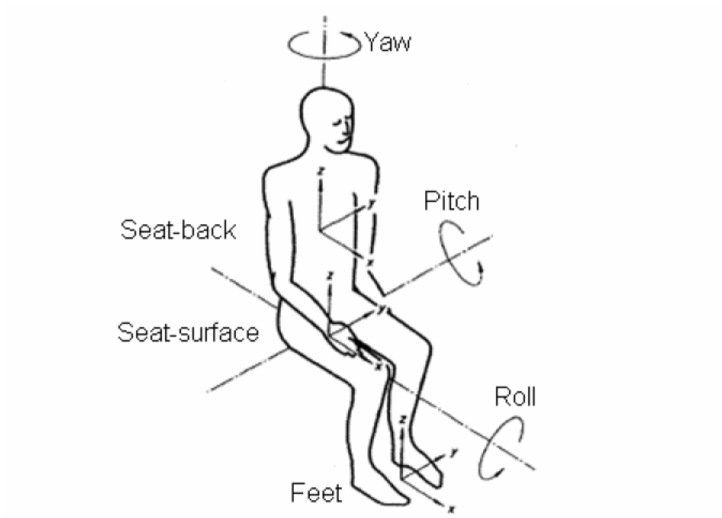

Figure 3.1 Basicentric axes of a seated person
Source: ISO 2631-1, 1997

Cycling and vibration studies have reported on mainly dominant axis of the vibration, z-axis, with respect to bicycle-rider basicentric coordinate system (Lewis and Paddan, 1990; Torbic et al, 2003; Waechter et al, 2002; Faiss et al, 2007) with some exceptions which also investigated y-axis acceleration (Waechter et al, 2002) and pitch motion in rotational axis (Torbic et al, 2003).

3.1.4. Location of Measurement

Vibration is measured according to a coordinate system originating at a point from which vibration is considered to enter the human body (e.g. on the seat surface between the saddle and cyclist for whole-body vibration measurements or on the handle bar for hand-transmitted vibration measurements). When direct measurements are not obtainable, vibration from rigid surfaces may be measured on the supporting surface closely adjacent to the interface between the body and that surface. Another option is to take the vibration measurements from a rigid portion of the vibrating surface. If it is not feasible to obtain precise alignment of the vibration transducers with the preferred basicentric axes, the sensitive axes of transducers may deviate from the preferred axes by up to 15^{o} where necessary (ISO 2631-1, 1997).

The findings of the previous studies on vibration transmission to the bicycle-rider system demonstrated that the different part of the bicycle-rider system revealed different results in terms of effective frequency range or the amplitude of the vibration. Therefore it is important to report the location of the measurement where the accelerometer has been placed and compare the findings with previous studies in which the same measurement point was selected.

Lewis and Paddan (1990) measured vibration in the z-axis and mounted the accelerometers on the saddle, the handlebars, and the bottom bracket of an ATB type bicycle. They found a steadily increasing acceleration magnitude from 5 Hz to 14 Hz at the saddle and at the bottom bracket. The acceleration measured on the handlebars was found to be greater than at the saddle for all frequencies between 5 Hz and 30 Hz, which was explained by the frame pitched about an axis closer to the saddle than the handlebars. Lewis and Paddan (1990) also measured head accelerations of the subjects for two different riding postures via a bite bar held between the teeth. The maximum seat to head transmissibility was found to occur at lower frequencies up to 4 Hz in forward leaning, and between 5 to 10 Hz in upright sitting postures.

Torbic et al (2003) have also investigated translational acceleration along the z-axis (which corresponds to bounce or vertical motion) as well as the rotational acceleration around y-axis (which corresponds to pitch motion) measured at the saddle surface in order to compare the vibration characteristics among different bicycle types. The oscillation centres for both vertical and pitch motion were found to be located near the front or rear axles for any of the bicycles, which results in poor ride quality.

Waechter et al (2002) found acceleration level at the handlebars to be higher than that of the saddle for two different bicycles on each of four different surfaces which includes cobblestone pavement, old asphalt layer, concrete pavement or brick pavement.

Faiss et al (2007) have also investigated vibration transmitted to the bicycle at the wheel level in addition to saddle level of front and full suspension MTBs. They found that peak frequency of vertical displacements occurred around 2 to 5 Hz at the saddle and around 10 to 15 Hz at the wheel.

3.1.5. Duration of Measurement

ISO 2631-1 (1997) offer little guidance on the duration of measurement. Time dependency was incorporated in the assessment of subjective response to whole body vibration in the previous versions of ISO 2631 (i.e. ISO 2631, 1974; 1978; 1985).The scientific basis of the time dependency concept was not well supported by research results and consequently was removed from the current version of ISO 2631-1 (1997) (Griffin, 1998). The new version of ISO 2631 indicates that the duration of the measurement should be reported and should be sufficient to ensure reasonable statistical precision and to ensure the vibration is typical of the exposures that are being assessed.

Waechter et al (2002) defined the length of their measurement duration as the longest possible distance that allowed collection of as much data as possible for the respective surface (which was around 200m). In their first laboratory experiment Lewis and Paddan (1990) reported that their measurement duration was limited to 60 seconds while a subject was exposed to vertical vibration on an electro- dynamic vibrator. Pivit (1988) also set the same measurement duration on each surface.

3.2. Evaluation of Severity of the Vibration

The severity of an exposure might be given by some measures of the vibration magnitude. Crest factor and magnitude of acceleration which is corrected, or weighted, according to the vibration frequency and the exposure duration and frequency weighted rms accelerations are used for describing the severity of vibration. To the best of our knowledge, ISO 2631-1 (1997) recommends describing the severity according to the frequency-weighted rms acceleration when the crest factor is less than or equal to 9, which can be defined as the ratio of the maximum instantaneous peak value of the frequency-weighted acceleration signal to its rms value.

While quantifying the whole body vibration experienced by the cyclist, Torbic et al. (2003) also calculated crest factors to determine a suitable measure to report the severity of vibration on a bicycle itself. Since crest factors were calculated as less than 4, they concluded that the frequency-weighted rms acceleration is more appropriate to evaluate the severity of vibration the cyclist is exposed to.

3.2.1. Frequency Weightings for Health, Comfort and Perception

In recent years it has been common to use a frequency weighting, to reflect relationships between vibration frequency and human responses and to allow for the differing injury potential of different frequencies (Griffin, 1990; Mansfield and Griffin, 1998). Table 3.1 shows the frequency-weightings as defined in ISO 2631-1 (1997) for the effects related to health, comfort and perception. The vibration magnitude is multiplied by the factor to 'weight' it according to its effect on the body. Frequency-weightings have higher values at frequencies of greater importance. Measured frequencies are weighted differently depending on the direction of the vibration. Two principal frequency weighting are used; W_k for the z axis and W_d for the x and y axes. Some special cases require additional frequency weightings. There are seven weightings defined in the International Standards (ISO 2631-1, ISO 5349-1, BS 6841) (Table 3.2). Frequency weighting curves (ISO 2631-1, 1997) have also been illustrated in Figure 3.2.

Table 3.1 Frequency weightings for different axes depending on health, comfort or perception

Symbols	Health	Comfort	Perception
W_k	z-axis, seat surface	z-axis, seat surface z-axis, standing x-,y-,z-axes, feet sitting	z-axis, seat surface z-axis, standing
W_d	x-axis, seat surface y-axis, seat surface	x-axis, seat surface y-axis, seat surface x-,y-axes, standing y-,z-axes, seat back	x-axis, seat surface y-axis, seat surface x-,y-axes, standing

Table 3.2 Frequency weightings given in ISO 2631-1, ISO 5349-1 and BS6841

Symbols	Direction	Primary context of use	Standard
W_b	Vertical	Seat Vibration	BS 6841
W_d	Fore-aft , Lateral	Seat Vibration	ISO 2631-1, BS 6841
W_f	Vertical	Motion Sickness	ISO 2631-1, BS 6841
W_g	Vertical	Activity Interference	BS 6841
W_h	Fore-aft, Lateral, Vertical	Hand-Arm Vibration	ISO 5349-1
W_k	Vertical	Seat Vibration	ISO 2631-1
W_j	Vertical	Seat Vibration	ISO 2631-1

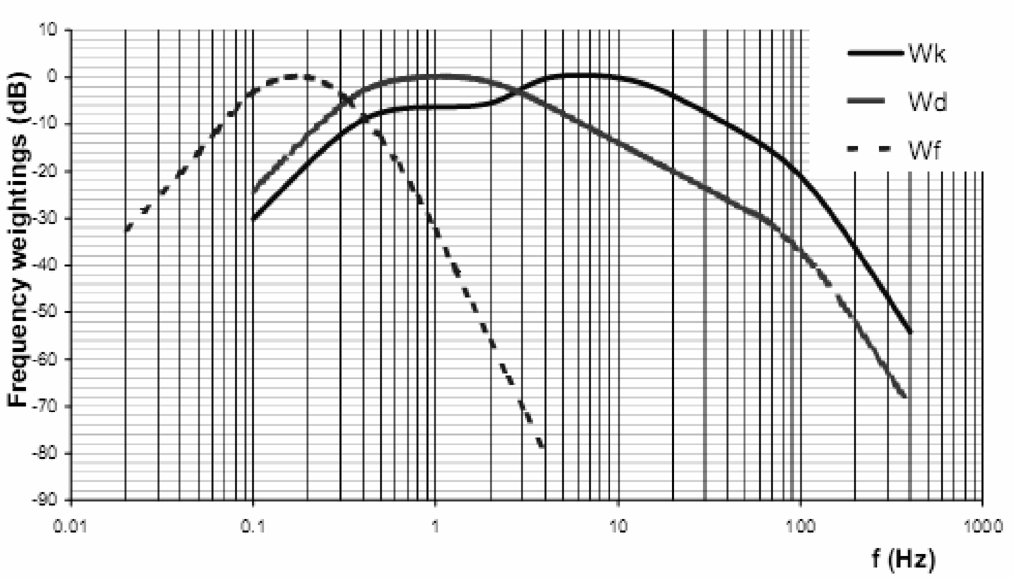

Figure 3.2 Frequency weighting curves
Source: ISO 2631-1, 1997

3.2.2. Vibration Transmission Calculations

The extent of the movement at any point on the body is related to the magnitude of the input vibration at the seat or floor and the transmissibility at the driving frequency. The absolute transmissibility indicates the steady-state magnitude of the motion of the mass relative to the steady-state magnitude of the motion at the input as a function of the vibration frequency. Therefore, transmissibility is calculated as the ratio of the vibration expressed by accelerations measured between two points. For supporting surfaces, transmissibility is defined as;

$$\mathrm{T}(f) = \frac{\mathrm{a}_{\text{supporting surface}}(f)}{\mathrm{a}_{\text{floor}}(f)} \qquad (3.2)$$

If transmission of vibration from the supporting surface to a certain body part is considered, then the equation changes to;

$$\mathrm{T}(f) = \frac{\mathrm{a}_{\text{body part}}(f)}{\mathrm{a}_{\text{supporting surface}}(f)} \qquad (3.3)$$

Here $\mathrm{a}_{\text{supporting surface}}(f)$ is the acceleration at the seat or at the handlebar and $\mathrm{a}_{\text{body part}}(f)$ is the acceleration at the given body part at frequency f. So, transmissibility of 2 would mean that there was twice as much vibration at the given body part than at the driving point.

Lewis and Paddan (1990) calculated transmissibility between head and saddle and concluded that the saddle and handlebars were driven by the same acceleration function and they are 100% coherent. Therefore, they designed separate experiments to determine separate transfer functions for two transmission paths to the head, via the saddle and via the handlebars. By removing the handlebar from the frame they also calculated handlebar to head transmissibility with a different experiment. The researchers concluded that the contribution of the transmission path depends on the posture maintained by the cyclist and the frequency of vibration. To illustrate, in the forward leaning posture more low frequency vibration was transmitted to the head via the handlebars than via the seat.

3.3. Human Response to Vibration

3.3.1. Vibration Total Value

The vibration total value (vector sum of the weighted acceleration in the x-, y-, z-axes), is calculated as follows:

$$a_v = \sqrt{k_x^2\ a_{wx}^2 + k_y^2\ a_{wy}^2 + k_z^2\ a_{wz}^2} \qquad (3.4)$$

Where

a_{wx}, a_{wy}, a_{wz} = the weighted rms accelerations with respect to the orthogonal axes x, y, z, k_x, k_y, k_z = multiplying factors.

While assessing the effect of vibration on health, (k_x, k_y, k_z), are suggested to be taken respectively as (1.4,1.4 and 1).In case of assessment for comfort $k_x = k_y = k_z$ have to be taken as 1.

ISO 2631:1 (1997) suggests the assessment of vibration total values, a_v, of the frequency-weighted accelerations corresponding to any measurement to be done following the guidance given in Table 3.3.

Table 3.3 a_v values for comfort ratings
Source: ISO 2631-1, 1997

a_v	Comfort rating
less than 0.315 ms^{-2}	not uncomfortable
0.315 to 0.63 ms^{-2}	a little uncomfortable
0.5 to 1 ms^{-2}	fairly uncomfortable
0.8 to 1.6 ms^{-2}	uncomfortable
1.25 to 2.5 ms^{-2}	very uncomfortable
greater than 2 ms^{-2}	extremely uncomfortable

3.3.2. Power Spectral Densities

Although the spectrum analysis is a fundamental component of many frequency analysis methods, it is more common to illustrate the frequency composition of a vibration environment with a power spectral density function. The power spectral density function $G_{xx}(f)$ of a time series is formulated so that its integral between two frequencies is the mean-square value of the signal between these frequencies. The integral over all frequencies is variance of the data. The power spectral density, PSD is, therefore, the distribution of the mean square value of time history over frequency.

Power spectral density is the most common technique for analyzing the frequency content of signals for human vibration applications as it is ideally suited to the analysis of transient and random signal types. It generates a measure of the energy contained within a frequency band. PSD splits up the original signal into shorter segments and calculates the FFT for each section. The length of each individual segment is selected such that the FFT generates an appropriate frequency resolution. For example, if a frequency resolution of 0.25 Hz is required, each segment must last 4 seconds. Usually, the segments overlap and are "windowed" to ensure data integrity. The units of a PSD for an acceleration signal are $(ms^{-2})^2.Hz^{-1}$.

3.3.3. Critical Frequency Ranges

In physics, the tendency of a system to oscillate at maximum amplitude at certain frequencies may lead to the resonance of the system. At these frequencies, even small periodic loads can produce large amplitude vibrations, because the system stores vibration energy. For example, the resonance frequency of bicycles has been shown to be 3 Hz (Pivit, 1988).

The human body can be compared to a mechanical structure and like all other mechanical structures it has specific frequencies where the joining parts exhibit a maximum mechanical response. Most of the tissues in the human body usually show a resonance at about 5 Hz (e.g. head), while some resonate at higher frequencies (e.g. Eyeball resonates at about 20 Hz). If a person is exposed to a sinusoidal signal that gradually increases in frequency, then different parts of the body will resonate in turn. In Figure 3.3, resonance frequencies that are responsible for some of the impaired body functions are represented. All people respond differently to whole body vibration because of their variations in physique and posture (Johansson and Nilsson, 2006).

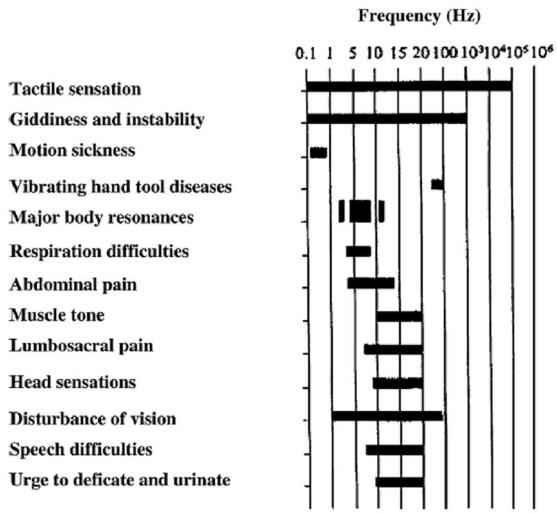

Figure 3.3 Frequency ranges for different physiological effects of body vibrations Source: Cole, 1982

CHAPTER IV

4. EVALUATION OF MUSCULAR ACTIVITY

4.1. Surface Electromyography (EMG)

Electromyography (EMG) is a technique for measuring muscular electrical activity. The EMG signal is generated by the electrical activity of the muscle fibres during a contraction. EMG signal is composed of the Motor Unit Action Potentials (MUAPs) from groups of muscle fibres organized into functional units called Motor Units (MU s) and represents a summation of tissue-filtered signals generated by a number of active motor units. EMG can be detected by intramuscular electrodes (needle EMG) or by surface electrodes (surface EMG) attached to the skin.

Surface Electromyography provides a non-invasive way of studying muscular function. The surface EMG signal detected during voluntary contractions is the summation of the contributions of the recruited MUs that are observed at the recording site (Merletti, 2004). Typically, two electrodes are taped on the skin surface over the muscle belly, and the difference of potentials between the electrodes is amplified. Surface EMG signals are usually processed by using some data reduction techniques to obtain quantities describing their amplitude and dominating frequency. The most often used parameters to evaluate surface EMG signals are root mean square (rms) and Mean Absolute Value (MAV) for amplitude, and median frequency (F_{med}) and mean frequency (F_{mean}) for frequency characteristics.

The amplitude of an EMG signal is generally defined after a first processing step consisting of filtering and calculating a rectified, integrated or root mean square value (rms) from raw data. The use of normalization procedures has also been proposed in order to compare experimental EMG results obtained for different muscles from different subjects. EMG normalization is a technique that permits access to the relative level of activation of a given muscle (Hsu et al, 2006) by expressing the absolute amplitude of the signal measured during the exercise as a percentage of a meaningful reference EMG value. The most powerful solution for physiologic interpretation is to measure the reference EMG value while the subject performs a muscle contraction for a calibrated test condition. Normalization can be performed with respect to the reference value recorded when the subject exerts Maximal Voluntary Contraction (MVC) of the muscle or alternatively, when the subject exerts a standard level of force (Latash, 1998). The reference EMG values generally correspond to the peak or mean value of the EMG signal.

4.2. Surface EMG in Vibration Exposure Studies

Research on epidemiology of vibration induced injuries has been an important area of occupational health. In this regard, muscular response to mechanical vibrations has been widely investigated via surface electromyography in occupational medicine and ergonomics (Seidel, 1988; Pope et al, 1998; Cardinale and Lim, 2003; Aström et al, 2009). Extensive research has been conducted on back muscle response to whole body vibration to explain the possible mechanisms of low back pain which is a very common complaint among the working population who are subjected to whole body vibration. There are also studies investigating postural effects on muscular activity and occurrence of low back pain while being subjected to whole body vibration in a seated position (Zimmermann et al, 1993; Zimmermann and Cook, 1997). In the literature, reviews are available which provide an overview of the relation between vibration exposure and low back pain, as well as other musculoskeletal injuries (Bovenzi and Hulshof, 1999; Lings and Leboeuf-Yde, 2000; Seidel, 2005).

In general, whole body vibration exposure is characterized by an increased amplitude of EMG signals compared with no vibration trials in trunk muscles (Pope et al, 1998; Zimmermann, 1997), lower extremity muscles (Cardinale and Lim, 2003) and in upper extremity muscles (Aström et al, 2009).

In cycling, the arms and consequently the arm muscles are of importance in providing stability on the bicycle and support for the forward leaning body, however the muscular activity of the upper body in response to exposed vibration on a bicycle has yet to be studied. So far, the only study focusing on muscular activity during simulated shock exposure conditions while riding a hard tail and full suspension MTB has been conducted by Rambarran and Roy (2001). The muscles selected for investigation during their measurements were erector spinae in the trunk, and vastus lateralis and biceps femoris in the lower extremity. They placed a ramp on a force plate to simulate the bump effect and investigated the ability of axial and lower extremity muscles to actively attenuate shock during rear wheel impacts with and without a suspension system. They found increased muscular activity in the erector spinae muscle shortly after the rear wheel contacted the ground after descending from the bump which coincided with an increase in vastus lateralis and biceps femoris activity. The authors have pointed out that the average muscle activity of erector spinae muscle was higher in full suspension MTB. On the contrary, the low extremity muscles had greater activity during trials performed with hard tail MTB.

CHAPTER V

5. METHODOLOGY OF THE STUDY

5.1. Data Collection and Instrumentation

Equipment and data collection procedures that were used in this study are explained in the context of this section.

5.1.1. Measurement of Vibration Transmission

Experimental setup and the data collection tools for vibration transmission measurements are summarized in Figure 5.1. Tri-axial accelerometers (B&K, 4515B, Denmark) were used to measure the level of vibration at different locations on bicycle-rider system and also at the platform surface in the laboratory. In the laboratory measurements, vertical dynamic load was applied to the platform by the electromechanical shaker, and the vibration data were collected simultaneously using tri-axial accelerometers mounted on the bicycle-rider system on a stationary road bike (11 kg aluminium frame) fixed on the shaker by a home trainer (Tacx, USA). During the field measurements, data acquisition units were powered by batteries. In order to fulfil the time limit requirements of the battery powered equipment in the field settings and to eliminate possible cumulative effects of fatigue as a result of a series of consecutive trials, the measurement duration was set at 4 and 16 seconds in the field and in the laboratory experiments, respectively. The analysis of the vibration data were performed by Pulse (B&K, Denmark) and MATLAB mathematical software.

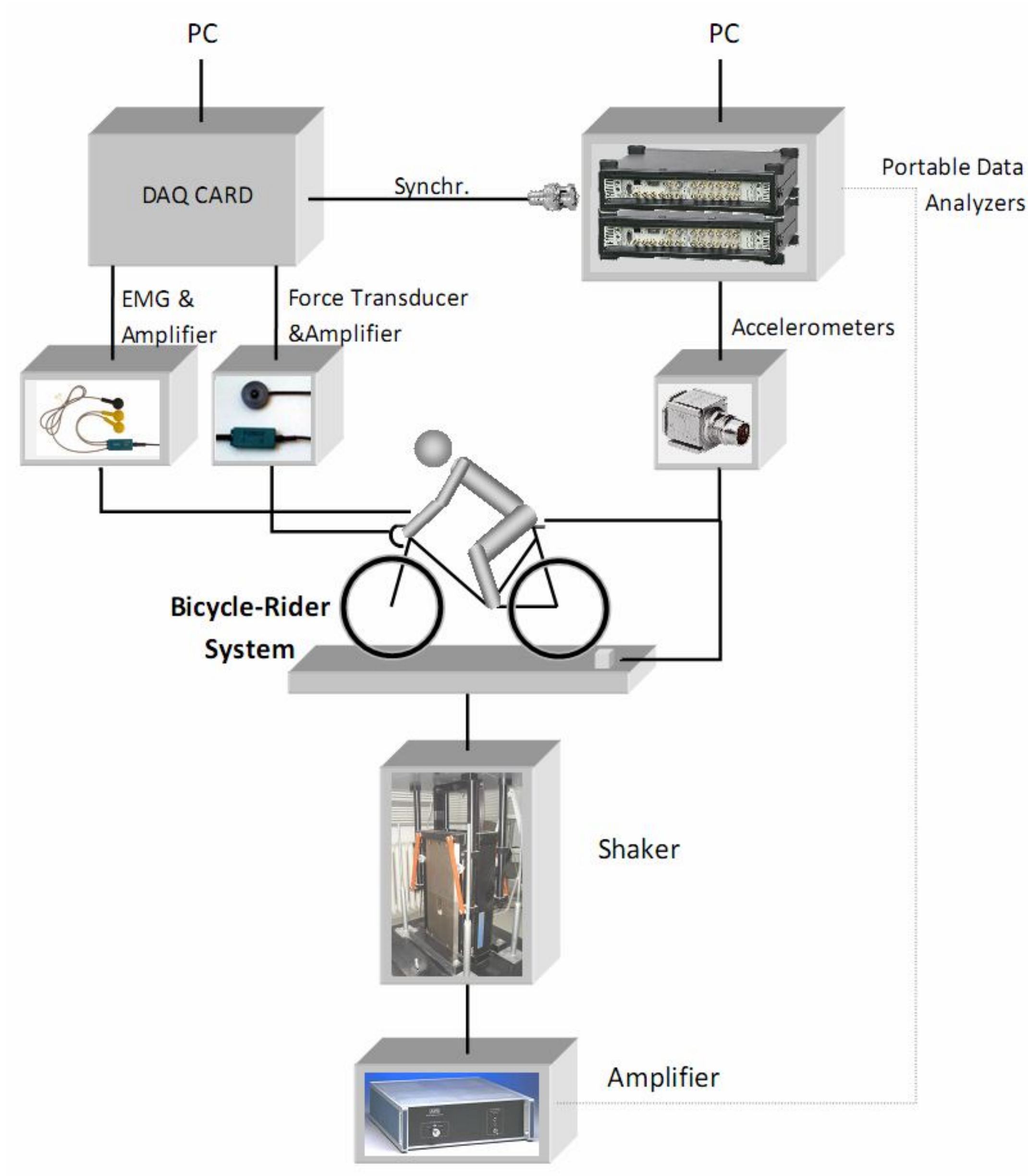

Figure 5.1 Experimental set-ups for Vibration Measurements

5.1.2. Measurement of the Level of Force Production

Measurement of acceleration magnitude at the contact surface between the rider's hand and the vibrating surface is the first step in the evaluation of vibration exposure. Transmitted vibration energy determines the extent and severity of its biological effects (ISO 5349-1, 2001). It is affected by the contact of the hand-arm system with the source of vibration and varies depending on magnitude and direction of the force and pressure applied at the contact surface. For this reason, international standards have recently pointed out the necessity of measuring the forces applied by the hand. A standardized method however has not been proposed yet in the literature. Previous research dealing with the measurement of grip and or push forces made use of force transducers attached on the handles (McDowell, 2006; Radwin and Yen, 1999; McGorry, 2001).

In this study, force measurements were done during laboratory measurements. A test bike was equipped with load cells (Biovision, Germany) integrated bilaterally to the handlebar-brake lever interface to control force output during sub-maximal contractions. Before the experiments, each subject underwent three bilateral maximal isometric force production trials with 2 min rests between each. Force output measurements during Maximal Voluntary Contractions (MVC) were achieved by gripping the brake lever with the index and middle finger of both hands while subjects were sitting on a stationary test bike with their hands on the drop of the bar. Subjects were asked to gradually increase the force level from rest to a maximal effort within 2 seconds and to sustain it (i.e., steady maximal exertion is maintained) for 3 seconds (Caldwell et al, 1974).

The maximal force outputs for each side were used as index values to determine the target force levels during sub-maximal contraction trials. Target force levels were determined as 10 and 20 % of each subjects' MVC. In addition to no contraction trials, each subject repeated each target force level in random order for 5 and 7.5 Hz vertical sinusoidal vibration with the total acceleration values of 1, 1.5 and 2 ms^{-2} rms.

In order to ensure subjects reached and maintained the target force level, an LCD screen was placed on the wall at the eye level of (approximately 80-90 cm far from) the subjects and the visual feedback were given to the subject through the MATLAB routine simultaneously with the measurements.

5.1.3. Measurement of the Muscle Activity

The electromyographic activity (EMG) of superficial forearm flexor (m.flexor carpi radialis) and extensor muscles (m.extensor digitorum) that are involved in force production during gripping and grasping movements were recorded by surface Ag/AgCl electrodes. Prior to electrode placement, all electrode sites were cleaned and mildly abraded with 70% alcohol with cotton wipes and allowed to dry before the electrode placement. The active area of the electrodes was positioned at 2, 5 cm centre-to-centre distance near the midline of the muscle belly. Analogue EMG signals were amplified (5000 times) and converted to digital form using a 12 bit A/D converter and sampled at a rate of 1000 Hz. After digitalization, EMG signals were band-pass filtered with cut-off frequencies of 8 Hz (high-pass) to 500Hz (low-pass) and were stored in the computer for further analysis in MATLAB version 7.5. EMG values were normalized with respect to peak amplitude of EMG output of the respective muscles attained in the best maximal voluntary contraction trial. Then, the root mean square EMG activity (Rms EMG) was calculated for the selected time periods.

Prior to electrode placement any hair that might be under the patches were shaved and the region was thoroughly cleaned with alcohol (70%) pads and allowed to dry before the electrode placement.

The recordings of the EMG signals were synchronized with input signal of the shaker and force output of the load cell.

5.2. Experimental Procedures and Data Analysis

In order to answer the research questions, vibration transmission, force production and muscular activity measurements are performed using different protocols (Table 5.1).

Table 5.1 Measurement Parameters

Measurement Name	Measurement Duration (sec)	Input Waveform	Surface Slope	Hand Position	Riding Speed (kmh^{-1})	Accelerometer Locations	Measurement Direction
Field (Preliminary)	4	random (f = 0-100 Hz)	0%	on drops	~20	Saddle Waist	x, z x, z
Lab (Preliminary)	16	sinusoidal $a=1ms^{-2}$ (f=5 Hz)	0%	on drops, brake hoods, top of the bar	NA	Platform Saddle Waist	x, y, z x, z x, z
Field	4	random, (f = 0 -100 Hz)	0%	on drops	~20	Stem Saddle Shoulder Head	x, y, z x, y, z x, y, z x, y, z
Lab	16	sinusoidal a =1,1.5,2 ms^{-2} (f=5, 7.5 Hz)	5%	on drops, brake hoods, top of the bar	NA	Platform Stem Saddle Elbow Shoulder	x, y, z x, y, z x, y, z x, z x, y, z

5.2.1. Preliminary Studies

Before the actual measurements, preliminary studies (both in the field and in the lab) were conducted to find out the level of vibration transmitted to the bicycle-rider system and to determine the parameters (that have to be considered in the later stages of the study) that will provide the most conclusive answers to the research questions.

Considerations of different types of bicycles on different road surface conditions were thought to serve to that purpose.

The accelerometers were placed on the saddle and were mounted over L1-L3 spinous processes on the cyclist's low back and on the bicycle-rider interface at the saddle beneath the ischial tuberosities of the rider. The acceleration values were measured for vertical and frontal axes to determine the vibration exposure levels on the saddle and at the lumbar region of the cyclist's body. Also, the transmissibility ratios were determined.

Laboratory Study: Prior to the field measurements, a laboratory study was also carried out in order to determine the effects of different riding postures on vibration transmission. A 27 years old healthy female competitive tri-athlete was exposed to whole body vertical sinusoidal vibration at a constant frequency of 5 Hz on her own road bike (aluminium frame, with dropped handlebars) mounted on an electro-dynamic vibrator. Total weight of the bicycle-rider system was 66 kg. Measurement duration was triggered manually and set at four seconds. Measurements were repeated three times for three different hand positions; on the drops (T1), on the brake hoods (T2) and on the top of the bar (T3) (Figure 5.2).

(T1) (T2) (T3)

Figure 5.2 Different hand positions on road bike (on the drops (T1), on the brake hoods (T2) and on the top of the bar (T3))

Field Study: The field measurements were performed on the same subject and for different road surface conditions, (i.e., asphalt, cobblestone tracks (CS1), and old cobblestone strip on the asphalt road (CS2)). Two types of bicycles that the subject is familiar with (road bike and MTB-rigid frame) were used during the trials. The speed was kept constant at 20 kmh^{-1}. A constant sitting posture was maintained during the measurements with the hands located on the top of the bar and with shoulders about mid-way between the bottom bracket and the head tube of the bicycle. The subject was instructed not to pedal or stand up from the saddle during the measurement period and verbally informed before the recording was initiated.

5.2.2. Field Measurements

Field measurements were performed to determine the magnitude and the frequency range of the transmitted vibration to the vehicle and the rider and to find out possible differences attributed to different road surfaces and bicycle types.

5.2.2.1. The Procedures of Vibration Transmission Measurements: Test Bikes and Considered Tracks

The level of vibration exposure was investigated for road bike and mountain bike (MTB, with front suspension) while riding on asphalt road, rough road and concrete stone pavement.

10 voluntary healthy male subjects between the ages of 19-33 participated in the field measurements. Descriptive characteristics of the subjects with at least 2-year regular training background in cycling have been presented in the results chapter. Subjects had no history of neurological or musculoskeletal pathology. After being informed both verbally and in writing about the method and the possible risks provided, all participants signed an approved, informed consent form (See Appendix A). The protocol was approved by the Ethics Committee of the Middle East Technical University (See Appendix B).

Subjects were tested on their own bicycles during the field measurements. The frames of the MTBs were aluminium-carbon, and except the bicycle of subject 1 and 5, the frames of the RBs were of aluminium. Apart from subject 1's bicycle (MTB), handlebars of all bicycles were made of aluminium. Wheel diameters of MTB and RB were 26 and 28 inch, respectively. The weight of the helmets ranged from 230 to 300 gr. The properties of the bikes used by the subjects are summarized in Table 5.2. Field measurements consisted of three trials for each subject on the same course and were repeated for different road surfaces. Measurements were performed on roads with no curves and were in the order of asphalt road, rough road and concrete stone pavement.

Table 5.2 Characteristics of the bikes and the riders participated in the field measurements

Type of the Bicycle	Bicycle model (year)	Subject No	Age (years)	Body Height (cm)	Body Weight (kg)	Weight of the bicycle(kg)	Saddle Height (cm)	Handlebar Height (cm)	Frame Size (cm)	Suspension Type	Tyre Thickness (mm)	Wheel Diameter (inch)	Tyre Pressure (psi)
MTB s	2004	Subject 1	24	168	57	11	99	94	42	front	2.1	26	45
	2006	Subject 2	22	170	70	11.5	100	94	43	front	2.1	26	45
	2006	Subject 3	18	168	52	11.5	100	96	42	front	2.1	26	45
	2006	Subject 4	21	176	63	12	102	94	42	front	1.9	26	45
	2008	Subject 5	25	183	80	12.5	99	95	42	front	2.1	26	45
Road Bikes	2003	Subject 1	32	181	83	8.5	101	93	56	-	1.3	28	90
	2002	Subject 2	23	179	73	9.5	100	92	54	-	1.3	28	90
	2005	Subject 3	20	180	68	10.2	100	92	54	-	1.3	28	90
	2006	Subject 4	33	173	65	9	101	92	56	-	1.3	28	90
	2008	Subject 5	25	182	73	9	102	94	55	-	1.3	28	90

The saddle-rider interface and the handlebar stem were selected for the placements of the accelerometers on the bicycle. On the riders' body, measurement locations determined as the under surface of acromion at scapula and the forehead. The accelerometers were mounted by double-sided adhesive foam tape. Rigid thin metal layers served as a base to increase the surface area of the attachments were used on the body. Also, a high density elastic head strap was used to fix the accelerometer to the forehead. The reference coordinate system that was used during the placement of the accelerometers is shown in Figure 5.3.

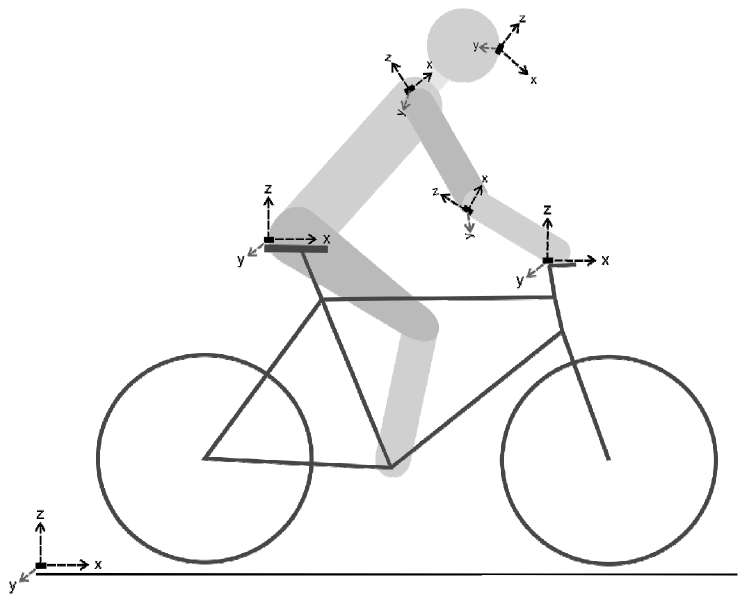

Figure 5.3 The reference coordinate system adopted for accelerometer placements

The data acquisition unit was placed in a car moving at the same speed with the bicycle and its connection with the accelerometers was established via 3-m long data cables. Figure 5.4 displays the different road surfaces tested in the measurements and the connection of the data acquisition unit with the rider. While maintaining a constant driving speed of 20 kmh^{-1}, data recordings were initiated when the bicycle passed the reference point on each course. Subjects were instructed not to pedal or stand up from the saddle during the measurement period and verbally informed before the recording was initiated. The duration was set at 4 seconds for data recordings. When the riders arrived at the reference point, they stopped pedalling and maintained a regular sitting position with their feet placed on the pedals on the same horizontal line parallel to the road surface, the arms supported on the handlebar, and the head in a forward looking position toward the direction of locomotion. Subject's hands were placed on the drop of the handlebar of the road bike (RB), whereas with mountain bike (MTB) the hands were placed on top of the handlebar with the index finger at the brake lever on both sides. During the field measurements, subjects wore their cycling jerseys, cycling shoes with clipped pedals, padded cycling tights and helmets.

Figure 5.4 Test Tracks (left: asphalt road, middle: rough road, right: concrete stone pavement)

5.2.2.2. The Procedures of Muscle Activity Measurements during Cycling

In order to determine the effects of the level of vibration transmitted to the hand-arm system on the muscular activity level in the forearm, surface electromyography was recorded at forearm flexor and extensor muscles of both of the upper limbs during cycling. EMG recordings were gathered through the data acquisition unit placed in the car, simultaneously with the measurements explained in section 5.2.2.1. The portable EMG data acquisition unit was designed to be worn back pack style and was fixed to the subject's body with shoulder straps in order not to cause any respiratory restriction or discomfort to the rider. After the EMG cables were attached to the data acquisition unit, a 3-m long USB cable was used to establish the connection with a computer placed in the car. EMG measurements were repeated both on RBs and on

MTBs on the aforementioned road surfaces. Three trials were done in order to reveal the possible differences in muscle activity in forearm muscles.

Before the trials, subjects underwent 3 consecutive maximal isometric gripping tasks according to the previously explained procedure. The muscular activity levels attained by the subjects (for forearm flexor and extensor muscles on both sides) were recorded for use in the post normalization procedures.

5.2.3. Laboratory Measurements

Laboratory measurements were designed to clarify the effects of frequency and magnitude of vibration and different handling positions on the level of vibration transmitted to the bicycle-rider system and to find the effect of vibration exposure on the muscular activity of forearm muscles under controlled conditions.

5.2.3.1. The Procedures of Vibration Transmission Measurements: Effects of Vibration Amplitudes, Force Contraction Levels and Different Hand Positions

Vibration transmission values for different handling positions that lead to change in joint angles in trunk and upper extremity (Figure 5.5) were investigated on a stationary road bike (frame: aluminium, weight: 11 kg) fixed on the shaker platform by a home trainer unit (Tacx, USA). The measurements were repeated for different positions of hands namely, the hands on drop of the handlebar (T1), on the brake hoods (T2) and on the top of the bar (T3) (Figure 5.2). The laboratory trials were done, in random order, at 0^o slope of the platform for each of the three acceleration total values (i.e., 1, 1.5 and 2 ms^{-2} rms) and for each of the two frequencies (i.e., 5 and 7.5 Hz).

Test parameters are listed in Table 5.3. Similar to the field measurements, the measurement locations on the bicycle were selected as the saddle-rider interface and the stem. The under surface of acromion at scapula and the superficial surface of the ulna's proximal end near to the elbow joint were chosen as the measurement locations on the rider's body. The accelerometers were mounted by double-sided adhesive foam tape. Rigid thin metal layers were used on the body to serve as a base to increase the surface area of the attachments.

Table 5.3 Test Parameters for section 5.2.3.1

	Lab -Experiment 1	Lab- Experiment 2
Input Waveform (in z direction)	Sine	Sine
Frequency (Hz)	5,7.5	5,7.5
Total value(m/s^2)	1,1.5,2	1,1.5,2
Slope of the Platform	0^0	0^0
Hand Position	T1	T1,T2,T3
Level of Contraction(%MVC)	0,10 and 20	0

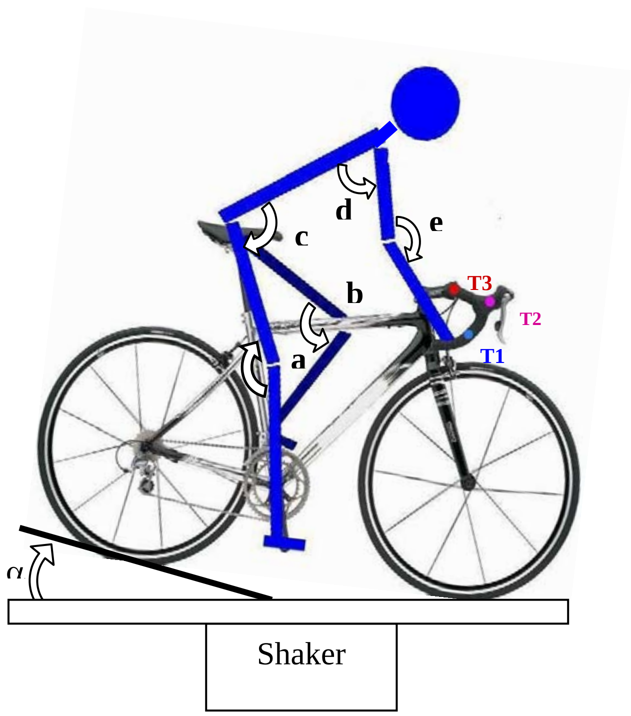

Figure 5.5 Locations of the Test parameters on bicycle-rider system (Lab measurements)

Subjects were asked to keep the stationary sitting position with their feet placed on the pedals on the same horizontal line parallel to the platform surface, the arms were supported on the handlebar and the head was in a forward looking position. Descriptive information on subjects and joint angles for three different handling positions are presented in the results chapter. Possible undesired changes in posture were prevented by visual control. Post test goniometric measurements were also done.

5.2.3.2. The Procedures of Vibration Transmission Measurements: Effects of Vibration Frequency, Level of Contraction and the Slope of the Platform

Possible effects of vibration frequency and the slope of road on the level of vibration transmitted to the hand-arm system were investigated in the lab during the submaximal contraction of the forearm muscles. The stationary test bike (aluminium frame road bike, weight: 11 kg,) fixed on the platform of the electromechanical shaker was adjusted to a 5^{o} decline above the horizontal line of the platform by raising the contact point of the rear wheel. The vibration measurements explained in the method section 5.2.2.1 were done in random order with 2-minute rest intervals for each of the two frequencies (5 and 7.5 Hz) and for each of the two submaximal contraction levels(%10 and %20 of MVC) and for null contraction for both flat (0^{o}) and declined (5^{o}) configurations. Details of the experimental procedure have been summarized in Table 5.4. During the measurements the hands were placed on the drop of the bar. In order to gather data regarding vibration transmitted through the hand-arm system, measurement points on the subjects were selected as the under surface of acromion at scapula and the superficial surface of the ulna's proximal end near to the elbow joint. The duration of the measurements was set at 16 seconds, the longest time that can be provided in order to minimise any cumulative effect of fatigue on the rider which may be caused by a series of consecutive trials that corresponds approximately 40-min total exposure time for each rider(Figure 5.6).

Table 5.4 Test Parameters for section 5.2.3.2

	Lab- Experiment 3
Input Waveform (in z direction)	Sine
Frequency (Hz)	5, 7.5
Total value (ms^{-2})	1, 1.5, 2
Slope of the Platform	5^{0}
Hand Position	T1
Level of Contraction	0, 10, 20 %

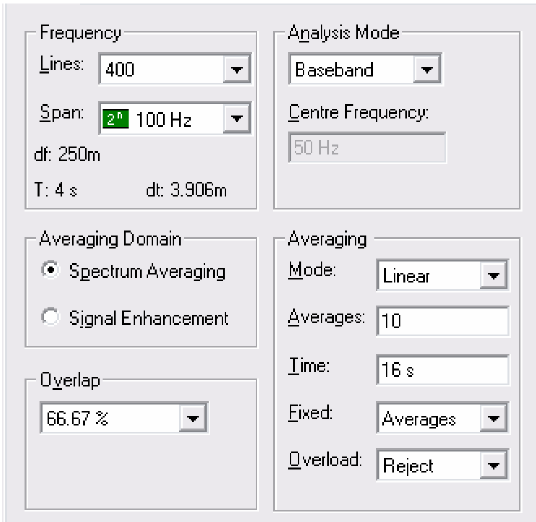

Figure 5.6 FFT analyzer setup (Lab measurements)

The bilateral maximal force outputs were used as the index values to determine the target force levels during submaximal contraction trials. Visual feedback was provided to the subjects by showing the target force level on an LCD screen (Figure 5.7). After completion of the protocol, including a 2-min rest periods between each individual measurement, maximal bilateral force production was assessed as a sign of fatigue. The protocol for the assessment of maximal force production has been explained in detail in section 5.1.2.

Figure 5.7 An illustration of the electrode placement, and setup for force output feedback

Descriptive characteristics of the subjects and the joint angles have been presented in the results chapter. After being informed about the method and the possible risks which were provided both verbally and in written form, all participants signed an approved informed consent form. Subjects had no history of neurological or musculoskeletal pathology.

5.2.3.3. Measurement of Muscle Activity in the Forearm

The effects of vibration frequency on muscular activity level of forearm muscles have been examined in relation to submaximal force production applied by the hand. Surface electromyography measurements were obtained from forearm flexor and extensor muscles, bilaterally. EMG recordings were collected in random order for 10% and 20% of submaximal contraction levels under 2 ms^{-2} rms amplitude of cyclic sinusoidal vertical load at each of 5 and 7.5 Hz frequencies. Also, no vibration and no contraction trials were implemented as controlling conditions. The recordings were performed simultaneously with the vibration transmission measurements explained in the results chapter. Test parameters chosen for the measurement of muscle activity are listed in Table 5.5.

Table 5.5 Test parameters for 5.2.3.3

	Lab- Experiment 4
Input Waveform(in z direction)	Sine
Frequency(Hz)	5, 7.5
Total Value (ms^{-2})	2
Slope of the Platform	0^{0}
Hand Position	T1
Level of Contraction	0, 10, 20 %

Before the trials, the muscular activity levels attained by the subjects during maximal isometric gripping tasks were recorded from forearm flexor and extensor muscles on both sides for further normalization procedures according to the previously explained procedure in method section 5.2.2.2. Immediately after the subject reached the target force level, the vibration stimulus was applied to the platform. The period when the vibration stimulus was initiated and terminated was marked on the EMG signals .The analysis of the EMG signals was established for selected periods on the time domain. An illustration of the synchronized recordings of the vibration stimulus, force output and EMG signals are displayed in Figure 5.8.

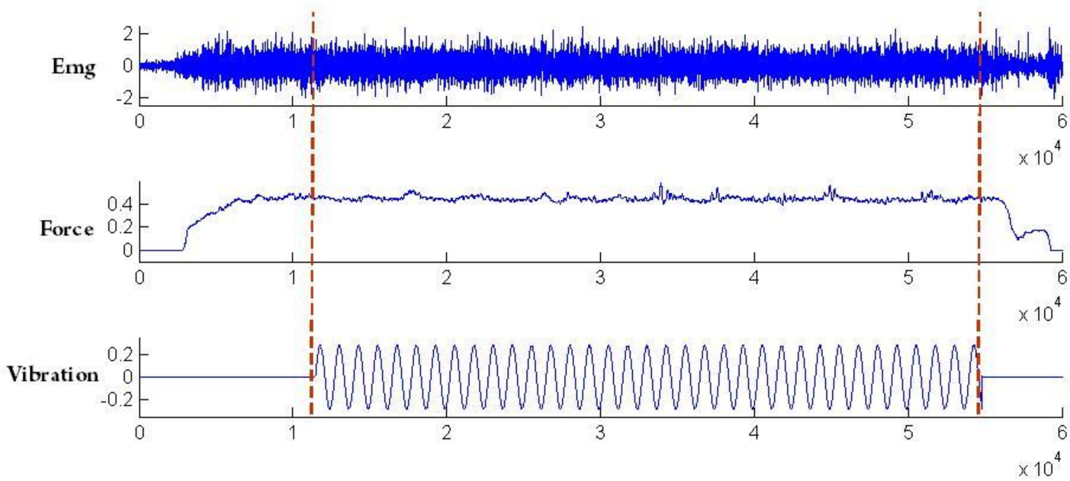

Figure 5.8 The synchronization of vibration stimulus, force output and EMG signals.

CHAPTER VI

6. RESULTS AND DISCUSSION

6.1. Findings of the Preliminary Study

In the laboratory part of the preliminary study, it has been found that the vibration magnitude in x direction measured at the saddle increased approximately two-folds compared to input vibration magnitude. To be able to compare vibration transmission levels among different hand positions, transmissibility ratios were normalized to input vibration magnitude measured at the platform. Normalized peak values (NPV) showed a higher amount of vibration transmission to the cyclist's waist for different hand positions, i.e., with the hands on top of the bar, on the brake hoods and on the drops, respectively (Table 6.1).

Table 6.1 The effect of hand position on the vibration transmitted to the bicycle rider system

Measurement	Direction		Hand Position		
			T3	T2	T1
waist	z	Peak Acceleration (ms^{-2})	0,812	0,886	0,885
waist	x		0,179	0,065	0,292
saddle	z		1,021	1,093	1,054
saddle	x		0,965	1,154	1,343
platform	z		0,504	0,539	0,669
$peak_{waist}/peak_{saddle}$	z	NPV	0,795	0,811	0,840

The findings gathered through the field measurements revealed that the cyclist was exposed to the considerably high levels of vibration on the bike on rough road conditions and which in turn caused an increase in the vibration transmitted to the saddle and to the waist of the cyclist in both x- and z-axis (Table 6.2).

Table 6.2 Peak acceleration magnitudes observed in the field during Road Bike and MTB trials

		waist x		saddle x		waist z		saddle z	
		a (ms^{-2})	f (Hz)	a (ms^{-2})	f (Hz)	a (ms^{-2})	f (Hz)	a (ms^{-2})	f (Hz)
Road Bike	Asphalt	0.18	13.5	0.51	34.5	0.38	5	1.00	21.5
	CS1	0.99	20.5	1.65	19	1.06	8.5	3.39	20.5
	CS2	1.09	8.5	4.06	17.5	2.93	8.5	4.06	17.5
MTB	Asphalt	0.27	25	0.55	25	0.38	10	0.59	24
	CS1	0.81	11	2.71	16	1.04	9	1.58	26
	CS2	1.23	7	3.81	30	1.44	6	1.72	30

Saddle-to-waist transmissibility ratios ($a_{z(waist)}/a_{z(saddle)}$) for Road Bike trials in the field are displayed in Figure 6.1. The increase in the vibration transmission from saddle to waist as a result of road roughness was apparent in z-axis. The transmissibility ratios reached their peak values in the frequency range of 5-10 Hz in Road Bike and MTB trails. Transmissibility ratios reached the highest value in CS1 trials (cobblestone tracks). Moreover, the frequency shift towards lower frequencies was observed in both Road Bike and MTB measurements during CS1 trials, whereas unexpected roughness and sudden upward movement during CS2 trials (old cobblestone strip on the smooth asphalt road) resulted in a frequency shift towards the higher frequencies. As the roughness of the road surface increases, worst case being the CS2 trials, prominent differences between the levels of vibration transmitted to the rider's body was observed.

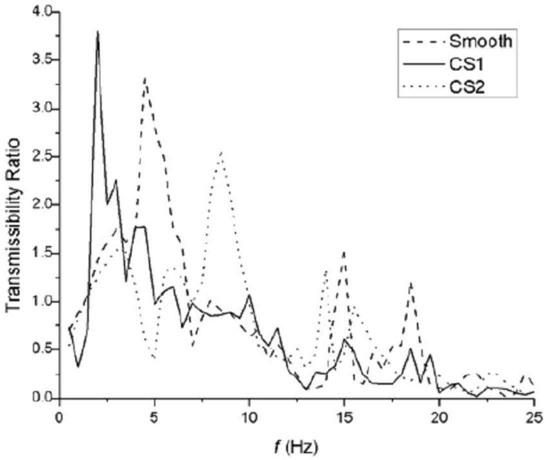

Figure 6.1 Saddle-to-waist transmissibility ratios (z-axis) in Road Bike trials

6.2. Findings of the Field Studies

The field measurements were performed on both road bike and MTB. 10 healthy volunteer male cyclists between the ages of 19-33 who have participated in the study were grouped as Road Bike and MTB Groups according to their preferences for cycling training. Descriptive characteristics of the subjects with at least 2-year regular training background in cycling are presented in Table 5.2.

6.2.1. Vibration Transmission to the Bicycle-Rider System: The Effects of Road Surface Conditions and Type of the Bicycle

The results of the field measurements revealed that the vibration levels measured on the selected locations (i.e., saddle, stem, shoulder, and forehead) on the bicycle-rider system are effective in x-axis (in the line of motion) and z-axis (perpendicular to the line of motion).

Peak acceleration values observed in field measurements in x-, y-and z-corresponding to road bike and MTB trials on asphalt road, rough road and concrete stone pavement are presented in Tables 6.3 -6.8. As seen in Tables, peak acceleration values increased as the road roughness increased. The values were highest on the rough road and lowest on the asphalt road.

MTB measurements revealed that the level of vibration transmitted to the bicycle was found to increase depending on the severity of roughness and showed slightly higher scores at stem with the dominance of z axis vibration exposure. In addition, during the road bike measurements performed on smooth asphalt road, un-weighted peak acceleration values were also slightly higher at stem than at saddle for all subjects. These finding coincides with the study of Waechter et al (2002) who found that acceleration level at the handlebars was higher than that of the saddle for two different bicycles on each of four different surfaces which includes cobblestone pavement, old asphalt layer, and concrete pavement or brick pavement.

Shoulder acceleration levels on the riders' body of road bike go from lowest to highest in the order of asphalt road, concrete stone pavement and rough road .Forehead accelerations were found higher for trials on concrete stone pavement compared to those on rough road. Asphalt road resulted in lowest transmission of vibration to the riders' body also during the MTB trials. Like in road bike trials, in MTB trials shoulder accelerations were observed to have higher scores than forehead at each axis while riding on rough road. Interestingly, the vibration transmission to different body parts on different road surfaces which tends to increase with increased roughness has been found not to be influenced by different bicycle designs.

The frequency range where the peak accelerations occurred at dominant axes (x and z) was relatively wide for all subjects on smooth asphalt road for saddle and stem on both MTB (~between 5-40 Hz) and road bike (~between 20-70 Hz). As a result of increased roughness, it reduced to 15-30 Hz range for both bicycles. In a similar manner, studies investigating vibration transmission to the bicycle have reported the attenuation of vibration, with an increase in frequency ,after reaching its peak value for all measurement points (i.e., Saddle, handlebar, bottom bracket and wheel) regardless of the type of bicycle (Lewis and Paddan, 1990; Waechter et al, 2002; Faiss et al, 2007). The effective spectrum range for vibrations was found to be between 0 and 50 Hz at the measurement points on the bicycles (Waechter et al, 2002; Faiss et al, 2007; De Lorenzo and Hull, 1999).

The results of the field measurements have revealed that the level of transmitted vibration measured at the forehead and the shoulder reached their maximum values at the frequencies between 3 -12 Hz for the dominant axes on each road regardless of the input acceleration magnitude. On the road bike forehead accelerations even shifted to lower frequencies of 3.5-7 Hz on both asphalt and concrete stone pavement. It is well known that vibration transferred to the body at lower and intermediate frequencies may coincide with the resonance frequencies of different body parts. Moreover, human being is known to be most sensitive to whole body vibration within the frequency range of 1 to 20 Hz (Mansfield, 2004) In the literature, for example, the resonance frequency has been reported as being between 1-9 Hz for head and neck complex (Fard et al, 2004), and between 4-8 Hz for shoulder (Hazarin and Grzesik, 1998). It can be concluded that the effective frequency range in which the maximal vibration amplitudes occurred on the bicycle coincides with the resonance frequency of the body parts. It might, therefore, negatively affect the comfort and health of the rider.

Table 6.3 Measured un-weighted peak acceleration values and associated frequencies of Road Bike trials performed on asphalt road

Asphalt Road (Road Bike)		Saddle			Stem			Forehead			Shoulder		
		x	y	z	x	y	z	x	y	z	x	y	z
Subject 1	a_{peak} (ms^{-2})	0,58	0,27	0,49	0,48	0,77	0,50	0,44	0,20	0,51	0,28	0,20	0,23
	f_{a_peak} (Hz)	69,25	6,50	62,75	26,50	6,75	68,75	3,75	7,25	3,75	12,00	17,25	4,75
Subject 2	a_{peak} (ms^{-2})	1,16	0,31	1,06	1,31	0,86	1,63	0,46	0,17	0,25	0,36	0,15	0,22
	f_{a_peak} (Hz)	33,75	33,75	24,25	33,75	6,50	22,50	3,75	3,75	4,75	6,50	10,00	3,75
Subject 3	a_{peak} (ms^{-2})	0,96	0,37	0,65	0,93	0,42	0,85	0,27	0,19	0,22	0,25	0,23	0,22
	f_{a_peak} (Hz)	28,50	37,75	28,50	30,75	53,75	21,00	4,00	3,00	5,25	21,00	28,50	28,50
Subject 4	a_{peak} (ms^{-2})	1,44	0,19	0,74	1,79	0,27	1,03	0,37	0,18	0,27	0,26	0,18	0,31
	f_{a_peak} (Hz)	32,75	32,75	42,00	32,75	53,25	32,75	5,50	5,25	5,50	10,75	13,25	5,50
Subject 5	a_{peak} (ms^{-2})	0,87	0,35	0,44	1,11	0,31	0,57	0,63	0,61	0,56	0,17	0,30	0,38
	f_{a_peak} (Hz)	31,25	26,25	32,00	31,25	6,00	36,75	5,25	6,00	5,25	3,50	6,00	6,00

Table 6.4 Measured un-weighted peak acceleration values and associated frequencies of Road Bike trials performed on rough road

Rough Road (Road Bike)		Saddle			Stem			Forehead			Shoulder		
		x	y	z	x	y	z	x	y	z	x	y	z
Subject 1	a_{peak} (ms^{-2})	5,14	1,42	5,88	4,81	3,93	5,37	1,15	1,24	1,71	1,61	2,11	2,21
	f_{a_peak} (Hz)	17,75	23,75	17,50	17,75	6,50	19,75	10,75	6,25	10,75	10,75	10,75	10,75
Subject 2	a_{peak} (ms^{-2})	7,00	1,76	6,06	4,89	1,01	7,24	0,59	0,24	0,70	1,22	1,32	1,59
	f_{a_peak} (Hz)	15,75	16,75	18,25	15,75	8,25	18,25	7,50	6,75	11,75	11,75	11,50	15,75
Subject 3	a_{peak} (ms^{-2})	3,13	1,09	3,78	2,12	0,64	3,75	0,62	0,49	0,70	1,38	1,27	1,45
	f_{a_peak} (Hz)	19,00	29,75	17,25	19,00	12,75	17,25	10,50	1,50	4,25	10,50	10,50	10,50
Subject 4	a_{peak} (ms^{-2})	3,67	1,37	4,72	2,77	1,21	4,50	0,95	0,76	0,98	0,98	0,94	1,00
	f_{a_peak} (Hz)	26,75	33,25	15,00	32,75	15,25	15,25	5,75	8,75	8,50	8,50	15,50	9,25
Subject 5	a_{peak} (ms^{-2})	6,56	1,10	4,34	4,74	1,05	6,10	1,08	0,44	0,91	1,15	1,06	1,35
	f_{a_peak} (Hz)	15,50	20,75	15,50	15,75	50,25	18,75	6,25	1,75	5,25	11,50	15,50	15,50

Table 6.5 Measured un-weighted peak acceleration values and associated frequencies of Road Bike trials performed on concrete stone pavement

Concrete Stone Pavement (Road Bike)		Saddle			Stem			Forehead			Shoulder		
		x	y	z	x	y	z	x	y	z	x	y	z
Subject 1	a_{peak} (ms^{-2})	2,62	1,66	3,82	3,78	1,26	4,27	2,02	1,13	1,81	0,98	1,07	1,36
	f_{a_peak} (Hz)	27,75	4,00	45,75	23,75	6,00	45,75	4,00	4,00	4,00	8,25	11,75	4,00
Subject 2	a_{peak} (ms^{-2})	4,51	0,84	4,65	3,27	0,58	3,41	1,05	0,37	0,86	0,51	0,33	0,90
	f_{a_peak} (Hz)	19,00	37,00	37,00	19,00	1,50	24,25	3,25	1,50	4,50	3,25	8,25	3,25
Subject 3	a_{peak} (ms^{-2})	7,20	0,87	3,16	4,71	0,44	4,39	0,91	0,53	0,85	1,33	1,56	1,27
	f_{a_peak} (Hz)	19,75	39,50	19,75	19,75	49,25	19,50	3,50	2,50	5,00	19,75	19,75	19,50
Subject 4	a_{peak} (ms^{-2})	1,69	0,58	6,59	2,30	0,80	2,29	1,43	0,52	0,82	0,65	0,36	1,40
	f_{a_peak} (Hz)	39,00	39,00	39,00	38,75	39,00	38,75	4,50	4,50	6,75	6,75	20,00	4,50
Subject 5	a_{peak} (ms^{-2})	2,93	0,78	2,73	2,04	0,45	2,78	0,75	0,17	0,80	0,30	0,23	0,31
	f_{a_peak} (Hz)	20,00	20,00	38,50	20,00	38,25	20,00	4,00	4,25	5,25	4,00	6,00	4,00

Table 6.6 Measured un-weighted peak acceleration values and associated frequencies of MTB trials performed on asphalt road

Asphalt Road (MTB)		Saddle			Stem			Forehead			Shoulder		
		x	y	z	x	y	z	x	y	z	x	y	z
Subject 1	a_{peak} (ms^{-2})	0,43	0,25	0,39	0,35	0,32	0,59	0,48	0,16	0,26	0,44	0,35	0,55
	f_{a_peak} (Hz)	14,25	4,00	4,25	14,25	4,50	14,25	4,25	6,00	10,25	10,25	14,25	4,50
Subject 2	a_{peak} (ms^{-2})	0,55	0,14	0,44	0,96	0,36	0,55	0,34	0,22	0,25	0,34	0,30	0,35
	f_{a_peak} (Hz)	24,50	3,25	24,50	24,50	3,25	24,50	4,00	1,50	3,75	7,25	12,00	4,00
Subject 3	a_{peak} (ms^{-2})	0,29	0,14	0,20	0,30	0,16	0,62	0,30	0,11	0,29	0,25	0,25	0,22
	f_{a_peak} (Hz)	26,00	61,25	30,00	23,00	8,50	9,50	4,25	5,00	5,00	8,00	9,50	4,25
Subject 4	a_{peak} (ms^{-2})	0,46	0,38	0,46	0,29	0,29	0,61	0,39	0,22	0,24	0,50	0,47	0,36
	f_{a_peak} (Hz)	15,75	66,75	26,00	15,75	6,75	15,75	4,50	6,75	11,50	15,75	15,75	15,75
Subject 5	a_{peak} (ms^{-2})	0,47	0,36	0,34	0,27	0,33	0,66	0,27	0,15	0,28	0,30	0,22	0,29
	f_{a_peak} (Hz)	24,75	59,50	26,75	35,50	40,50	40,50	3,00	1,50	3,75	8,25	12,75	3,50

Table 6.7 Measured un-weighted peak acceleration values and associated frequencies of MTB trials performed on rough road

Rough Road (MTB)		Saddle			Stem			Forehead			Shoulder		
		x	y	z	x	y	z	x	y	z	x	y	z
Subject 1	a_{peak} (ms^{-2})	2,76	0,67	3,06	1,96	1,36	2,97	0,85	0,27	1,45	1,19	2,26	1,16
	f_{a_peak} (Hz)	14,50	29,25	14,00	14,50	14,50	14,50	3,75	11,50	11,50	11,00	11,50	11,50
Subject 2	a_{peak} (ms^{-2})	3,20	0,95	2,26	2,14	0,77	2,36	0,50	0,45	0,54	1,07	1,37	0,91
	f_{a_peak} (Hz)	20,75	54,50	19,00	21,50	14,00	21,00	4,50	2,00	14,00	8,00	11,75	4,50
Subject 3	a_{peak} (ms^{-2})	3,25	0,57	2,37	2,84	0,48	2,59	0,95	0,36	0,69	0,74	0,96	1,24
	f_{a_peak} (Hz)	15,25	31,25	14,00	15,25	11,75	15,25	4,00	5,00	12,50	13,75	15,25	15,25
Subject 4	a_{peak} (ms^{-2})	2,28	0,81	2,69	1,77	0,63	3,41	1,24	0,86	1,26	1,61	2,56	1,96
	f_{a_peak} (Hz)	27,25	30,75	16,75	19,00	6,00	15,75	11,75	11,75	12,50	15,75	15,75	15,75
Subject 5	a_{peak} (ms^{-2})	3,41	0,54	1,95	1,76	0,68	3,54	0,60	0,73	0,69	0,67	0,73	0,72
	f_{a_peak} (Hz)	20,25	23,00	17,50	18,75	19,50	16,50	2,75	5,00	5,00	16,50	16,50	2,75

Table 6.8 Measured un-weighted peak acceleration values and associated frequencies of MTB trials performed on concrete stone pavement

Concrete Stone Pavement (MTB)		Saddle			Stem			Forehead			Shoulder		
		x	y	z	x	y	z	x	y	z	x	y	z
Subject 1	a_{peak} (ms^{-2})	2,43	0,44	1,63	1,34	0,55	1,57	0,78	0,37	0,66	0,68	1,46	1,10
	f_{a_peak} (Hz)	41,25	19,00	20,75	41,50	41,50	41,25	3,50	1,75	4,50	8,50	20,50	4,50
Subject 2	a_{peak} (ms^{-2})	3,43	0,66	1,61	1,69	0,37	2,09	0,70	0,25	0,86	0,84	0,92	1,09
	f_{a_peak} (Hz)	35,25	35,25	35,25	35,25	35,25	35,25	3,75	3,50	3,50	6,50	12,25	3,50
Subject 3	a_{peak} (ms^{-2})	1,35	0,47	1,13	1,01	0,28	1,10	1,50	0,35	0,68	0,70	0,58	1,47
	f_{a_peak} (Hz)	40,25	40,25	40,25	19,75	8,00	9,00	4,25	5,00	4,25	4,25	4,25	4,25
Subject 4	a_{peak} (ms^{-2})	2,28	0,43	1,14	1,39	0,43	1,90	1,40	0,59	0,53	0,92	0,66	1,16
	f_{a_peak} (Hz)	34,25	34,00	34,00	34,25	6,25	34,25	3,75	8,00	12,00	9,25	16,75	3,75
Subject 5	a_{peak} (ms^{-2})	1,53	0,48	1,20	1,23	0,30	1,91	0,88	1,39	0,84	0,60	0,51	0,82
	f_{a_peak} (Hz)	41,00	4,50	21,00	41,00	2,75	41,00	4,50	4,50	4,50	2,75	9,25	4,50

The main difference between the two bicycles was observed in the exposure levels. With respect to MTBs, the level of vibration in the road bikes was higher, and it approached to a value that was approximately two fold higher for each measurement location on the bicycle. Fatter tires of MTBs may explain the lower values gathered through their measurements. Amplitude differences between two bicycle types were especially apparent at saddle level among rough road and at stem level among concrete stone pavement trials. Accelerations vs. frequency curves, corresponding to each test track, on both of the bicycle types are illustrated in Figures 6.2-6.7 for x-, y- and z- axis. Especially in rough road trials the frequency response for all subjects was nearly identical.

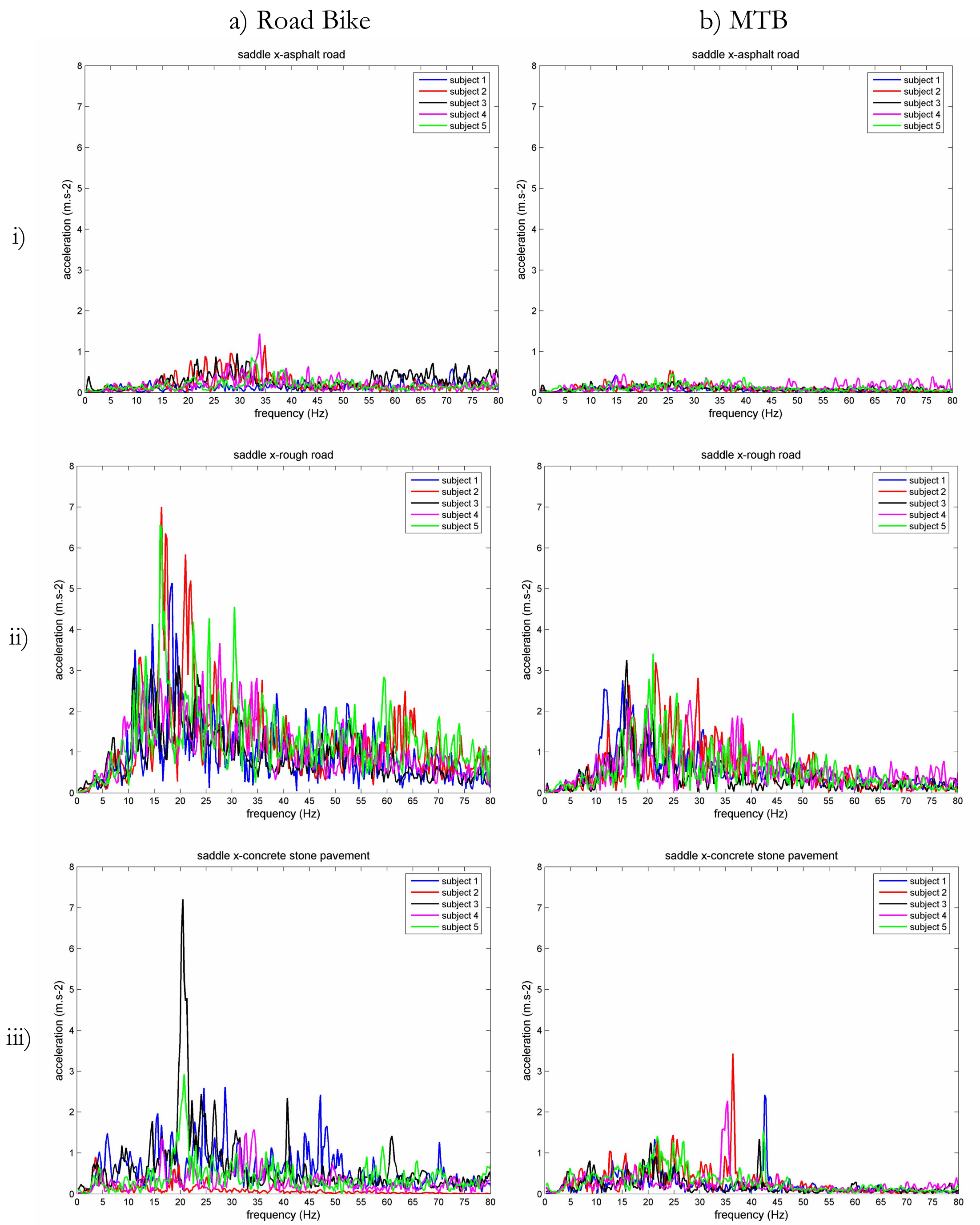

Figure 6.2 a_x (saddle)-f curves obtained from the field measurements for Road Bike (a) and MTB (b) on asphalt road (i), rough road (ii), concrete stone pavement (iii)

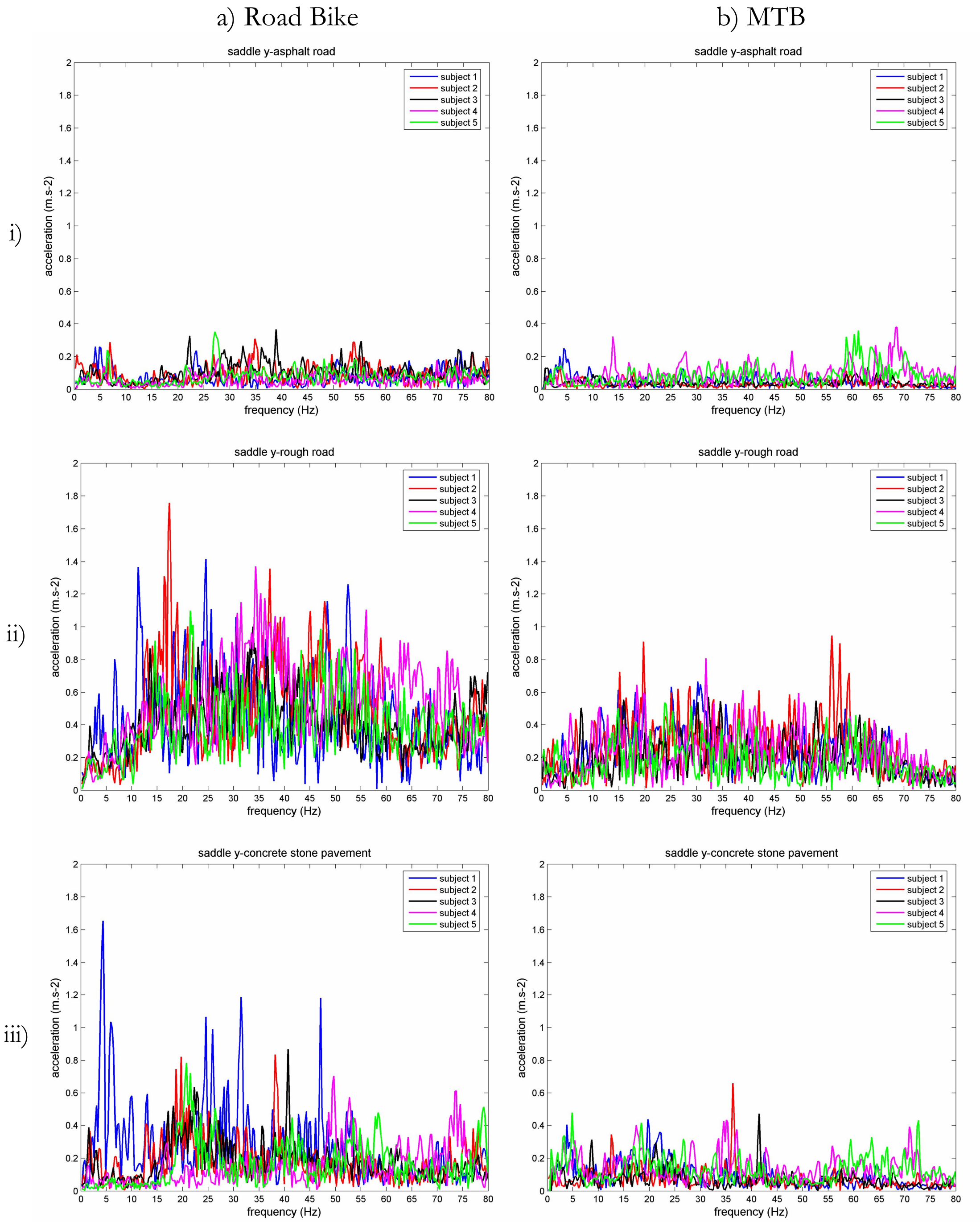

Figure 6.3 a_y (saddle)-f curves obtained from the field measurements for Road Bike (a) and MTB (b) on asphalt road (i), rough road (ii), concrete stone pavement (iii)

a) Road Bike b) MTB

i) ii) iii)

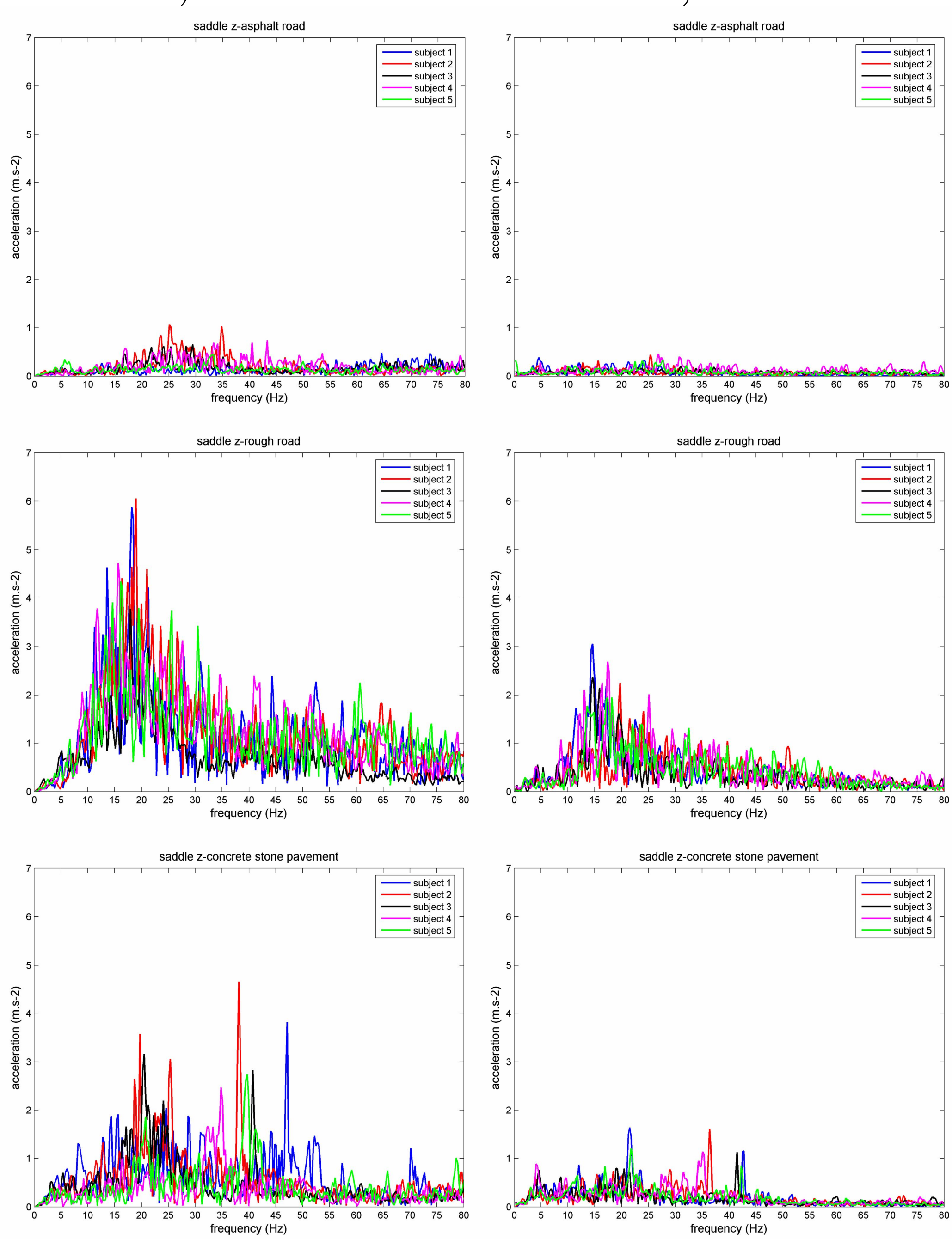

Figure 6.4 a_z (saddle)-f curves obtained from the field measurements for Road Bike (a) and MTB (b) on asphalt road (i), rough road (ii), concrete stone pavement (iii)

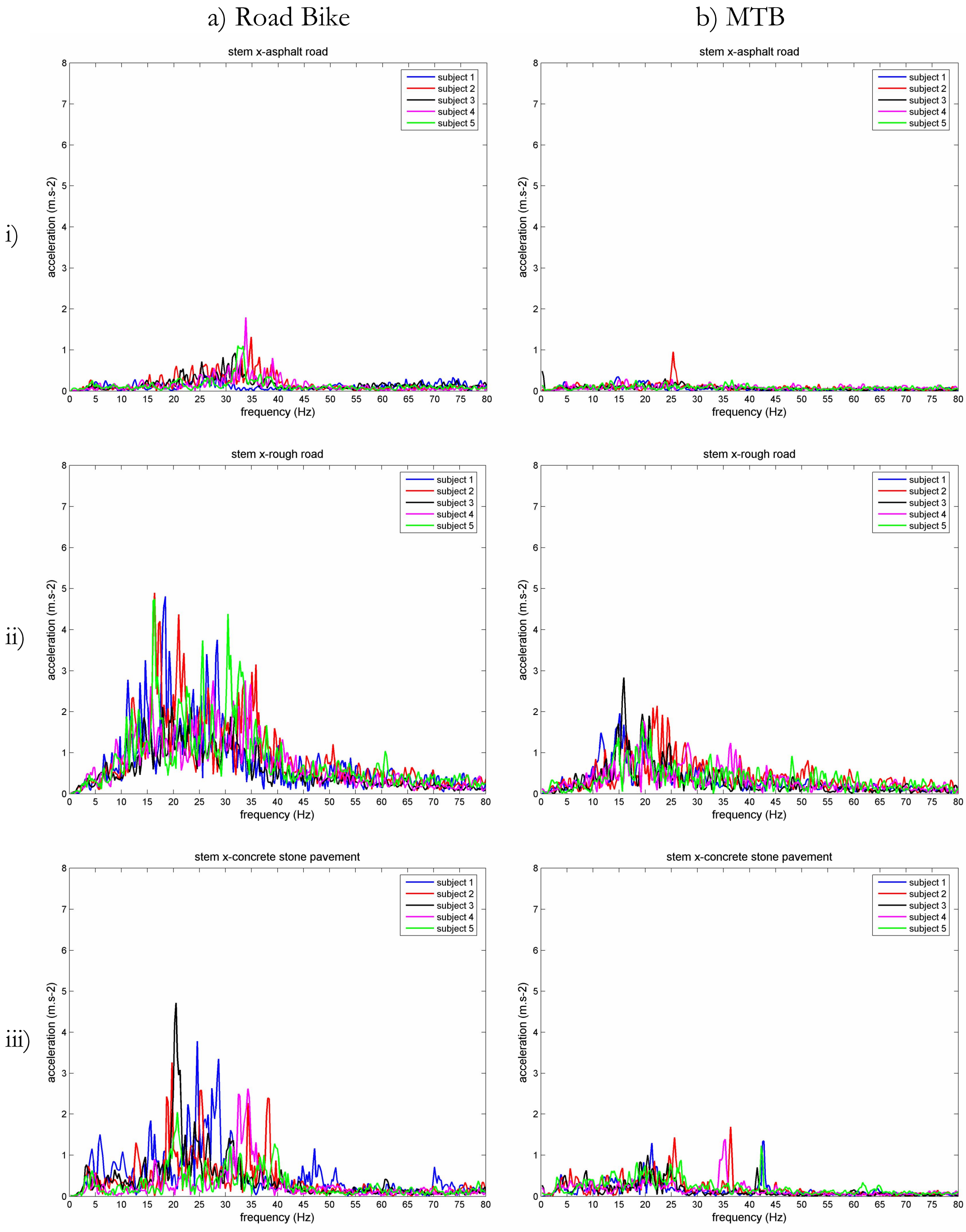

Figure 6.5 a_x (stem)-f curves obtained from the field measurements for Road Bike (a) and MTB (b) on asphalt road (i), rough road (ii), concrete stone pavement (iii)

a) Road Bike b) MTB

i)

ii)

iii)

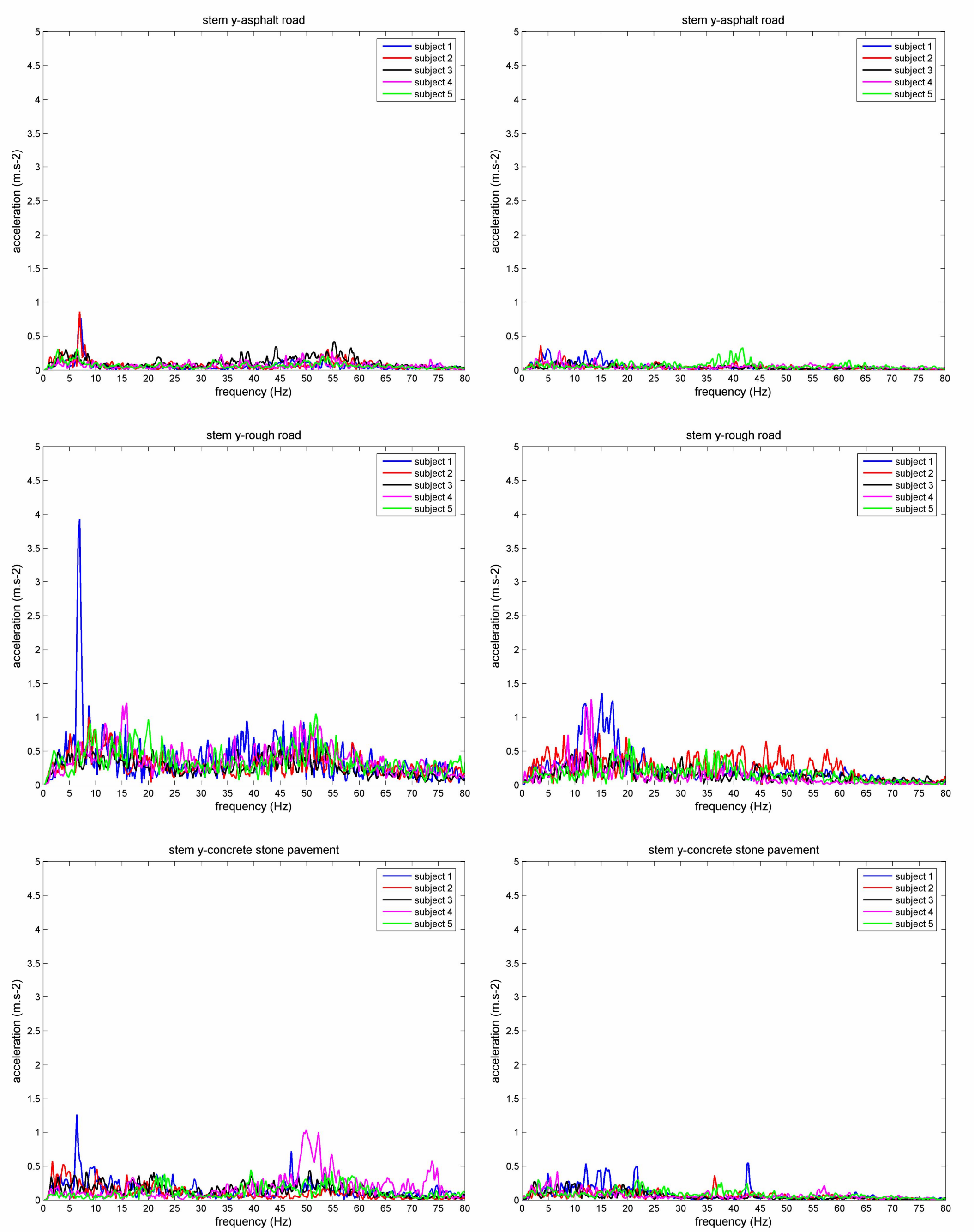

Figure 6.6 a_y (stem)-f curves obtained from the field measurements for Road Bike (a) and MTB (b) on asphalt road (i), rough road (ii), concrete stone pavement (iii)

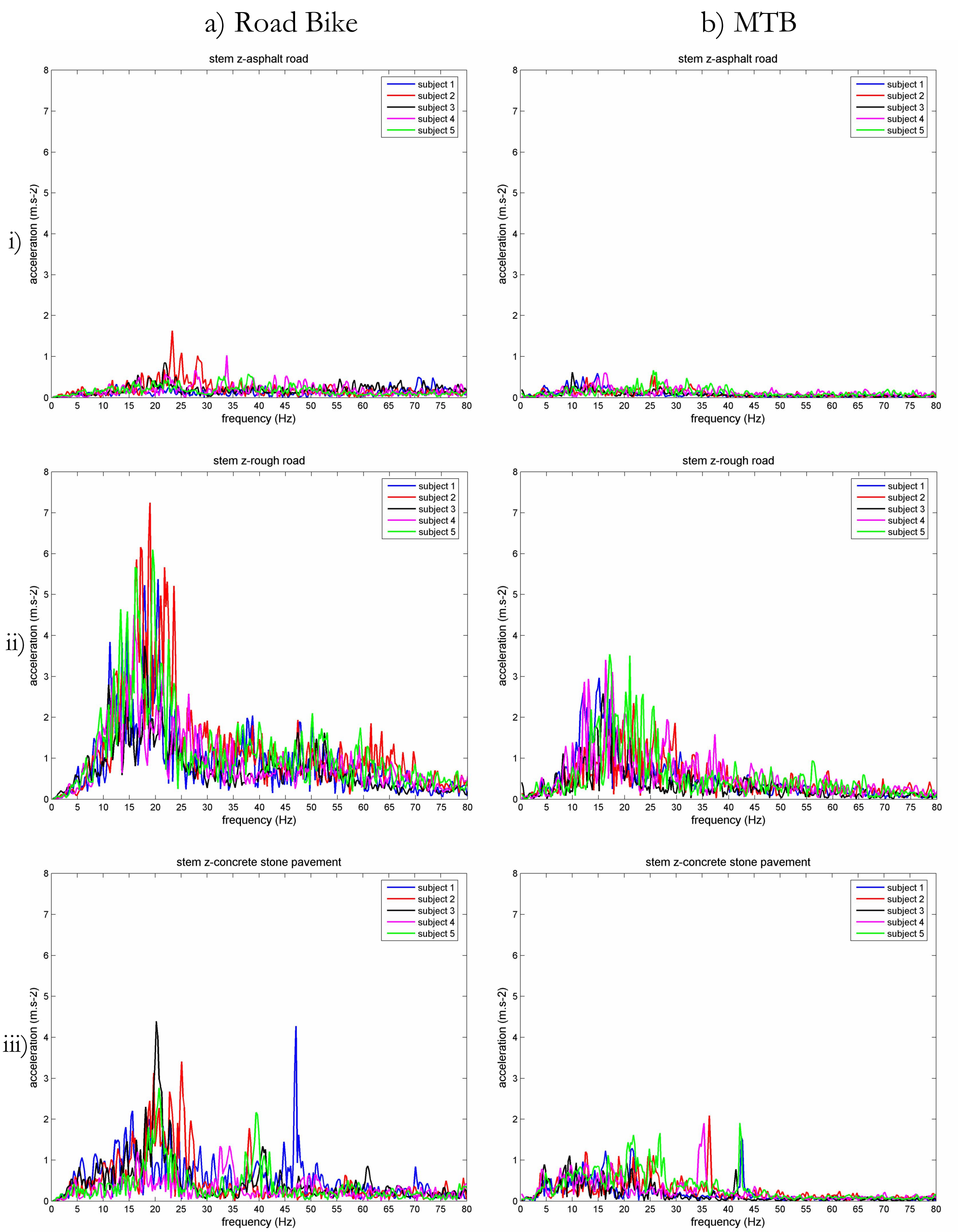

Figure 6.7 a_z (stem)-f curves obtained from the field measurements for Road Bike (a) and MTB (b) on asphalt road (i), rough road (ii), concrete stone pavement (iii)

The vibration total values, a_v in Table 6.9 are calculated (via Equation 3.4) for health as well as comfort and perception by using the weighted rms acceleration magnitudes corresponding to field saddle accelerations. a_{wx} ,a_{wy} ,a_{wz} and a_v values are presented in Table 6.9 for both RB and MTB trials. The results showed that the increase in road roughness resulted in higher values both in Road Bike and MTB. Vibration total values ranked, from lowest to highest, as asphalt road, concrete stone pavement and rough road (Figure 6.8). The severity of transmitted vibration to the bicycle was found to be considerably higher especially in road bike trials. To illustrate, rough road trials revealed the highest vibration total values between 4.5-6.9 $m.s^{-2}$ for road bike and between 2.4-5 $m.s^{-2}$ for MTB.

Previous studies have also revealed that cyclists experience high levels of vibration. At dominating frequencies between 5 to 10 Hz the vibration total values were found to range from 3.4 ms^{-2} to 28.5 ms^{-2} (Torbic et al, 2003).In another study, Lewis and Paddan (1990) calculated overall ride value from frequency weighted (weighting: w_b) z- axis acceleration as 1.46 ms^{-2} rms on the rider. As a result of the measurements on ATB type bicycle in an off-road course, Lewis and Paddan (1990) also found that overall-frequency weighted vibration magnitude measured on the bicycle was 3.14ms^{-2} rms for the saddle and 4.38 ms^{-2} rms for the handlebar. Compatible with ISO 2631, riding on the rough road can also be expected to be very uncomfortable in terms of rider's perception as the acceleration magnitudes measured on the bicycle are above the range of 1.25 to 2.5 ms^{-2} rms (see Table 3.3).

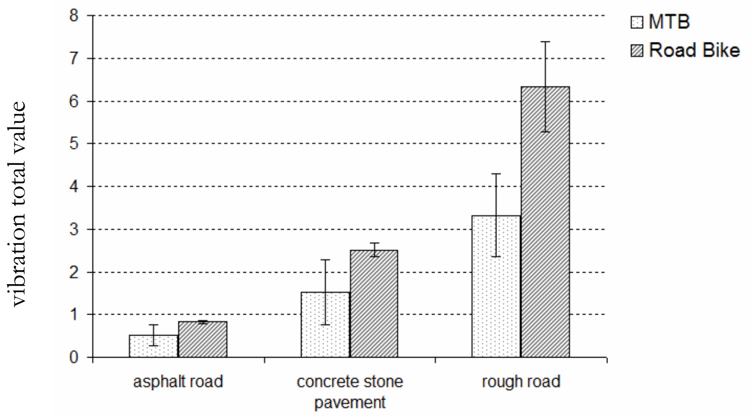

Figure 6.8 Comparison of vibration total values (for health) at the saddle for different surfaces

Table 6.9 Weighted saddle accelerations and vibration total values (a_v) for Road Bike and MTB trials on different road surfaces

			Road					MTB				
			Subject 1	Subject 2	Subject 3	Subject 4	Subject 5	Subject 1	Subject 2	Subject 3	Subject 4	Subject 5
Asphalt Road		a_{wx}	0,100	0,254	0,265	0,207	0,154	0,087	0,134	0,124	0,115	0,144
		a_{wy}	0,142	0,298	0,117	0,082	0,089	0,171	0,105	0,102	0,088	0,157
		a_{wz}	0,463	0,921	0,716	1,012	0,600	0,477	0,451	0,387	0,500	0,452
	(health)	a_v	0,522	1,071	0,823	1,059	0,649	0,547	0,510	0,448	0,540	0,541
	(comfort& perception)	a_v	0,494	1,000	0,773	1,036	0,626	0,514	0,482	0,419	0,521	0,499
Rough Road		a_{wx}	1,057	1,169	1,059	1,193	1,237	1,010	0,580	0,532	0,454	0,532
		a_{wy}	0,711	0,374	0,314	0,491	0,358	0,311	0,280	0,324	0,225	0,326
		a_{wz}	6,622	6,501	4,354	6,759	6,195	4,879	3,318	2,500	2,908	2,285
	(health)	a_v	6,858	6,725	4,621	6,996	6,452	5,099	3,439	2,648	2,993	2,446
	(comfort& perception)	a_v	6,743	6,616	4,492	6,881	6,327	4,993	3,380	2,576	2,952	2,368
Concrete Stone P.		a_{wx}	0,245	0,635	0,875	0,492	0,402	0,373	0,404	0,375	0,324	0,428
		a_{wy}	0,228	0,312	0,266	0,192	0,125	0,345	0,118	0,176	0,270	0,421
		a_{wz}	1,375	3,103	2,790	2,713	1,876	1,605	1,209	1,321	1,363	1,344
	(health)	a_v	1,453	3,257	3,070	2,812	1,967	1,755	1,344	1,442	1,485	1,585
	(comfort& perception)	a_v	1,416	3,183	2,936	2,764	1,923	1,683	1,280	1,384	1,427	1,472

Similar to the acceleration spectra, the power spectrum densities have revealed that road roughness resulted in frequency range to be shifted towards lower frequencies. Power spectra have also shown that most of the vibration energy was located between 5 and 25 Hz for all measurement points regardless of the amplitude difference between bicycle types (Figure 6.9). In a similar manner, Lewis and Paddan (1990) have found that the power spectra on saddle increased steadily from 5 Hz to 14 Hz, whereas the corresponding frequency range for handlebar was between 5 to 30 Hz and reached higher values than that at saddle.

The findings of Faiss et al (2007) have also shown that the frequency range for PSD of vertical accelerations ranges from 0 to 25 Hz at the saddle level with a peak frequency of 2.3 Hz for MTB with dual suspension and 4.8 Hz for MTB with front suspension. However, in this study the power spectral density of vibration at the saddle and stem (Figure 6.9) exhibited a similar shape for both road bike and MTB under rough road conditions. PSD of vertical accelerations corresponding to concrete stone pavement and asphalt road trials displayed a wider effective frequency range compared to rough road trials.

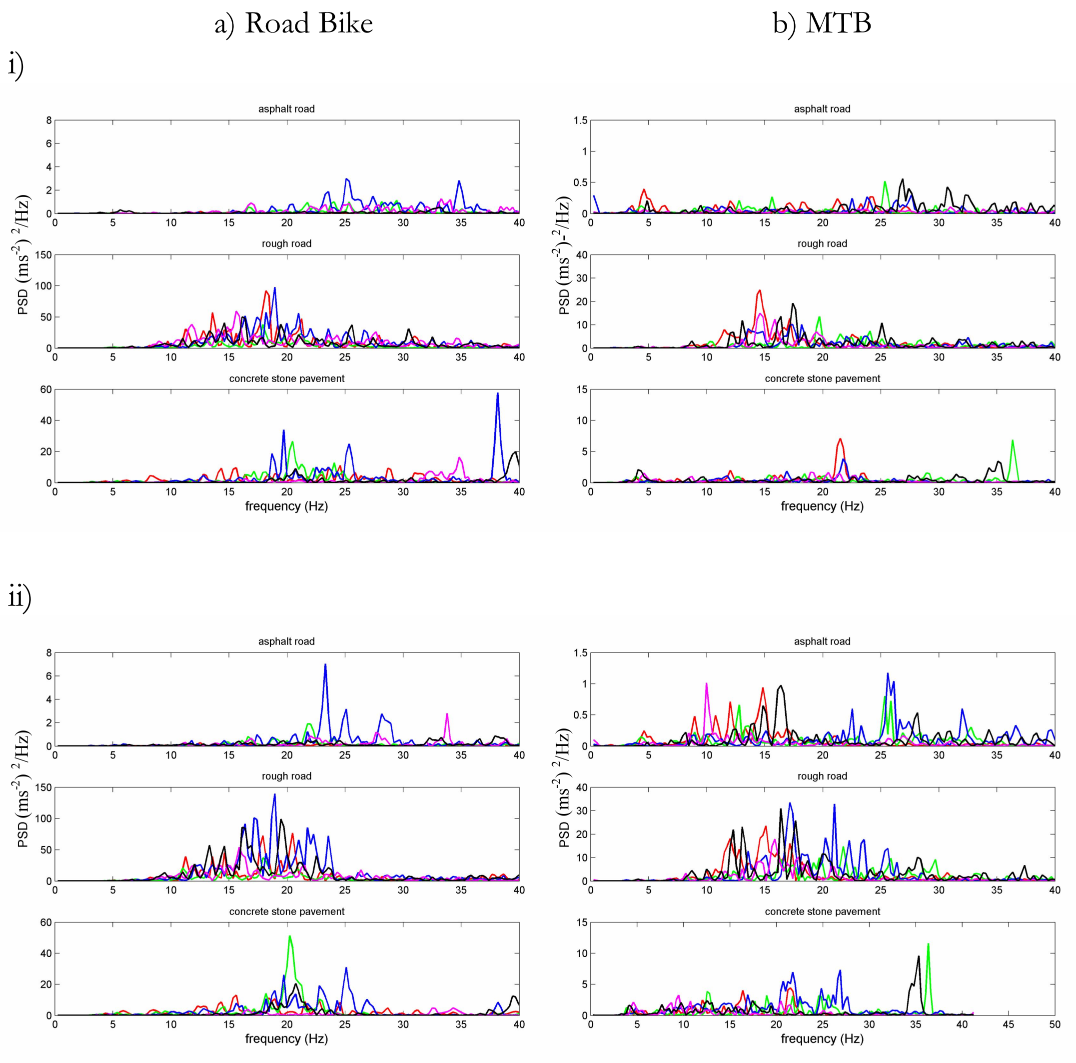

Figure 6.9 Saddle (i) and Stem (ii) a_z – f (PSD) curves obtained from the field measurements of Road bike (a) and MTB (b) on asphalt road (top), rough road (middle) and concrete stone pavement (bottom)

6.2.1.1 Vibration Transmission to the Saddle of the Bicycle: The Effects of Road Surface Conditions and Type of the Bicycle

In Figure 6.10 and 6.11 (in Figures C.1 and C.2 in Appendix C), the comparisons among different road surfaces were illustrated by means of median values of saddle accelerations at dominant axes (x and z).For both road bike and MTB trials, the acceleration spectrum was similar in shape for each of the road surfaces for both axes regardless of amplitude differences.

In road bike (Figure 6.10), effective frequency ranges for asphalt and rough road were observed to be over the full range of frequencies (i.e., 0.5 to 80 Hz). However, a_z-f (saddle) curves corresponding to trials on concrete stone pavement displayed two different effective frequency regions. The first one was between 0 and 35 Hz and involved the highest peak. The second one was between 35 and 50 Hz and involved the next highest peak.

The acceleration spectrum on each road surface was nearly identical in case of MTB trials with the effective frequency range between 0 and 50 Hz (Figure 6.11). As can also be seen in Tables 6.4-6.9, peak frequencies corresponding to x and z-axis saddle accelerations were more or less the same.

The comparison of bicycle types was also shown by median acceleration vs. frequency curves of saddle in Figure 6.12 for two different test tracks. As shown in the Figure, although the level of vibration exposure was greater in road bike on both surfaces, with increased roughness acceleration curves for both bicycles become similar. This trend was apparent for both x and z axes. The comparison of bicycle types for y-axis has also been presented in Figures C.3 and C.4 in Appendix C.

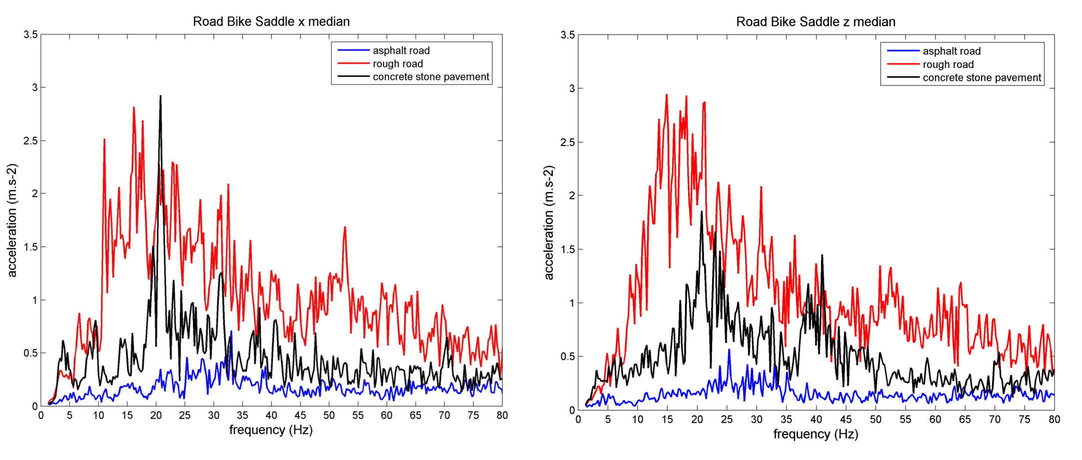

Figure 6.10 Median a_x (left) and a_z (right)-f curves obtained at the saddle during the field measurements with road bike on asphalt road, rough road and concrete stone pavement

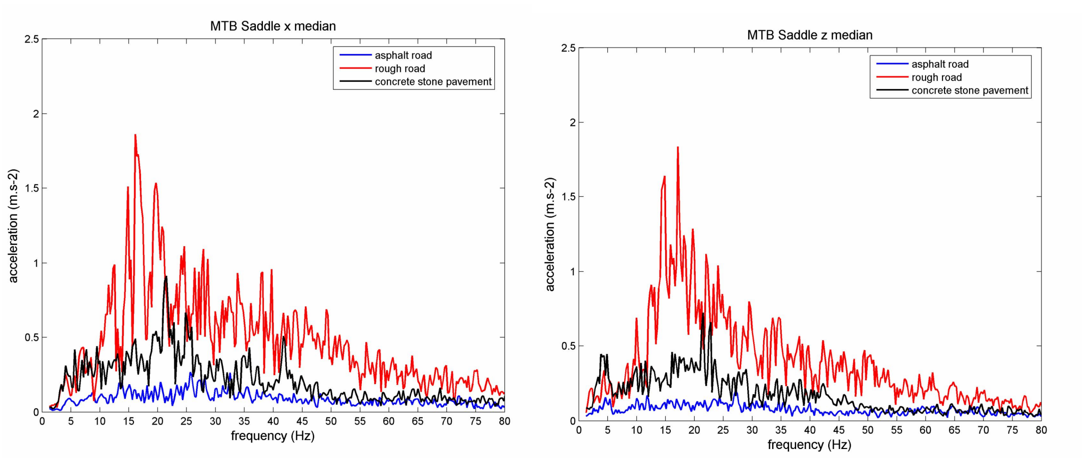

Figure 6.11 Median a_x (left) and a_z (right) -f curves obtained at the saddle during the field measurements with MTB on asphalt road, rough road and concrete stone pavement

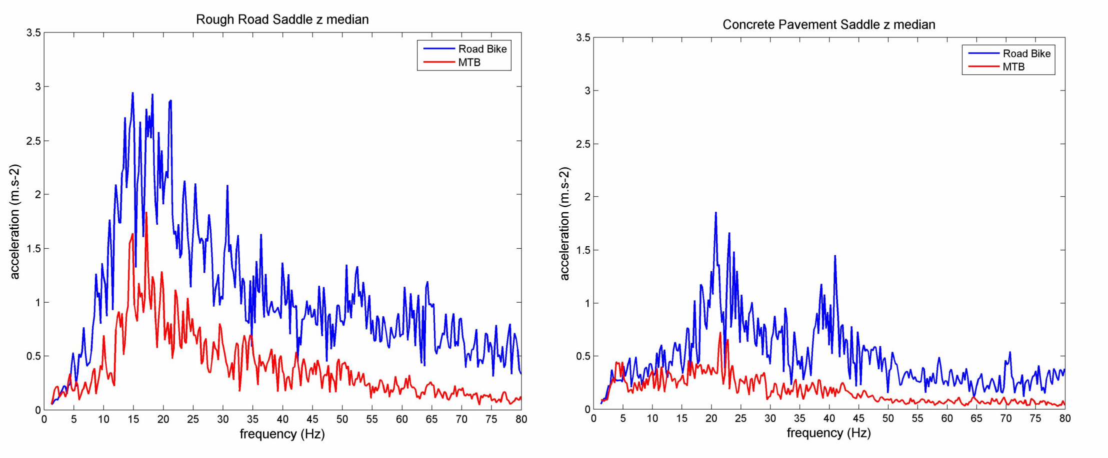

Figure 6.12 Comparison of Road Bike and MTB in terms of Median a_z (saddle)-f curves for different test tracks (rough road and concrete stone pavement)

6.2.1.2. Vibration Transmission to the Stem of the Bicycle: The Effects of Road Surface Conditions and Type of Bicycle

In Figure 6.13 and 6.14, the comparisons among different road surfaces were illustrated by median values of stem accelerations at dominant axes (x and z) calculated for subjects recruited to road bike (n=5) and MTB (n=5) measurements, respectively. In contrast to saddle acceleration, median acceleration values obtained at the stem of the road bike was substantially constant between the frequencies of 10 to 35 Hz on rough road. Effective frequency range of 0-40 Hz was observed on each of the road surfaces regardless of the type of the bicycle. Similar to the saddle, highest level of accelerations occurred in the road bike trials, whereas the lowest values were observed in asphalt road. The comparisons of stem accelerations among different surfaces were also illustrated for both road bike and MTB in Figure C.5 in Appendix C.

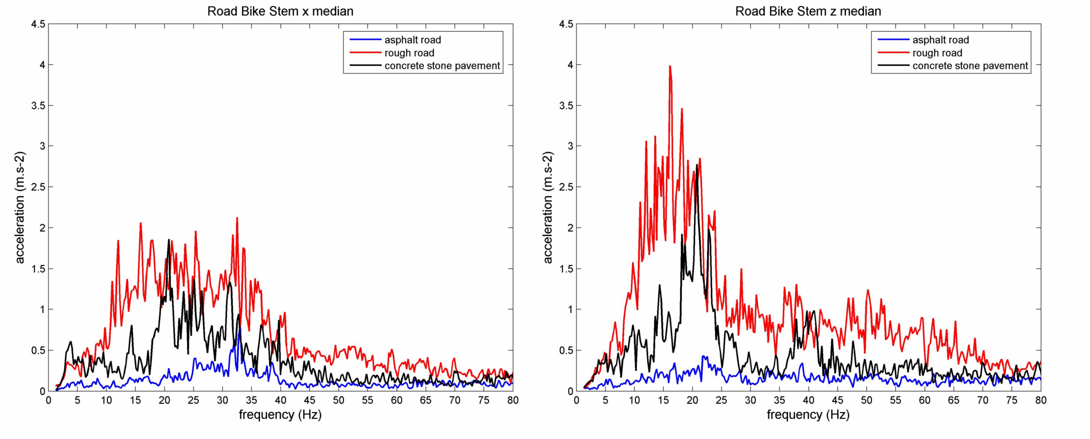

Figure 6.13 Median a_x (left) and a_z (right)-f curves obtained at the stem during the field measurements with road bike on asphalt road, rough road and concrete stone pavement

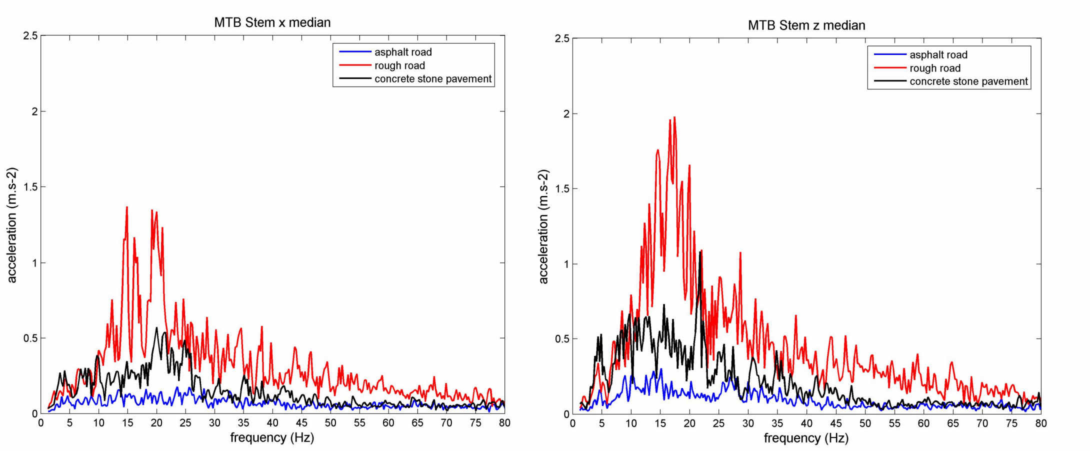

Figure 6.14 Median a_x (left) and a_z (right)-f curves obtained at the stem during the field measurements with MTB on asphalt road, rough road and concrete stone pavement

6.2.1.3. Comparison between Entry Points: Saddle vs. Stem

Acceleration spectra for median values corresponding to rough road measurements were illustrated in Figure 6.15 as an example for the comparison of median acceleration levels measured at the saddle and stem of road bikes. Median saddle accelerations were seen to be higher than stem accelerations in x-axis. In z direction however median stem accelerations were higher than saddle accelerations. Concrete stone pavement revealed the similar pattern with rough road comparisons.

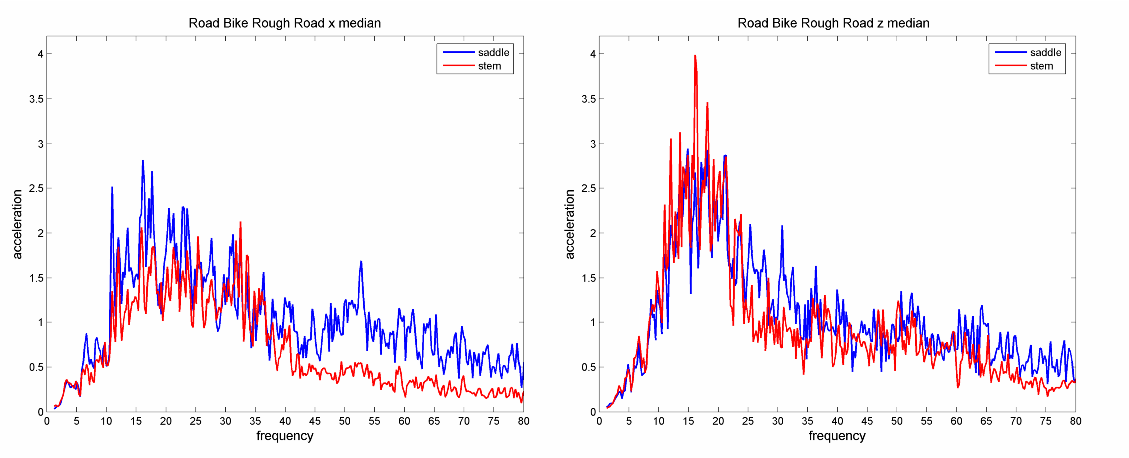

Figure 6.15 Median a_x and a_z -f curves (road bike) corresponding to rough road measurements: saddle vs. stem

6.2.2. Vibration Transmission to the Bicycle-Rider System: The Effect of Transmission Path

In order to better evaluate to what extent vibration is transmitted to the rider's forehead and shoulder through the saddle and stem, acceleration spectra corresponding to different road surfaces were illustrated in Figures 16-21 by sample graphs of Subject 2 for Road Bike and Subject 1 for MTB in each of the three axes.

The acceleration spectra of all subjects were also presented in Appendix C (Figures C.6-C.14 for road bike and Figures C.15-C.23 for MTB in Appendix C).

Vibration transmission to the rider's body, specifically to the rider's head, has only been investigated by Lewis and Paddan (1990) on ATB (all terrain bicycle) type bicycle without any suspension system. Researchers have pointed out that the level of vibration transmission to the head tends to decrease at frequencies above 25 Hz. In a similar manner, it has been found in the present study that the effective frequency range for both road bike and MTB trials were between 0-30 Hz for shoulder and between 0-25 Hz for forehead regardless of entry point of input vibration. Moreover, substantial damping of vibration has been observed at all measurement points above these frequencies similar to those reported in previous researches (Lewis and Paddan, 1990; Faiss, 2007).

(i) saddle-shoulder-head (ii) stem-shoulder-head

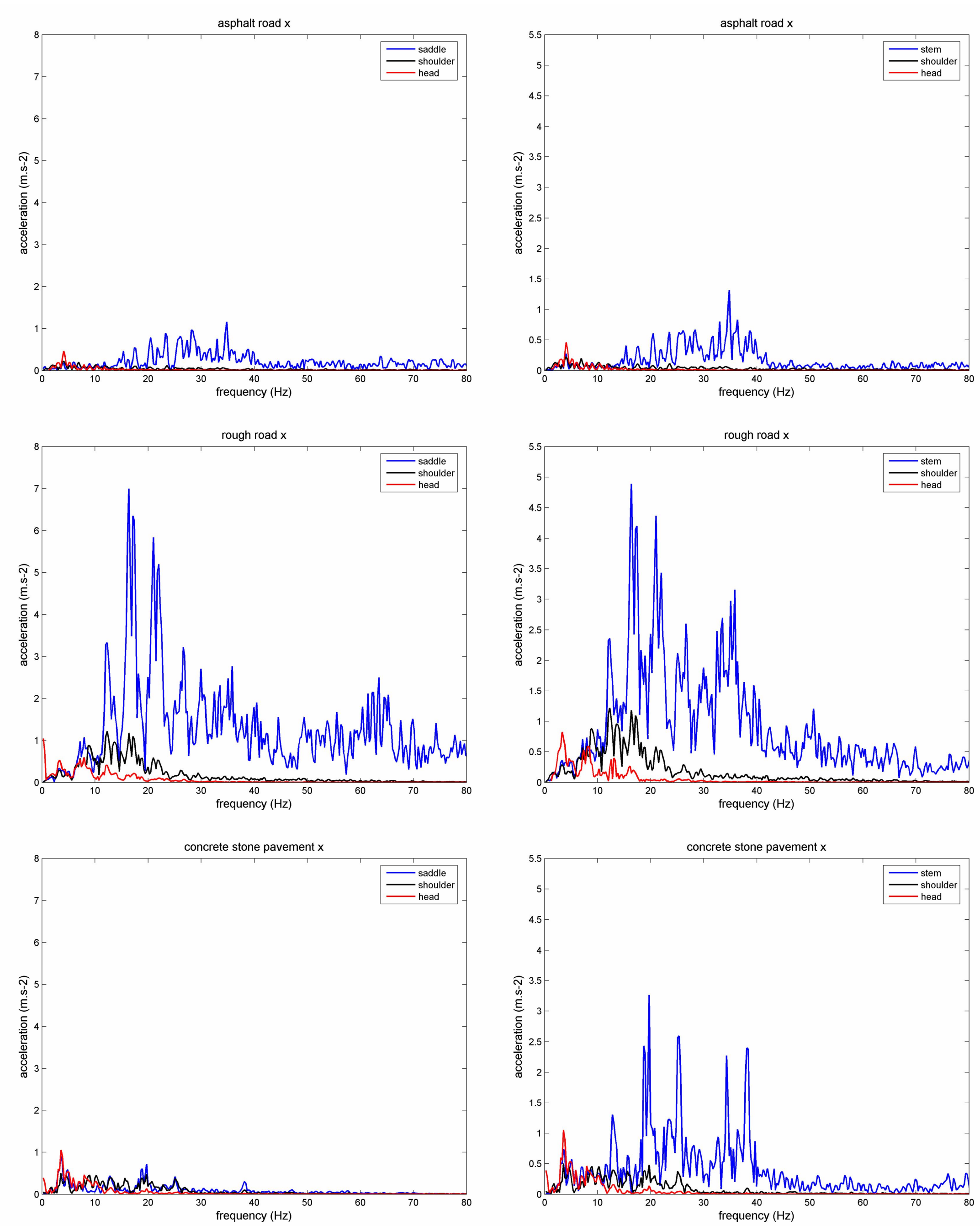

Figure 6.16 Vibration transmitted, in x direction, to subject 2 on road bike, through (i) saddle-shoulder-forehead and (ii) stem-shoulder-forehead, on different surfaces

(i) saddle-shoulder-head (ii) stem-shoulder-head

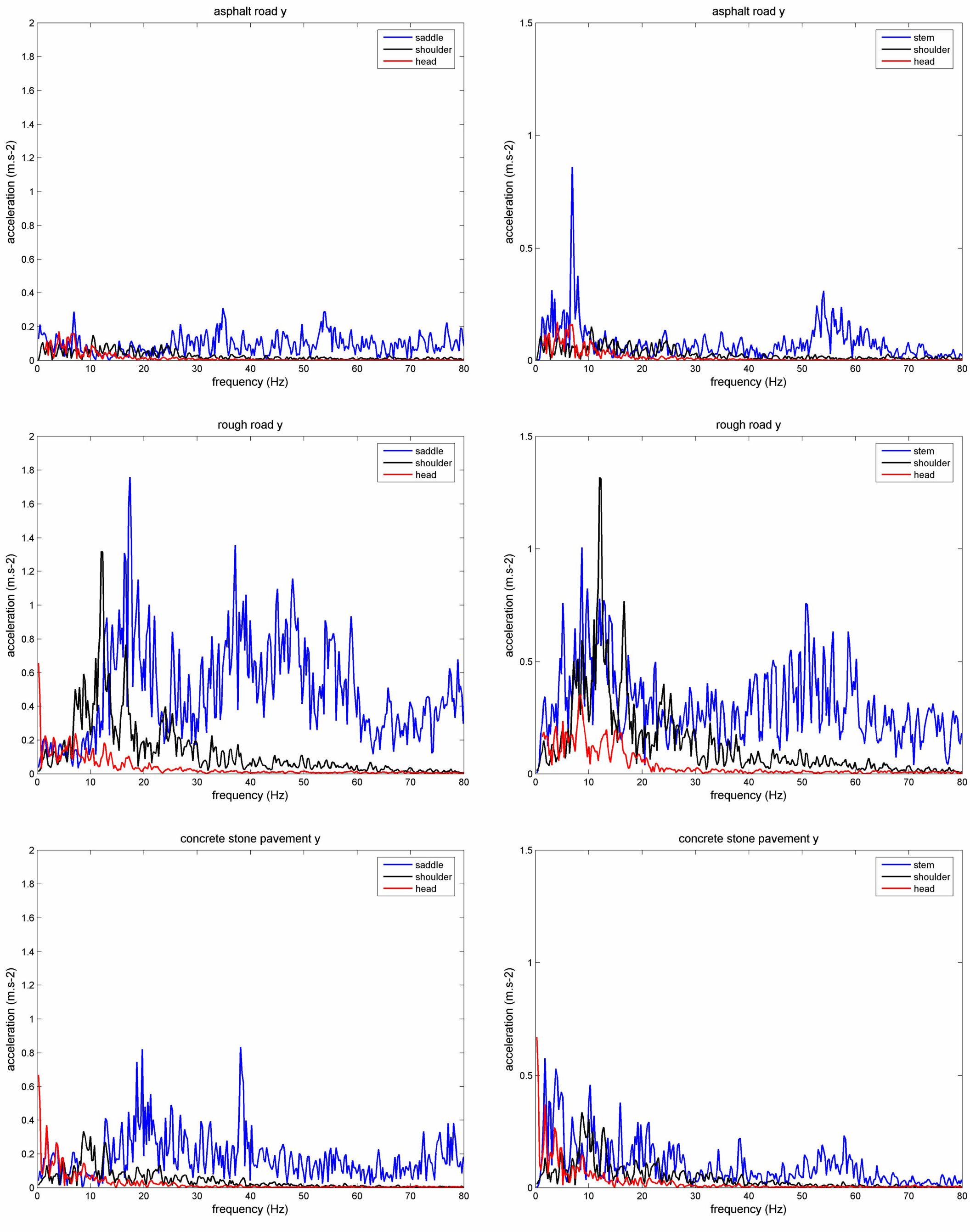

Figure 6.17 Vibration transmitted, in y direction, to subject 2 on road bike, through (i) saddle-shoulder-forehead and (ii) stem-shoulder-forehead, on different surfaces

(i) saddle-shoulder-head (ii) stem-shoulder-head

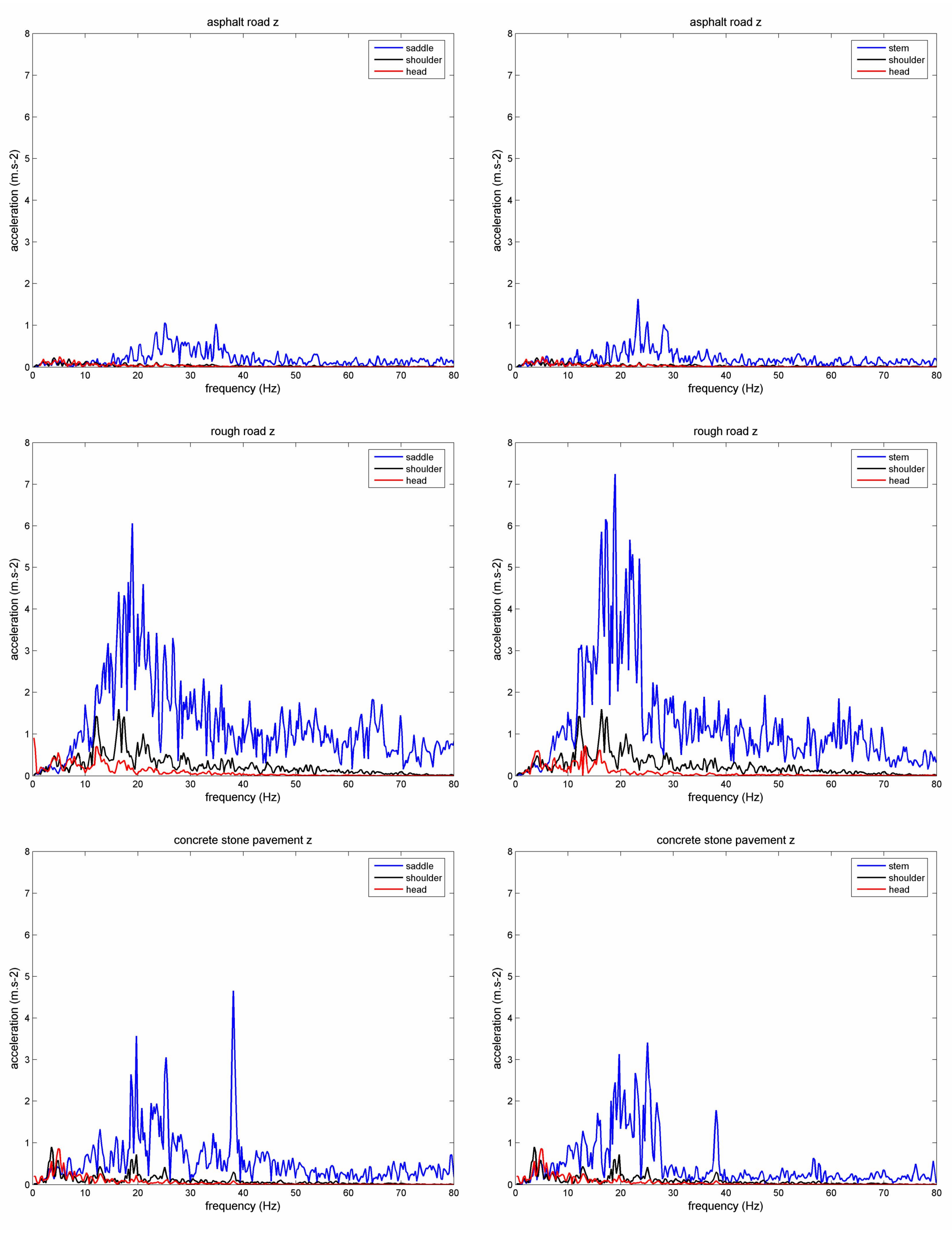

Figure 6.18 Vibration transmitted, in z direction, to subject 2 on road bike, through (i) saddle-shoulder-forehead and (ii) stem-shoulder-forehead, on different surfaces

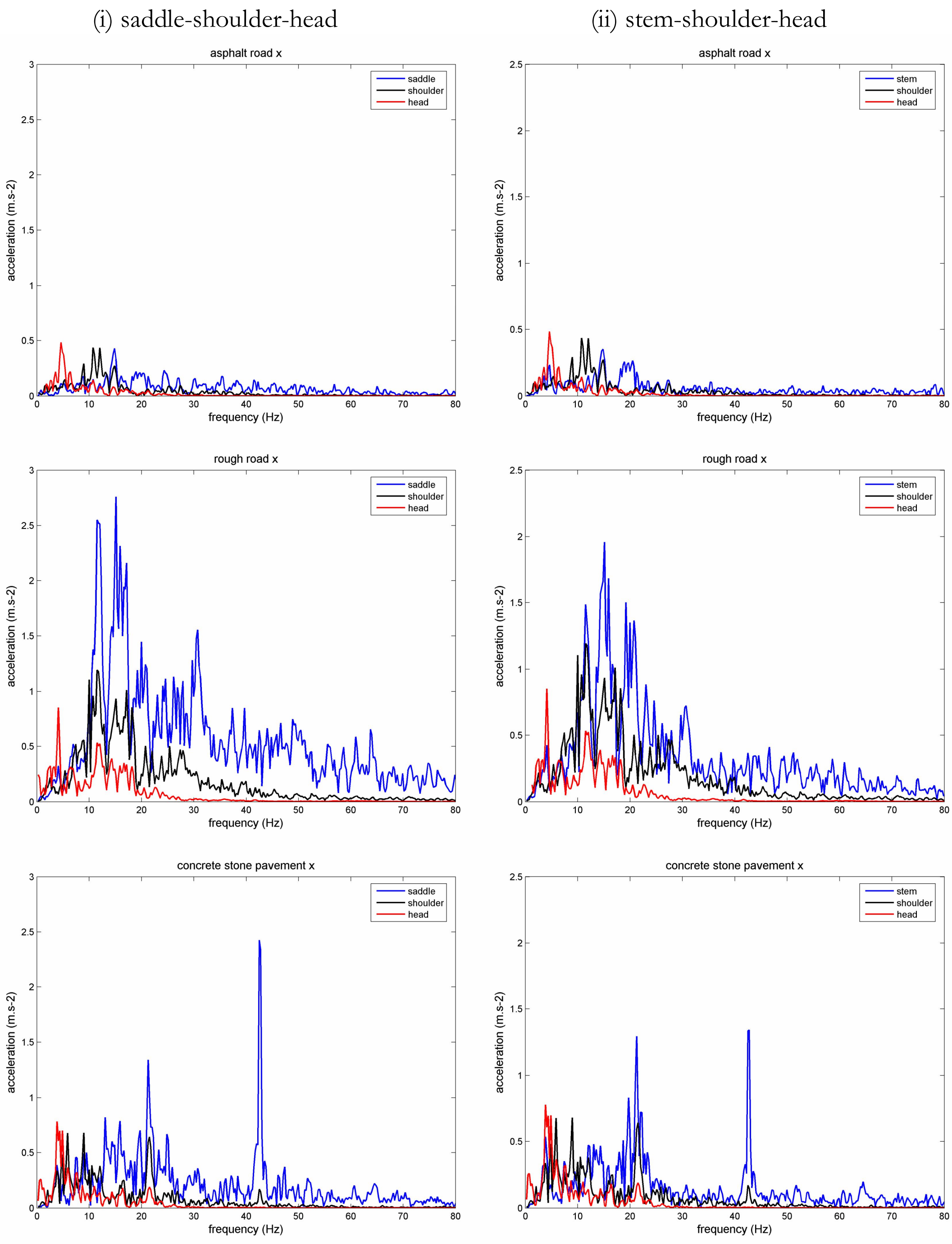

Figure 6.19 Vibration transmitted, in x direction, to subject 1 on MTB, through (i) saddle-shoulder-forehead and (ii) stem-shoulder-forehead, on different surfaces

(i) saddle-shoulder-head (ii) stem-shoulder-head

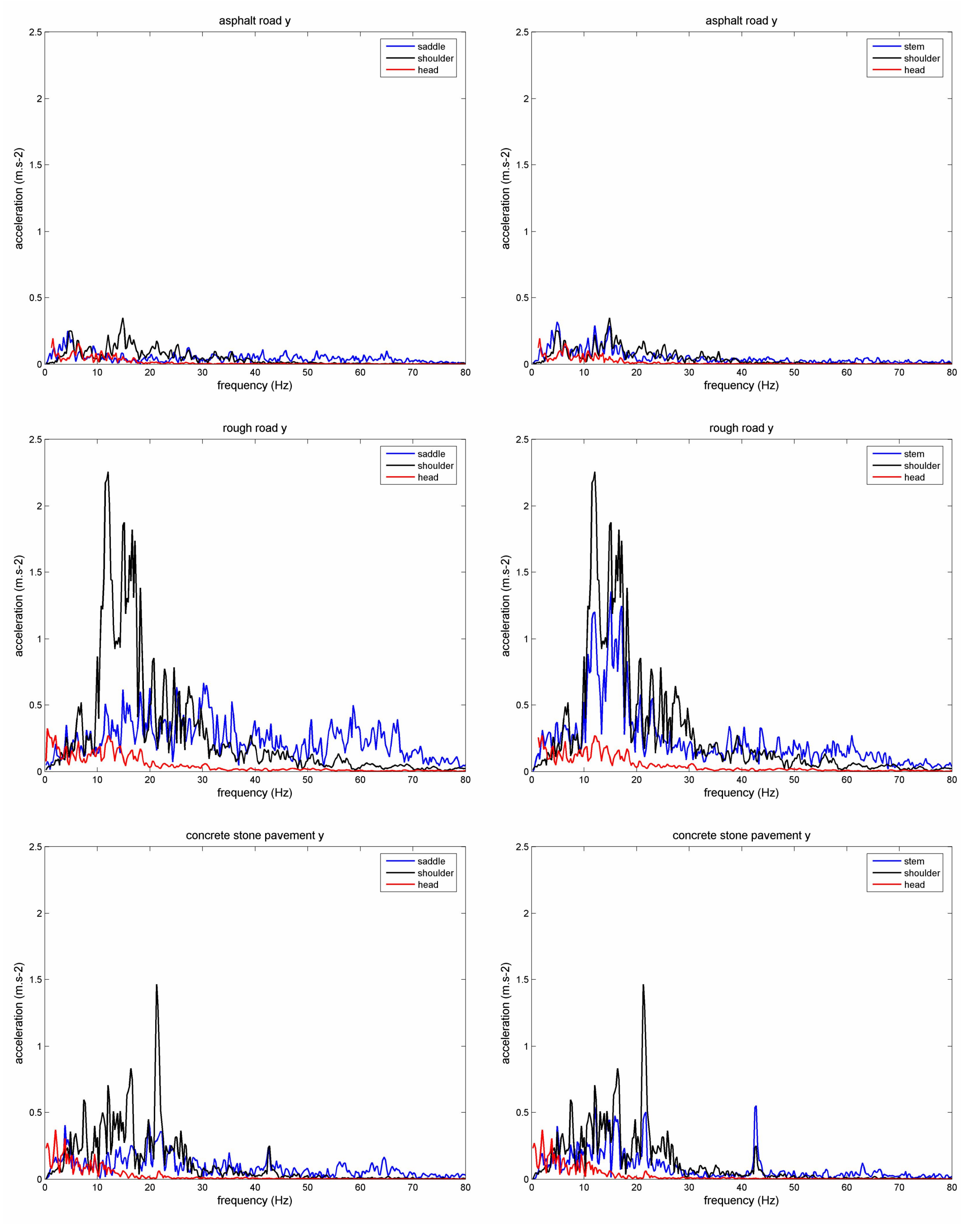

Figure 6.20 Vibration transmitted, in y direction, to subject 1 on MTB, through (i) saddle-shoulder-forehead and (ii) stem-shoulder-forehead, on different surfaces

(i) saddle-shoulder-head (ii) stem-shoulder-head

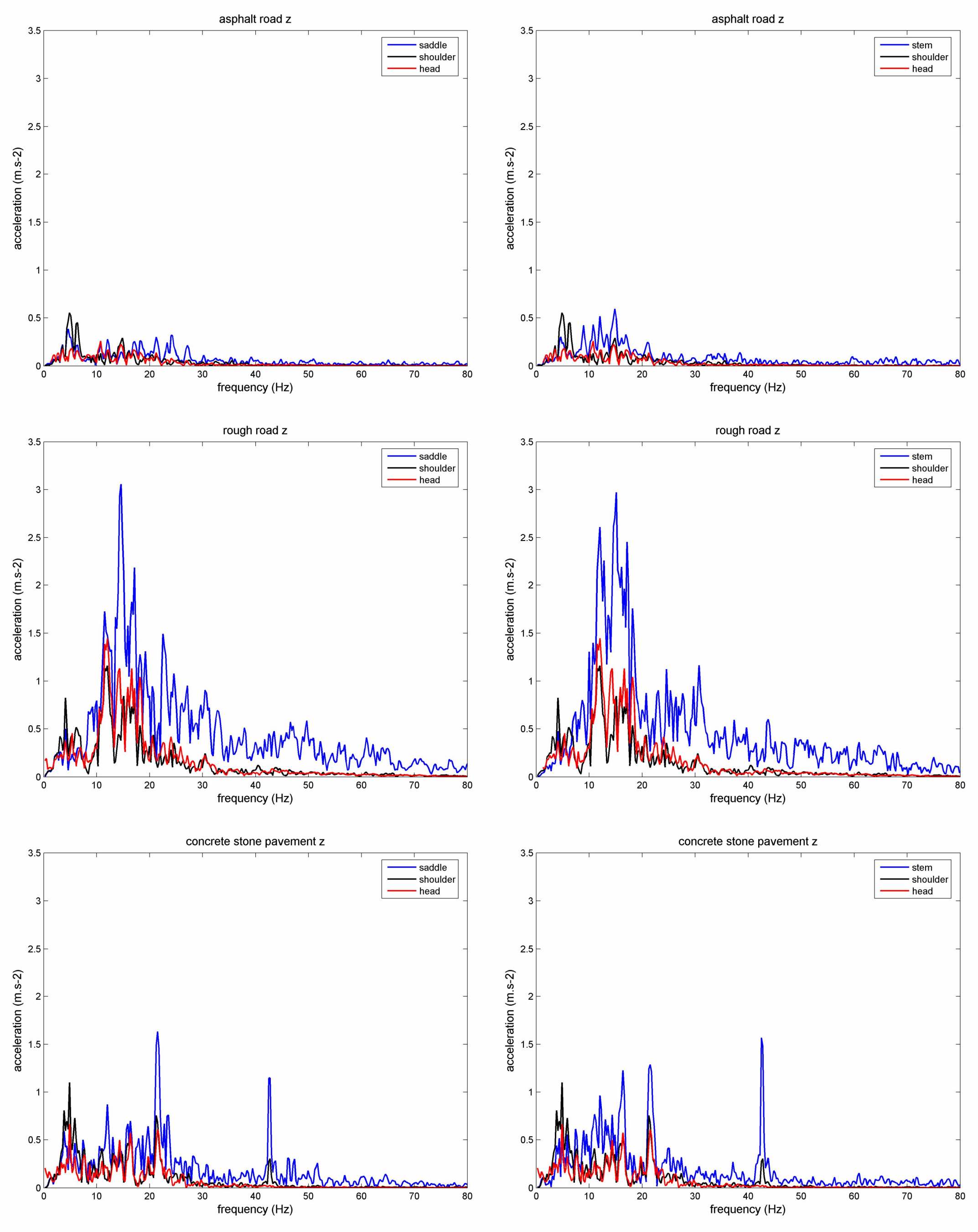

Figure 6.21 Vibration transmitted, in z direction, to subject 1 on MTB, through (i) saddle-shoulder-forehead and (ii) stem-shoulder-forehead, on different surfaces

6.2.2.1. Transmission of vibration to rider: saddle-shoulder-forehead

The vibration transmission to the riders' body (shoulder and forehead) was evaluated by two different transmission paths namely; through saddle or stem. The transmissibility ratios were calculated using the formula given by Equation 3.3.In this section saddle-shoulder-forehead transmission path is considered. First TR_{z_head} or $TR_{z\_shoulder}$ were calculated for each subject by dividing the measured head or shoulder acceleration levels in z-axis by the saddle accelerations in z-axis, then their medians were determined. Median TR_z (=T (f) in z direction) vs. frequency curves are displayed, for both bicycle types on each road surface, in Figure 6.22 .Median TR_x and TR_y vs. frequency curves whereas are given in Figures C.24-25 in Appendix C.

The findings revealed that road bike trials can be characterized as lower frequency dominant response compared to MTB. For each type of bicycle, TRs for different surfaces varied in similar pattern for both forehead and shoulder. The frequencies where the TR_z (Figure 6.22) values tend to shift to values lower than 1 were apparent at 10, 7 and 6 Hz for road bike, and at 10,10,7 Hz for MTB on asphalt road, concrete stone pavement and on rough road, respectively.

Road Bike MTB

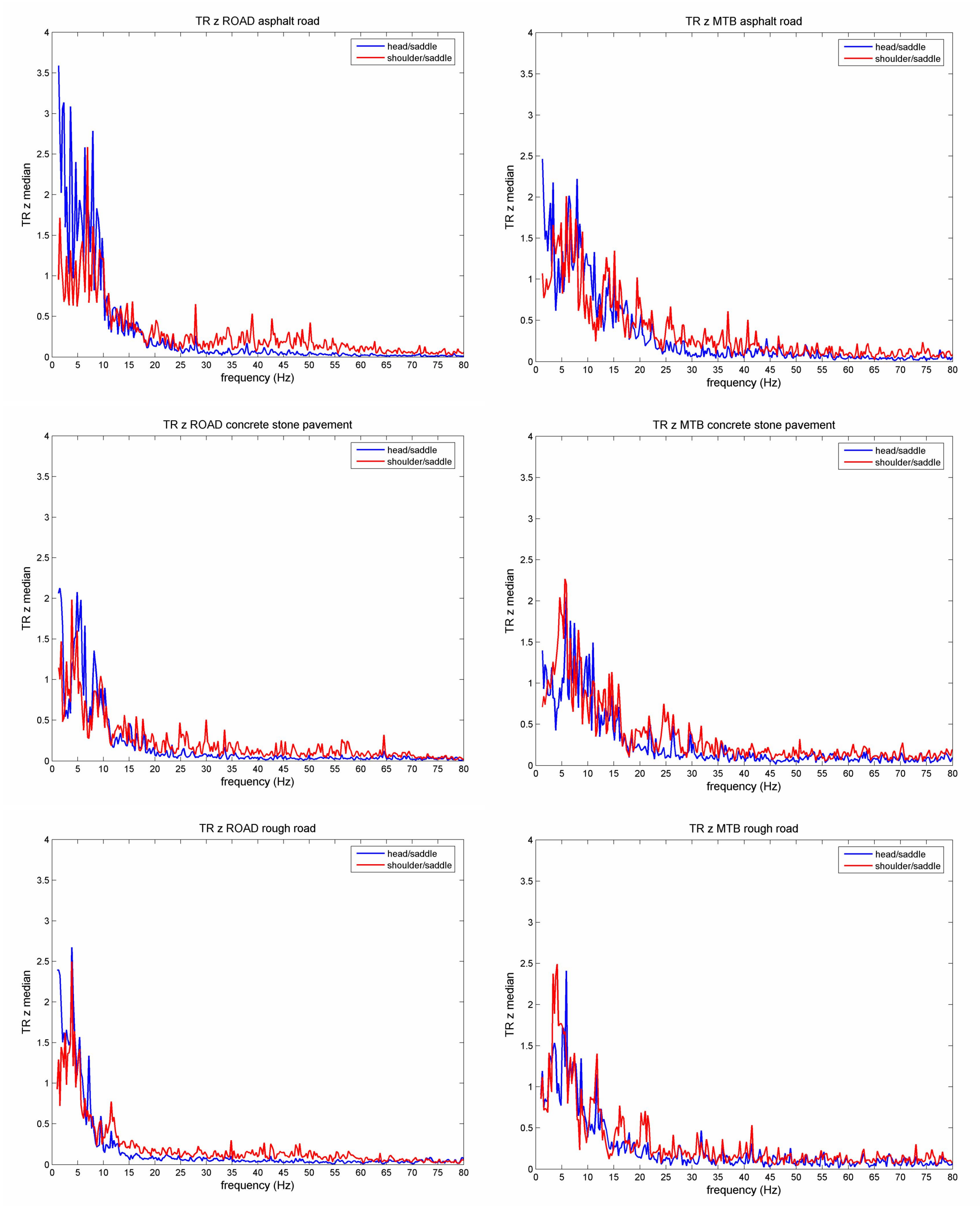

Figure 6.22 Median TR $_z$- f curves for Road bike and MTB on different surfaces (Transmission path: saddle- shoulder -head)

6.2.2.2. Transmission of vibration to rider: stem-shoulder-forehead

In this section stem-shoulder-forehead transmission path will be considered while assessing the vibrations transmitted to head and shoulder. First TR_{z_head} or $TR_{z\_shoulder}$ were calculated for each subject by dividing the measured head or shoulder acceleration levels in z-axis by the stem accelerations in z-axis, then their medians were determined. Median TR_z vs frequency curves are displayed, for both bicycle types on each road surface, in Figure 6.23.Median TR_x and TR_y vs. frequency curves whereas are given in Figures C.26-27 in Appendix C.

The frequencies where the TR_z values tend to shift to values lower than 1 were apparent at 7, 6 and 5 Hz for road bike, and at 8,7,6 Hz for MTB on asphalt road, concrete stone pavement and on rough road, respectively. The difference in the frequency shift where substantial damping occurs might be explained by the postural difference between two bicycles.

In a similar manner Lewis and Paddan (1990) have also concluded that the contribution of the transmission path depends on the posture maintained by the cyclist as well as the vibration frequency. For instance, in the forward leaning posture, at low frequencies, between 2.5 and 5 Hz, a greater portion of the head motion was explained to be caused by vibration transmitted through the hands and arms than through the torso. However, in the upright sitting posture, z-axis head motion was mainly produced by seat vibration at all frequencies and handlebar vibration transmitted through the hands and arms made little contribution at any frequency.

Road Bike MTB

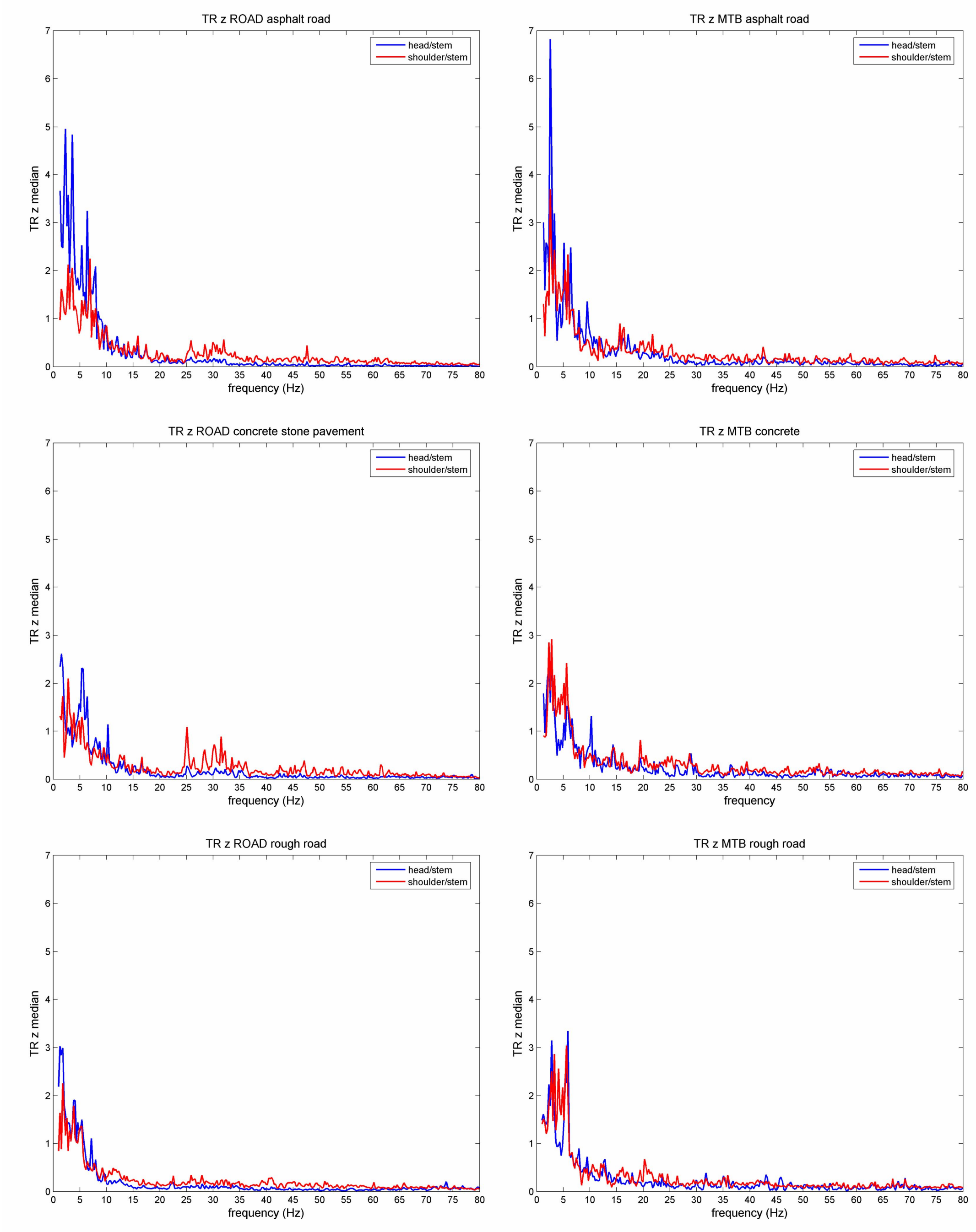

Figure 6.23 Median TR_z- f curves for Road bike and MTB on different surfaces (Transmission path: stem-shoulder -forehead)

6.2.2.3. Transmission of vibration to rider: Comparison of transmission paths

The comparisons of transmission paths (i.e., saddle-shoulder-head and stem-shoulder-head paths) with respect to vibration transmission to forehead and shoulder on both road bike and MTB were shown for z axis in Figures 6.24 and 6.25. Vibration transmission to the subjects' forehead through saddle or stem was not different (except asphalt road) for road bike trials. However, in MTB trials, it appeared that compared to saddle stem had greater contribution in the vibration transmitted to the rider. Moreover, when the two paths are compared, a slight frequency shift to lower frequencies was observed in stem-shoulder-head path. The comparisons of transmission paths for x and y has also been presented in Figures C.28-C.31 in Appendix C.

It has been suggested that the level of vibration transmitted to the body is related with the road surface conditions, bicycle properties, and riding posture sustained by the rider (Faiss et al, 2007; Lewis and Paddan, 1990; Waechter et al, 2002). The findings of the present study have already revealed that the level of vibration transmitted to the body is affected by the road surface conditions. It has to be noted that even though the same tracks were used during the measurements on road bike and MTB, the uneven surface characteristics of the track with randomly distributed small stones on the rough road render it difficult to make a definite comparison between two bicycles.

The difference in the frequency shift where substantial damping occurs might be explained by the postural difference between two bicycles. On the MTB, cyclists maintain more upright sitting posture which in turn resulted in much more of the body weight to be supported by the saddle. Likewise, Lewis and Paddan (1990) pointed out that in the forward leaning posture, at low frequencies, between 2.5 and 5 Hz, a greater portion of the head motion was explained to be caused by vibration transmitted through the hands and arms than through the torso. However, in the upright sitting posture, z-axis head motion was mainly produced by seat vibration at all frequencies and handlebar vibration transmitted through the hands and arms made little contribution at any frequency. Therefore, it is important to consider the postural differences in the evaluation of the contribution of the transmission path.

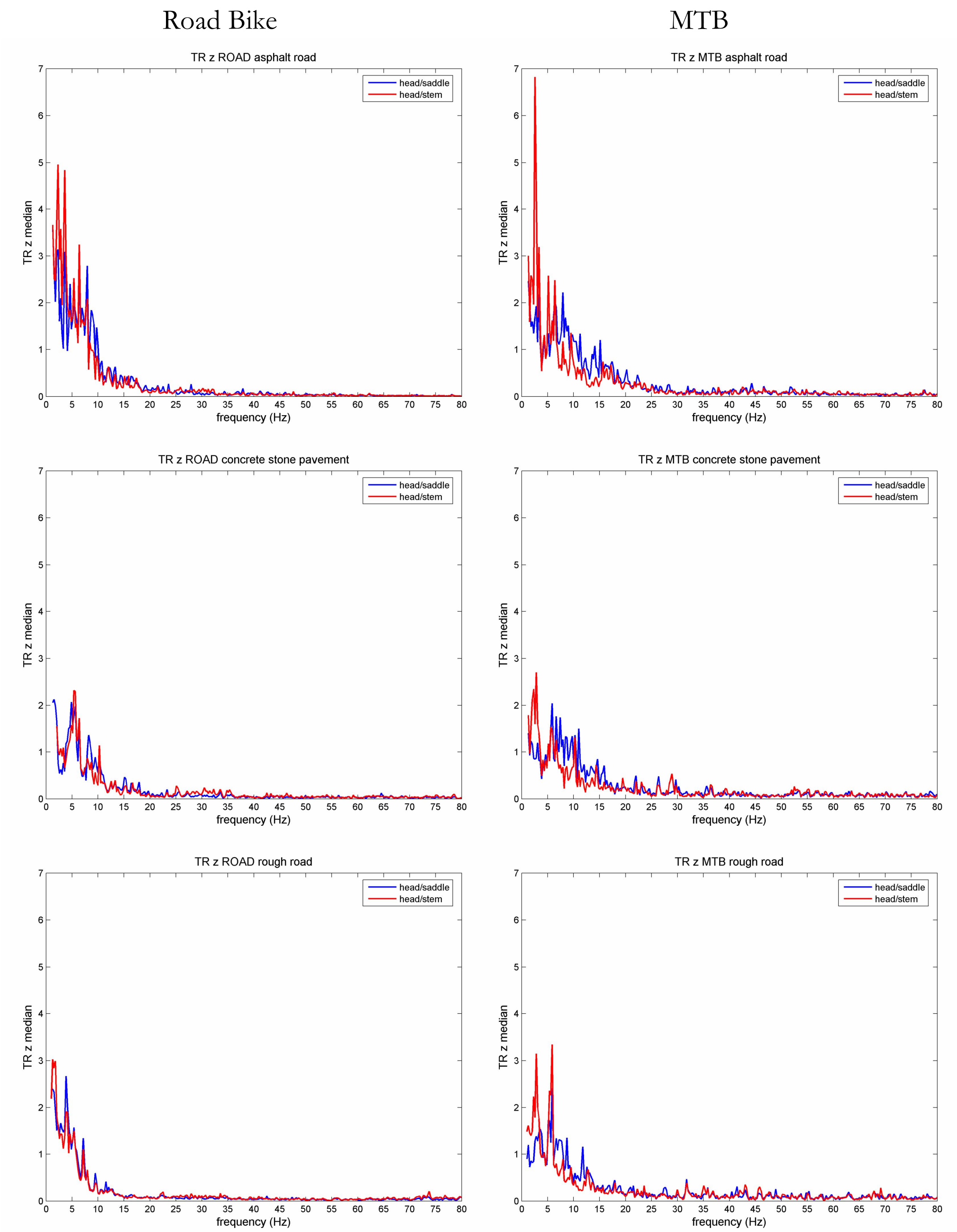

Figure 6.24 Comparison of transmission paths, for head, on road bike and MTB

Road Bike MTB

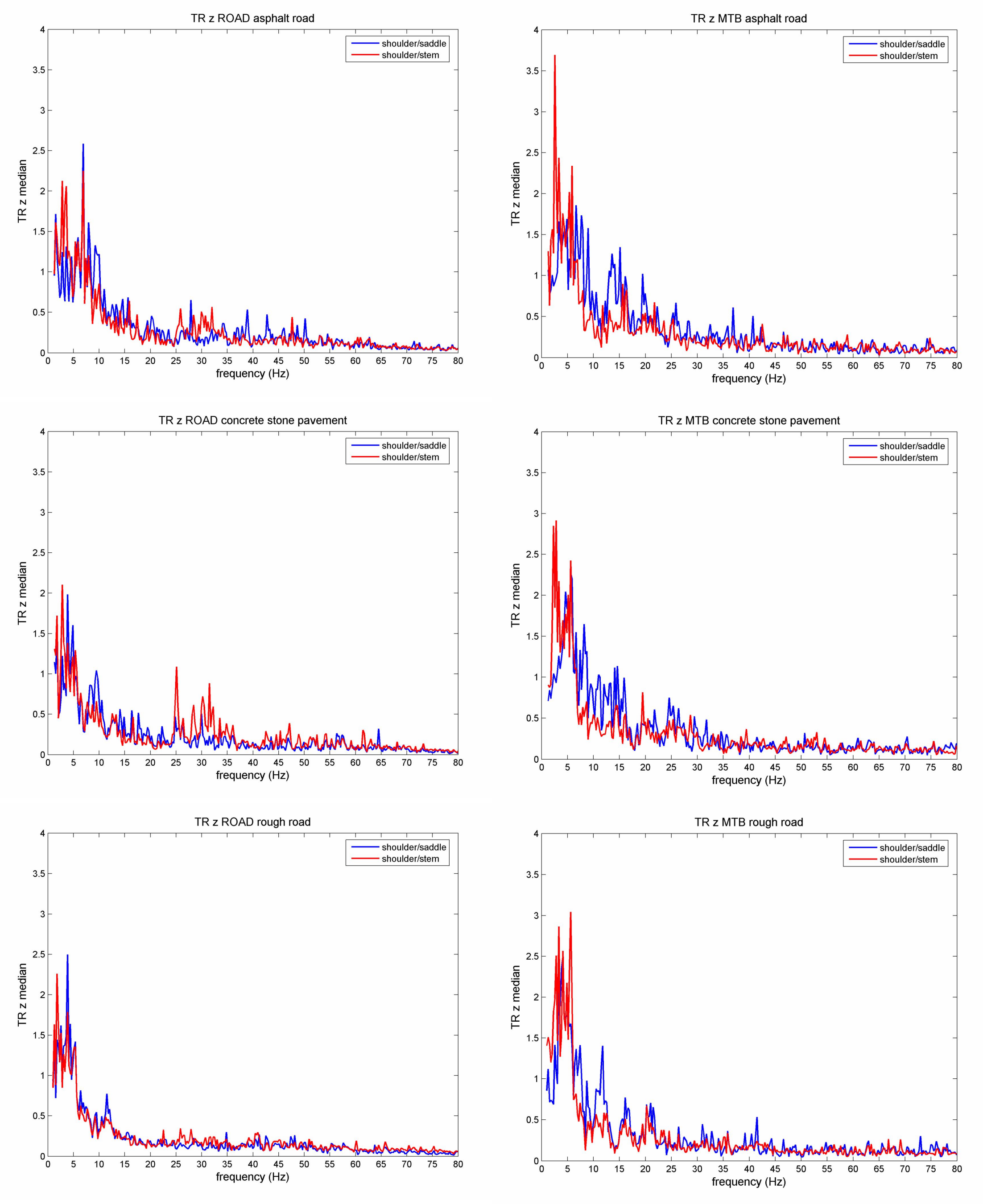

Figure 6.25 Comparison of transmission paths, for shoulder, on road bike and MTB

6.2.3. Forearm Muscle Activity in Controlling Handlebar Movements: The Effects of Road Surface Conditions and the Type of Bicycle

In many of the researches which have examined the effects of vibration by using electromyography (Seidel, 1988), have focused on whole body vibration and its effects on low-back muscles, whereas some others have investigated the effects of local vibration exposure applied to the neck muscles (Aström et al, 2007) and muscles of arm and forearm (Hansson et al., 1991; Bluthner et al., 1993; Rohmert, 1989). There are only a few studies in which the combined effects of both whole body vibration (WBV) and hand arm vibration (HAV) on muscular activity has been investigated (Aström, 2008). It is important to note that the present study is unique with regard to its experimental design in which muscular activity of forearm muscles have been investigated in relation to vibration transmission to bicycle and rider. Previously, variability of muscle activity with respect to road roughness has only been investigated by Rambarran and Roy (2001) for the muscles of trunk (i.e. erector spinae) and lower extremity (i.e. vastus lateralis and biceps femoris).

In the present study, rms EMG of extensor muscles during MTB trials had the same tendency with acceleration amplitudes which increased towards higher values with the increasing order of roughness (i.e., asphalt road, concrete stone pavement and rough road, respectively)(Figure 6.26). During rough road measurements it even reached to a value corresponding to approximately 50% of MVC. During the road bike trials performed in rough road conditions, rms EMG (%MVC) values for the forearm flexor muscles have reached the peak levels (Figure 6.27).

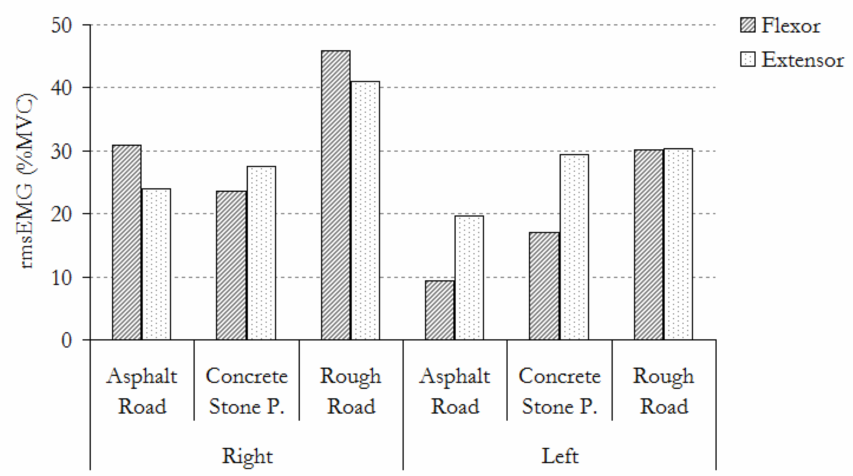

Figure 6.26 Rms EMG values (%MVC) of right and left flexor and extensor muscles computed for road bike on different road surfaces.

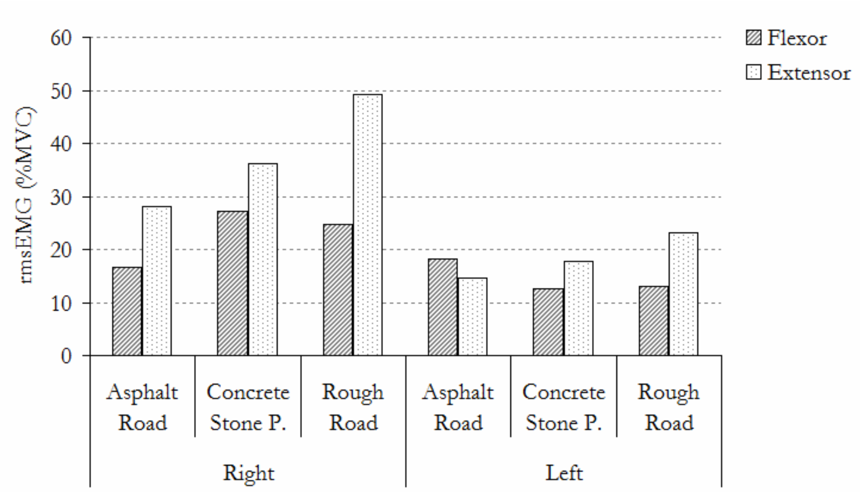

Figure 6.27 Rms EMG values (%MVC) of right and left flexor and extensor muscles computed for MTB trials on different road surfaces

The statistical differences between the rms EMG amplitudes derived from surface electromyography measurements that were simultaneously recorded with acceleration data while being exposed to vibration during riding on different road surfaces are shown in Table 6.10. The student t-test scores of differences between means have been presented for each comparison. According to the findings represented in the Table, the differences in muscle activity of right and left forearm flexor and extensor muscles were statistically significant between asphalt and rough road in both Road

Bike and MTB trials. On the other hand, the differences in rms EMG values of forearm flexor muscles has been found to be statistically significant between MTB and Road bike measurements while riding on asphalt and rough road.

Table 6.10 The statistical differences in rms EMG values for different road surfaces

Type of Bicycle	Compared pairs	R Flexor	R Extensor	L Flexor	L Extensor
Road	Asphalt-Rough	0,038*	0,006**	0,001**	0,033*
	Asphalt – Concrete S.P.	0,007**	0,135	0,012*	0,461
	Rough - Concrete S.P.	0,189	0,379	0,004**	0,140
MTB	Asphalt - Rough	0,000**	0,012*	0,019*	0,114
	Asphalt - Concrete S.P.	0,113	0,210	0,251	0,299
	Rough - Concrete S.P.	0,385	0,121	0,476	0,180
Road Bike vs. MTB	$\text{Asphalt}_{\text{MTB}}$ – $\text{Asphalt}_{\text{Road Bike}}$	0,011*	0,048*	0,006**	0,149
	$\text{Rough}_{\text{MTB}}$ – $\text{Rough}_{\text{Road Bike}}$	0,001**	0,174	0,003**	0,075
	$\text{Concrete S.}_{\text{MTB}}$ – $\text{Concrete S.}_{\text{Road Bike}}$	0,363	0,258	0,290	0,109

* p<.05, ** p<.01

In Figure 6.28, an illustration of the simultaneously collected EMG signal of forearm flexor muscle (upper trace) and the acceleration signal (lower trace), during a rough road trial, has been presented in the time domain. The effect of road roughness can be detected in acceleration signal with random acceleration peaks, while the roughness dependent rise in muscular activity of forearm muscles has been observed in the EMG signal.

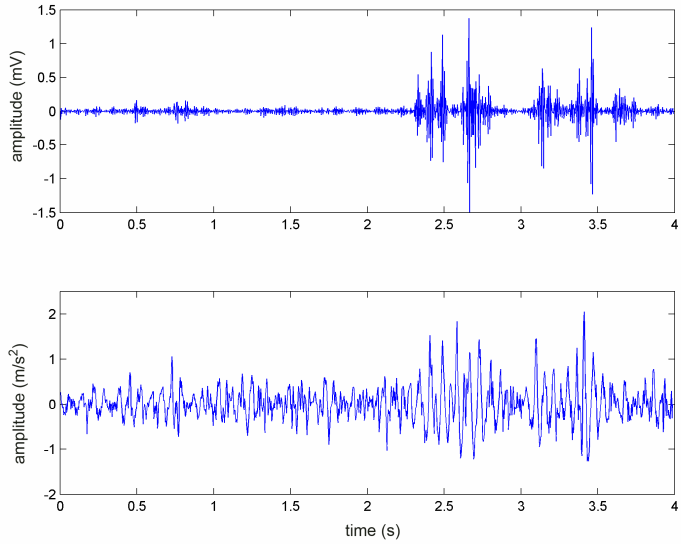

Figure 6.28 A time domain illustration of a simultaneously recorded EMG of extensor muscle (upper trace) and an acceleration (lower trace) signal recorded on the stem

The level of muscular activity of forearm muscles to control the handlebar movements is enhanced by the increase in the level of vibration exposed on the bicycle (Figure 6.26-.27). The unexpected changes in the handlebar direction have been compared through the changes in the Cumulative Normalized Muscular Activity levels (CNMA) associated with different road surfaces and bicycle types (Figures 6.29 and 6.30). The level of CNMA during MTB trials on different surfaces can be ranked in following order from lowest to highest value as: asphalt road, concrete stone pavement and rough road. Although road bike and MTB measurements were of similar pattern, in road bike CNMA values computed for rough road trials were higher than that in MTB. The CNMA level of flexor and extensor muscle groups while riding on different road surfaces has also been presented in Figures 6.31 and 6.32. As can be seen in the figures the CNMA level of forearm flexor and extensor muscle was higher in right side and had reached the highest value during rough road trials.

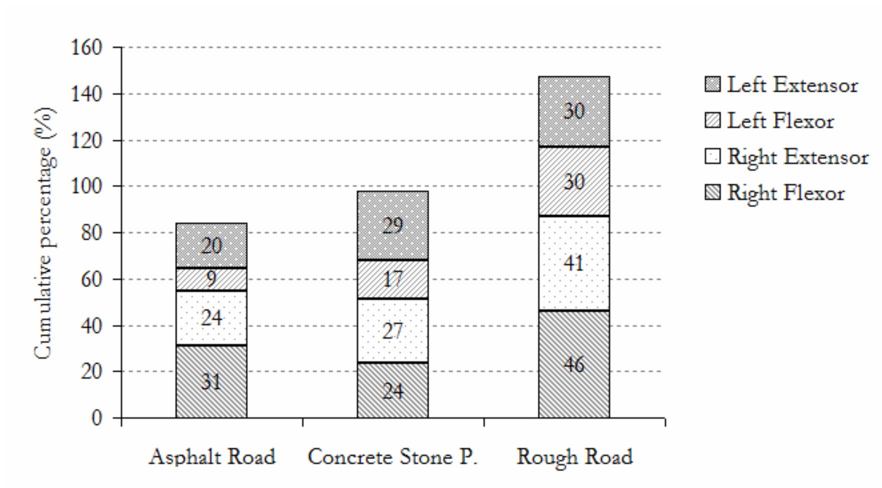

Figure 6.29 The comparison of the cumulative normalized muscular activity levels calculated for road bike trials

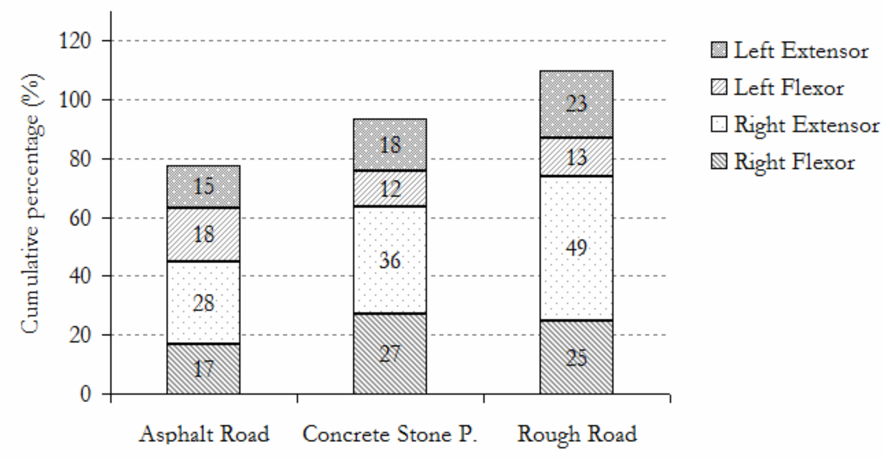

Figure 6.30 The comparison of the cumulative normalized muscular activity levels calculated for MTB trials

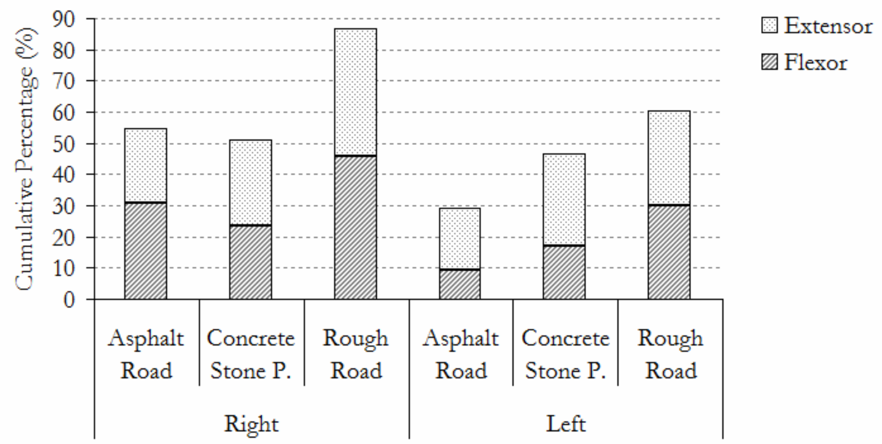

Figure 6.31 The comparison of cumulative normalized muscular activity levels in right and left forearm flexor and extensor muscle during road bike trials

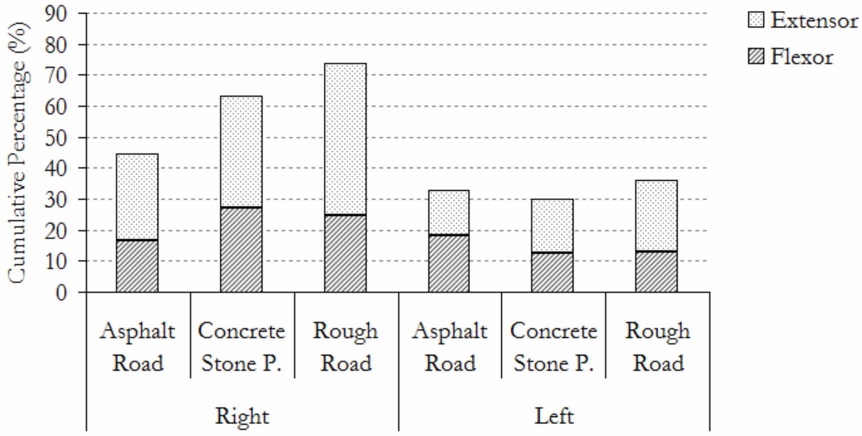

Figure 6.32 The comparison of cumulative normalized muscular activity levels in right and left forearm flexor and extensor muscle during MTB trials

6.3. Findings of the Laboratory Studies

Descriptive characteristics of the subjects participated in laboratory measurements have been listed in Table 6.11. In the same table segmental angles of the subjects have also been presented in reference to body segments illustrated in Figure 5.4.

Table 6.11 Descriptive data of subjects participated in laboratory measurements

Lab Measurements		Age (year)	Height (cm)	Weight (kg)	Hand Position	Segmental Angles (°)				
						a	b	c	d	e
α=0°(Lab5.2.3.2)	Subject 1	26	188	93	T1	118	86	86	96	140
	Subject 2	26	177	73	T1	150	99	89	109	146
	Subject 3	28	176	72	T1	120	90	85	110	150
	Subject 4	28	180	82	T1	135	91	92	113	143
	Subject 5	32	177	66	T1	142	103	89	116	145
α=5°(Lab5.2.3.2)	Subject 6	30	172	68	T1	135	90	86	117	137
	Subject 7	26	188	82	T1	121	93	82	110	140
	Subject 8	23	189	82	T1	122	89	83	105	155
	Subject 9	27	183	82	T1	126	91	84	111	144
α=0° (Lab5.2.3.1)	Subject 10	22	182	81	T1	122	91	82	112	140
					T2	122	91	92	112	180
					T3	122	91	94	104	180
	Subject 11	23	189	82	T1	110	89	90	103	155
					T2	110	89	95	100	180
					T3	110	89	95	92	180
	Subject12	26	188	82	T1	110	87	84	112	140
					T2	110	87	90	105	180
					T3	110	87	92	95	180
	Subject 13	26	180	77	T1	120	84	82	107	135
					T2	120	84	85	100	180
					T3	120	84	90	106	180
	Subject14	29	188	70	T1	120	85	94	84	148
					T2	120	85	92	105	180
					T3	120	85	100	94	180

6.3.1. Transmission of Vibration to Rider: Effects of Vibration Amplitudes and Entry Points

The results of the field measurements have revealed that the level of transmitted vibration measured at the forehead and the shoulder reached their maximum values at the frequencies between 3-12 Hz for the dominant axes x and z on each road regardless of the input acceleration magnitude. Therefore, in order to examine the effect of independent variables (i.e., amplitude, frequency, hand position) on the transmission of vibration to the rider, two frequencies, 5 and 7.5 Hz, within this region were selected for laboratory measurements. In the selection of the input vibration frequencies, subjective feelings of the road cyclists were also taken into consideration. According to their reports, at these two frequencies, they felt as if they were actually riding on uneven parts of a road surface.

Therefore, in the laboratory measurements these two frequencies were applied to the platform where the bicycle was fixed. While setting the input vibration amplitudes, the amplitude range of the transmitted vibration to the riders' body in actual conditions were also considered. Accordingly total acceleration value "a" was chosen to be 1, 1, 5 and 2 $m.s^{-2}$ rms in the experiments. In the figures, the amplitudes of transmitted vibration to the saddle and the stem were normalized with respect to the amplitude measured at the center of the platform.

Normalized vertical acceleration levels showed that ,compared to 7.5 Hz ,5 Hz input frequency of vibration at each of the three magnitudes resulted in higher transmission values at the saddle and stem, (Figure 6.33). The vibration transmitted to the saddle was found to be even equal to the amplitude of input vibration, whereas to the stem 80% of the input vibration was transmitted. On the other hand, when 7.5 Hz sine signal was applied, the normalized acceleration values for saddle and stem was respectively ~20 % and 40 % lower compared to the ones corresponding to 5 Hz sine signal. This finding coincides with the subjective feelings of subjects who felt 5 Hz more uncomfortable in comparison to 7.5Hz. Transmitted vibration to the shoulder and the elbow, expressed in terms of normalized accelerations (normalized with respect to the platform), were also found to be higher at the exciting frequency of 5 Hz (Figure 6.34). At both of the exciting frequencies, only the small amount of vibration was transferred to the shoulder (20-25%). Amplification of the vibration at the elbow was as high as 3 times at 5 Hz frequency regardless of the input amplitude. When it was normalized with respect to stem acceleration, elbow revealed 4 times higher values than the input vibration (Figure 6.35). Vibrations transmitted to the shoulder seemed to be not considerably affected by the entry points of the vibration. Likewise shoulder field accelerations (as seen in Figure 6.25) were observed to have similar frequency and amplitude response for two different entry points (i.e. saddle and stem) especially in road bike. However, in MTB only the amplitude was slightly higher with respect to the stem.

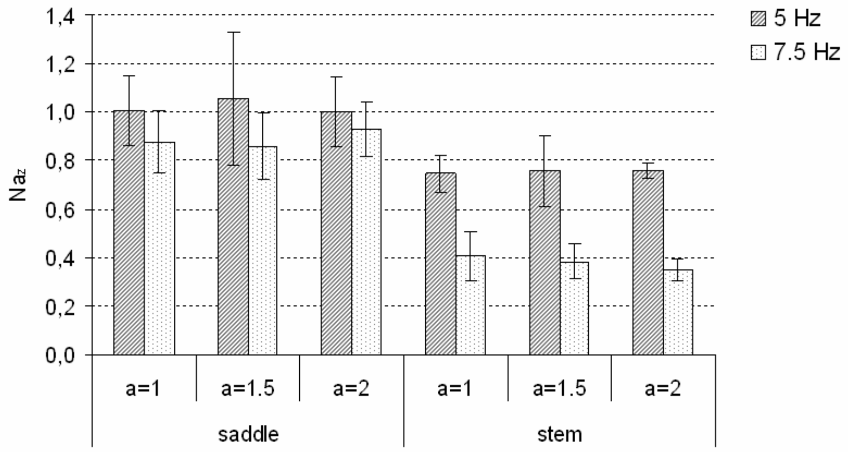

Figure 6.33 Effect of input amplitude and exciting frequency on the level of mean normalized a_z accelerations (Na $_z$) (at 5 or 7.5Hz) measured on the saddle and stem (hand position = T1, α=0) (n=5)

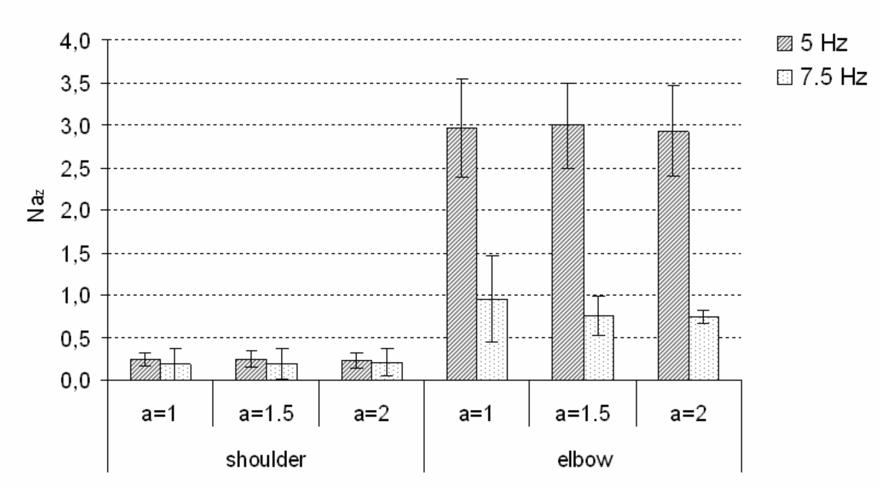

Figure 6.34 Effect of input amplitude and exciting frequency on the level of mean normalized a_z accelerations (Na_z) (at 5 or 7.5Hz) measured on the elbow and shoulder of the riders (hand position = T1, α=0) (n=10)

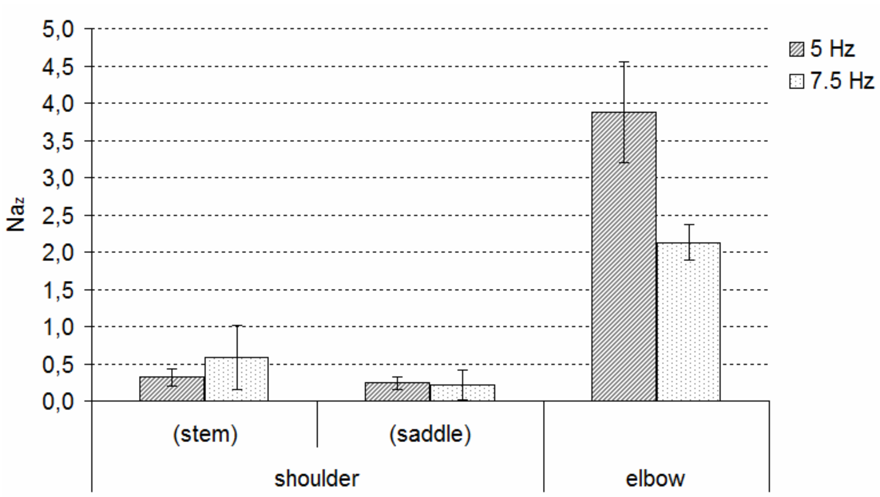

Figure 6.35 Mean Normalized elbow (with respect to stem) and shoulder acceleration (with respect to stem and saddle) levels at 5 and 7.5 Hz. (n =10, a =2ms^{-2}, hand position = T1)

6.3.2. Transmission of Vibration to Rider: Effect of Hand Positions, Vibration Frequency, Submaximal Contraction Level and the Slope of the Road

On the bicycle, in the seated position, it was reported that approximately 30 percent of the rider's mass was supported by the hands and the rest was distributed over the saddle and the pedals. In the downhill position, however, most of the weight was supported by the feet (~90%) and the rest by the hands (hand position=T3) (Wang and Hull, 1997). Change of hand position accompanied by change in the posture of the rider will naturally change the weight supported by the saddle and stem as confirmed in Figure 6.36. As the posture of the rider shifts to the upright sitting posture, the saddle accelerations tend to increase whereas stem accelerations tend to decrease at 5 Hz. The difference is prominent at the lowest amplitude ($a=1\ ms^{-2}$). Stem accelerations become stabilized at higher amplitudes. As can be seen in the figure, the direction of this trend was also frequency dependent.

Similarly, as a result of declined position of the bicycle and due to the changes in the posture of the rider, percentage of the weight transferred to the handlebar increased. Vibration transmitted to the elbow was observed to increase especially at 5 Hz input vibration, while acceleration measured at shoulder tends to be lower at both of the input frequencies (Figure 6.37).

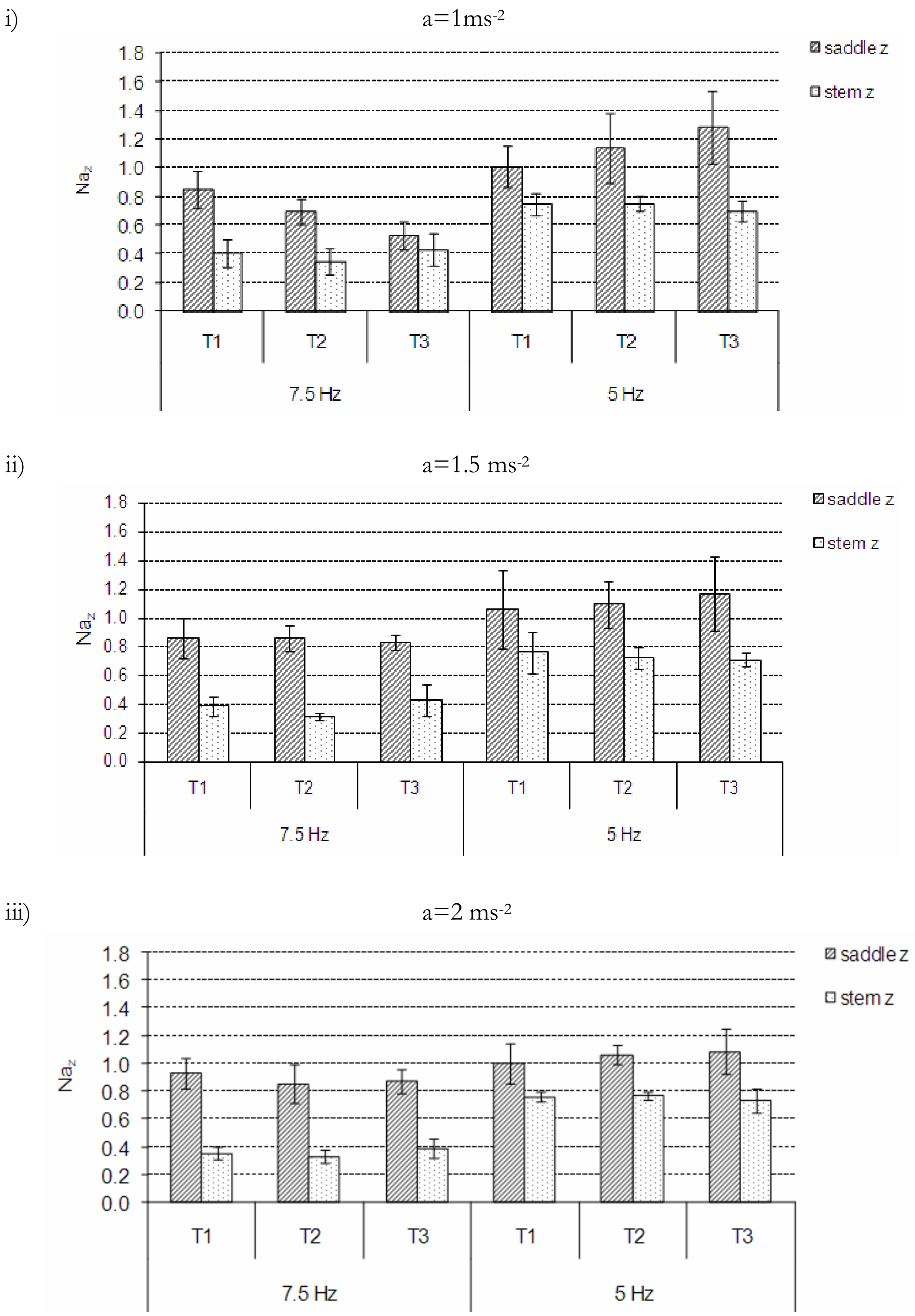

Figure 6.36 Effect of hand positions and exciting frequency on the level of mean Na_z accelerations (at 5 or 7.5Hz) measured on saddle and stem (α=0) (n=5) for different amplitudes: (i) a=1 m/s^2, (ii) a=1.5 m/s^2, (iii) a=2 m/s^2

Rohmert et al. (1989) have also investigated the effects of vibration on arm and shoulder for different body postures and found that postural changes had an effect on the level of vibration transmitted to the upper extremity. They have pointed out that as the muscle increases in length or as the intensity level of contraction increases, the vibration impact can become more severe. As seen in Figure 6.38, on flat surface, vibration transmitted to the shoulder (in each of 5 Hz and 7.5 Hz excitations) and elbow (only in 7.5 Hz) were higher, at 20% MVC force production levels, than contractions of 10% MVC. In parallel with acceleration magnitudes, normalized rms EMG values also revealed that in order to maintain the same level of contraction at 20% MVC, higher contribution of both flexor and extensor muscles were required under vibration loads at 5 Hz (Figure 6.39). When compared to no vibration trials, both 5 and 7.5 Hz vibration exposure conditions also resulted in higher muscular response to maintain the same level of contraction. However, it was also observed that the acceleration magnitudes, measured at shoulder and stem for no contraction trials, were almost as high as 10 and 20% MVC trials for both 5 and 7.5 Hz input frequencies. Even if subjects were visually controlled for possible changes in forearm posture the hypothesis that, subjects are able to adapt their response to vibration by varying the muscle forces through co-contraction of the flexor and extensor muscles without varying flexion angles, has to be considered (Wang and Hull, 1997).

In contrast to contraction tasks restricted with a specific force output during no contraction trials, any restriction, applied to the subjects on the forces applied by their hands, can be considered as another possible reason for the above finding.

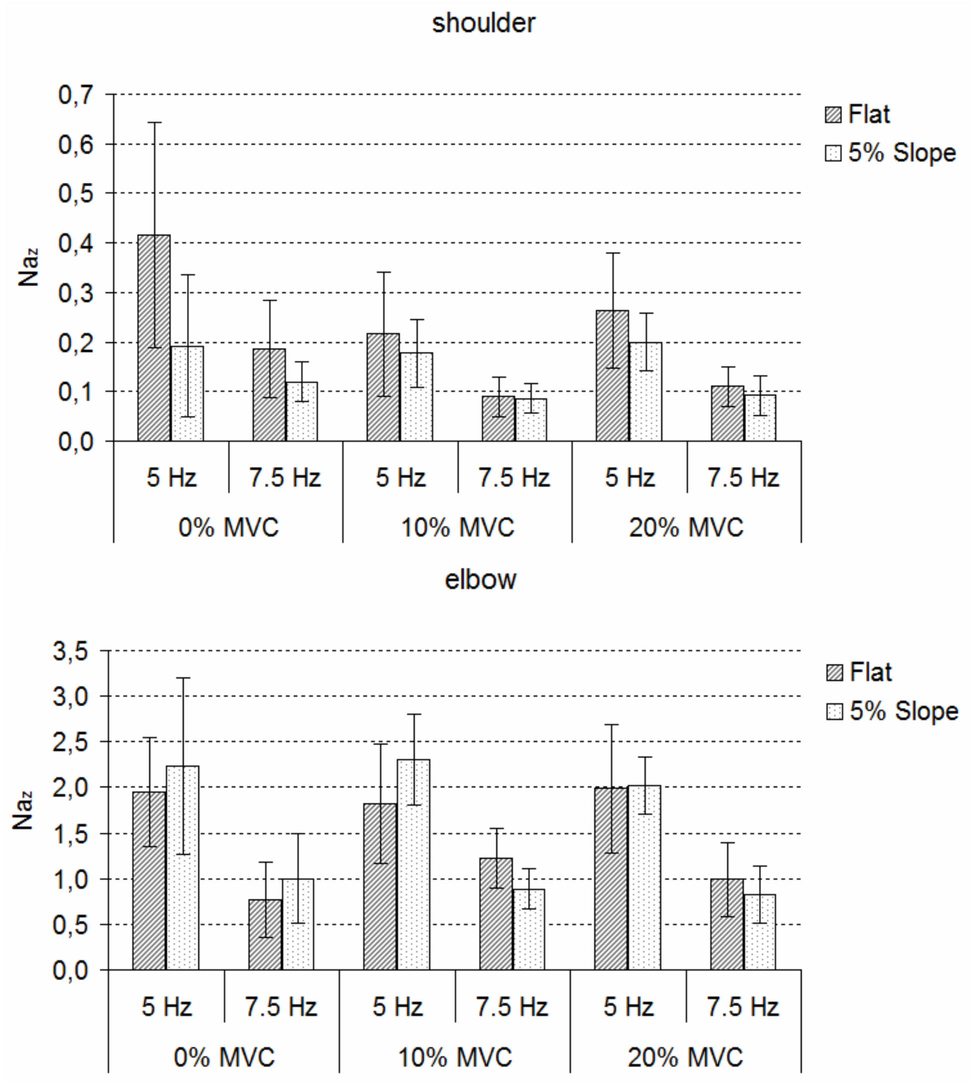

Figure 6.37 Effect of muscle contraction level, exciting frequency and α of the surface on the level of mean normalized a_z accelerations (at 5 or 7.5Hz) measured on the shoulder and elbow of the rider (n = 5) (a = 2 m/s^2)

The effect of hand-arm vibration on biodynamic response is also known to be influenced by changing joint angles in the hand-arm depending on the direction of exposure. When vibration transfers to the forearm (towards ulna and radius), it is transmitted to shoulder (scapula) through the upper arm (humerus) (Griffin, 1990). It has been concluded that the energy transmission decreases with the distance from the source (Sörensson and Burström, 1997).

In the present study, the level of vibration measured at the shoulder has increased towards upright sitting postures which correspond to increases in the shoulder and elbow angles (Figure 6.38). Similarly, it has been addressed that the acceleration ratio between vibration platform and upper extremity was increased when the arm angle increased (Nishiyama et al, 2000). Lewis and Paddan (1990) have reported that the transmissibility from seat to head was greater in the forward leaning posture at low frequencies, up to 4 Hz, but in the upright posture it was greater at high frequencies between 5 to 10 Hz.

In a study conducted by Fairley and Griffin (1989), it has been also reported that seat to head vibration transmission was two-fold higher in upright and erect sitting postures than that in trunk-flexed relaxed sitting postures. In the current study, as it was found that the peak acceleration values measured on the riders' body occurred at the frequencies between the ranges of 5 to 10 Hz, the transmissibility might be expected to be higher within that frequency range in more upright sitting postures which corresponds to hands located on top of the bar (i.e., hand position T3). The findings of the laboratory measurements provide evidence that the vibration transmission to different parts of the upper extremity is posture dependent. It was found that it tends to be higher at elbow for more forward postures, while higher values were reached at the shoulder in more upright sitting postures (Figure 6.38). When input acceleration magnitudes were compared, elbow accelerations were found to be higher than shoulder accelerations with the highest values, as well as highest difference, at 5 Hz input vibration corresponding to any of the three amplitudes. Again a reverse relation between shoulder and elbow was observed: when the acceleration measured at the elbow was the highest, the acceleration measured at the shoulder was the lowest.

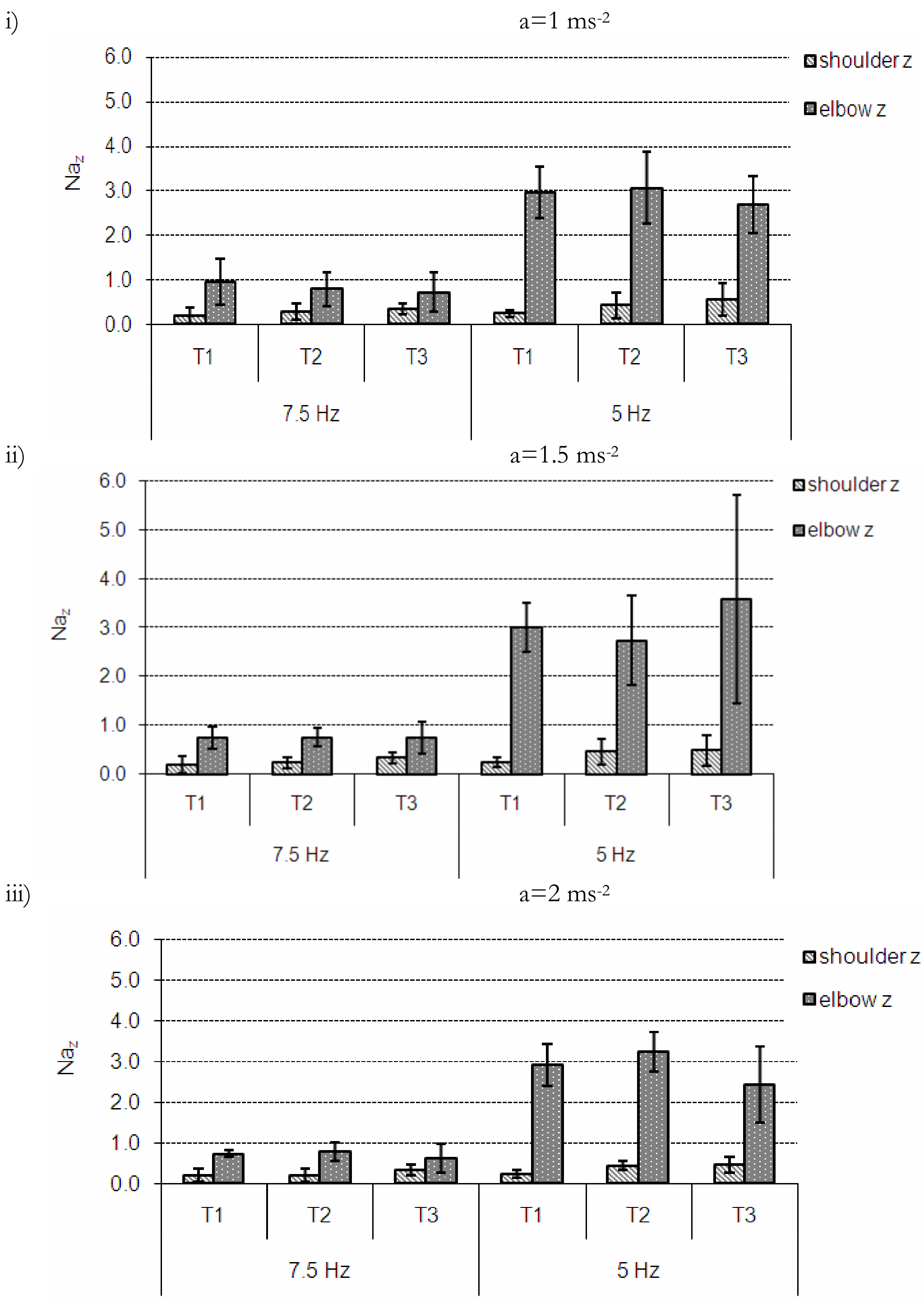

Figure 6.38 Effect of hand positions and exciting frequency on the level of mean normalized a_z accelerations (at 5 or 7.5Hz) measured on the shoulder and elbow of the rider (α=0) (n=5)) for different amplitudes: (i) a=1 m/s^2, (ii) a=1.5 m/s^2, (iii) a=2 ms^{-2}

6.3.3. Transmission of Vibration and Forearm Muscle Activity during Gripping: Effect of the Submaximal Contraction Level and Vibration Frequency

As mentioned previously increased road roughness enhances the muscle activity of the forearm. This gave rise to the question about whether or not the vibration transmission would be altered for different force production levels. Thus, within the scope of this study, the effect of different force production levels on the level of transmitted vibration was examined in the laboratory settings through the controlled conditions. The normalized rms EMG (%MVC) values representing the level of muscular activity measured for different contraction levels when subjected to 2 ms^{-2} rms amplitude of cyclic sinusoidal vertical load (f= 5 and 7.5 Hz) are shown in Figure 6.39.

In comparison with no vibration trial, during the vibration exposure trials at the afore-mentioned frequencies rms EMG of both flexor and extensor muscles increased in order to maintain the same force output. When two exciting frequencies are compared, the difference between increased muscular contraction levels was seen to be significant in submaximal isometric contraction at 10% of MVC.

Whereas the increase in muscular activity during no vibration trials was proportional to the level of contraction especially at f=5 Hz. The increases in right hand flexor and extensor forearm muscle activities were significant. Forearm extensor muscles were dominantly involved in the force production during gripping, and their activities were found to be higher when f=7.5 HZ and for %10 MVC. The differences between pre and post maximal force production levels were less than 10% for both right and left extremity.

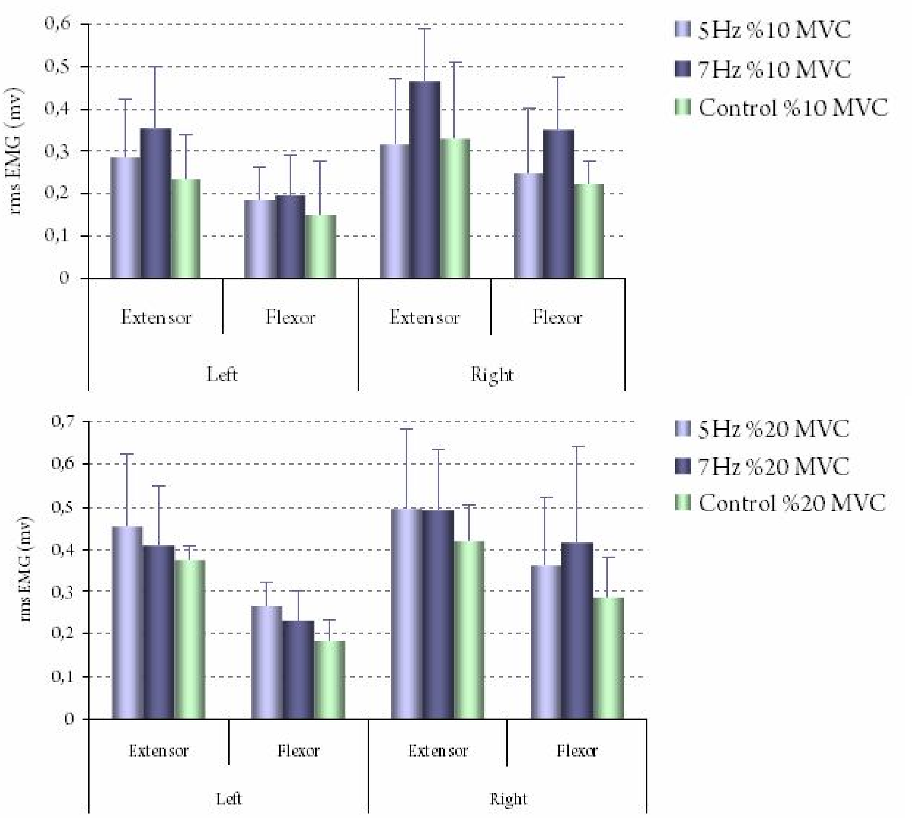

Figure 6.39 The level of muscular activity for different contraction levels at different vibration frequencies; 10% MVC (top), 20% MVC (bottom).

During the controlled measurements in which no vibration was applied, muscular activity levels of the each of the four muscles have increased proportional to the applied workload for 10% and 20% of submaximal force production levels. We found that rms EMG values increased for both of the 5 Hz and 7.5 Hz sinusoidal vertical loads. Especially in 20% submaximal contraction trials at 5 Hz frequency, increased level of activation was apparent in the right forearm flexor and extensor muscles. (Seidel, 1988), reported an increase in rms EMG values of low-back muscles in the frequency range between 3-10 Hz when exposed to vibration.

In a study conducted by Aström et al. (2007), the activity of trapezius muscle have been investigated under different vibration conditions and it has been observed that rms EMG values during isometric contraction at 4-5% of the MVC increased when vibration stimulus was applied. In this study, rms EMG values for both flexor and extensor muscle activity at 5 and 7.5 Hz frequencies have increased in order to maintain the same force output corresponding to no vibration trials. Likewise, Martin and Park (1997) have found an increase in rms EMG values of finger and wrist flexor activity when exposed to vibration. To the best of our knowledge, the increased rms EMG values are considered as an indicator of increased workload during an activity (Dimitriova and Dimitrov, 2003; Hagg et al, 2000).

The interrelation between vibration exposure and the muscular activity have been examined by many researchers. The studies investigating vibration transmitted to the low-back muscles have claimed that the increased muscle activity also tends to increase the magnitude of the vibration and resonance frequency of this region (Fairley and Griffin, 1989; Broman et al, 1991). Hand-arm vibration studies have also shown the increased biodynamic system stiffness, as a result of increased force production, which in turn caused increased muscular activity (McDowell, 2006; Dong et al, 2004; Kihlberg, 1995). The increased grip and push forces and the resultant muscular activation of forearm muscles observed in our study while increasing the stiffness of the hand-arm system might also influence the resonance effect at certain frequencies.

CHAPTER VII

7. CONCLUSION

The purpose of this study was to investigate the frequency and amplitude characteristics of vibration exposed to the bicycle and the rider as well as its transmission to the body, specifically to forearm, shoulder and head. Although the bicycle rider is considered to be the biggest part of the bicycle-rider system, vibration transmitted to the rider has been neglected by most of the previous research which only investigated the level of vibration transmitted to the bicycle itself. Thus, there is very limited knowledge of vibration transmission to the human body while riding on a bicycle.

In the present study, through field and laboratory experiments, the following research questions have been examined: i) what are the magnitude and the frequency range of the transmitted vibration to the bicycle-rider system? ii) are these values influenced by different road surfaces and bicycle types? iii) are the vibration transmission values for different body postures influenced by vibration characteristics? iv) does the vibration transmission to hand-arm-system affect forearm muscle activity during a bicycle ride? v) do the slope of the road and the vibration frequency affect vibration amplitude transmitted to the hand-arm system during submaximal force production? vi) does the vibration frequency affect the muscle activity level in the forearm during sustained submaximal contractions?

Within the limitations of the study, the findings of both the field and laboratory studies revealed the following conclusions regarding each of the research questions;

i) The acceleration magnitudes at dominant axes (x and z) were found to be similar at both measurements locations on the bicycle (i.e. saddle and stem) while riding on asphalt road. Corresponding un-weighted total acceleration values ranged from 2.2 to 4.3 ms^{-2} rms for road bike, and between 1.2 to 2.9 ms^{-2} rms for MTB. The frequency ranges where the peak accelerations occurred at dominant axes were found between 20-70 Hz for road bikes and between 5-40 Hz for MTB s at both saddle and stem.

ii) The severity of transmitted vibration to the bicycle was found to be considerably higher in road bike trials. In addition to aforementioned amplitude difference between two bicycle types on smooth road surface, road roughness also resulted in increased acceleration magnitudes. During rough road trials, the acceleration magnitudes measured on saddle and stem at dominant axes were between 6-12 ms^{-2} rms and 13-25 $m.s^{-2}$ rms for road bike and MTB, respectively. Concrete stone pavement revealed lower values for both road bike and MTB (8-15.6 $m.s^{-2}$ rms and 3.2-7 $m.s^{-2}$ rms, respectively). On the riders' body, shoulder accelerations ranged from lowest to highest in asphalt road, concrete stone pavement and rough road, respectively. However, forehead acceleration was found to be higher, for trials on concrete stone pavement, than on rough road. Interestingly, the vibration transmission to different body parts on different road surfaces which tends to increase with increased roughness has been found not to be influenced by different bicycle designs

As a result of increased roughness, the frequency ranges where the peak accelerations occurred for both saddle and stem reduced to the 15-30 Hz range for both bicycles. The level of transmitted vibration measured at the forehead and the shoulder reached their maximum values at the frequencies between 3-12 Hz for the dominant axes on each road regardless of the input acceleration magnitude. On the road bike effective forehead acceleration range shifted even to lower frequencies between 3.5 and 7 Hz on both asphalt and concrete stone pavement.

iii) In laboratory studies 5 Hz input frequency of vibration at each of the three selected magnitudes resulted in higher transmission values at the saddle and stem. The vibration transmitted to the saddle was found to be even equal to the amplitude of input vibration, whereas to the stem 80% of the input vibration was transmitted. On the other hand, when 7.5 Hz sine signal was applied, the normalized acceleration values for saddle and stem was respectively ~20 % and 40 % lower compared to the ones corresponding to 5 Hz exciting sine signal. Transmitted vibration to the shoulder and the elbow, expressed in terms of normalized accelerations (normalized with respect to the platform), were also found to be higher at the exciting frequency of 5 Hz. At both of the exciting frequencies, only the small amount of vibration was transferred to the shoulder (20-25%).Vibration amplification at the elbow was as high as 3 times at 5 Hz frequency regardless of input amplitude. Transmissibility even reached 4 times higher values with respect to stem accelerations.

Regarding the posture effect, the findings revealed that while posture shifts to the upright sitting postures as a result of different hand positions on the handlebar, the saddle accelerations tend to increase at 5 Hz. The direction of this trend was however frequency dependent.

iv) In the present study, the cumulative normalized muscular activity levels during MTB trials on different surfaces had the same tendency with acceleration amplitudes and have ranked in following order from lowest to highest value: asphalt road, concrete stone pavement and rough road. Although road bike measurements have resulted in similar trend of increment, the values computed for rough road trials were higher than those in MTB trials. During rough road measurements on MTB, rms EMG of extensor muscles reached to a value corresponding to approximately 50% of MVC. During the road bike trials performed in rough road conditions, rms EMG (%MVC) values for the forearm flexor muscles have reached their highest levels.

v) As a result of declined position of the bicycle and due to the changes in the posture of the rider, percentage of the weight transferred to the handlebar increased. Vibration transmitted to the elbow was observed to increase especially at 5 Hz input vibration, while acceleration measured at shoulder tends to be lower at both of the input frequencies. On flat surface, vibration transmitted to the shoulder (at each of the 5 Hz and 7.5 Hz frequencies) and elbow (only at 7.5 Hz) were higher at 20% MVC force production levels than contractions of 10% MVC.

vi) In parallel with acceleration magnitudes, normalized rms EMG values also revealed that in order to maintain the same level of contraction at 20% MVC, higher contribution of both flexor and extensor muscles were required under vibration loads at 5 Hz. When compared to no vibration trials, both 5 and 7.5 Hz vibration exposure conditions also resulted in higher muscular response to maintain the same level of contraction. Forearm extensor muscles were dominantly involved in the force production during gripping task, and their activities were found to be higher for %10 MVC when input frequency was 7.5 Hz.

In conclusion, it seems that both road roughness and the type of the bicycle affect the vibration magnitudes and the transmissibility ratios of the bicycle-rider system. However, on the bicycle, they affect only the effective frequency ranges. Vibration transmission to different body parts is not likely to be influenced by different bicycle designs. Acceleration magnitudes measured on the body tend to increase only with increased roughness. The level of acceleration also depends on the posture maintained by the cyclist as well as the vibration frequency. The field measurements revealed that the frequency range of the vibration exposure of the body parts were in between 0-30 Hz and independent of the level of vibration transmission the peak values were within the range of 3-12 Hz.

Since the magnitude and frequency of vibration is known to have some adverse effects on body functions such as impaired breathing pattern and increased muscle tone, vibration transmitted to the body during cycling might be considered to influence the riding comfort, controllability and overall health of the cyclist. Increased muscular activity of the forearm muscles under vibration loads can also be considered as a trigger for more effort to handle and stabilize the bicycle against impact forces which in turn affect the comfort and health of the cyclists.

REFERENCES

1. AKUTHOTA V, Plastaras C, Lindberg K, Tobey J, Press J, Garvan C, The effect of long-distance bicycling on ulnar and median nerves: an electrophysiologic evaluation of cyclist palsy, *Am J Sports Med*, 33(8), 1224-30, (2005).

2. ASTRÖM C, Lindkvist M, Burström L, Sundelin G, Karlsson JS, Changes in EMG activity in the upper trapezius muscle due to local vibration exposure, *J Electromyography and Kinesiology*, 19, 3, 407-415,(2009).

3. ASTRÖM C, *The effects of vibration on muscles in the neck and upper limbs*, (PhD), Umea University, Sweden (2008).

4. BAZRGARİ B, Shirazi-Adl A, Kasra M., Seated whole body vibrations with high-magnitude accelerations—relative roles of inertia and muscle forces, J *Biomech.* 41(12), 2639 – 2646, (2008).

5. BERRY MJ, Koves TR, Benedetto JJ. The influence of speed, grade and mass during simulated off-road bicycling, *Applied Ergonomics*, 31, 531-536, (2000).

6. BLUTHNER R, Hinz B, Menzel B, Seidel H, Back muscle response to transient whole-body vibration, *Int J Ind Ergonom*, 12,49–59, (1993).

7. BLUTHNER R, Seidel H, Hinz B, Myoelectric response on back muscles to vertical random whole-body vibration with different magnitudes at different postures, *J Sound and Vib*, 253(1), 37-56, (2002).

8. BOVENZI M, Hulshof CT, An updated review of epidemiologic studies on the relationship between exposure to whole-body vibration and low back pain (1986-1997), *Int. Arch Occup Environ Health,* 72, 351-65, (1999).

9. BOVENZI M, Zadini A, Self-reported low back symptoms in urban bus drivers exposed to whole body vibration, *Spine*, 17(9), 1048–1059, (1992).

10. BROMAN H, Pope MH, Benda M, Svensson M, Ottosson C, Hansson T, The impact response of the seated subject, *Journal of Orthopedic Research,* 9,150–154, (1991).

11. BURKE ER, Science of Cycling, Champaign, IL: Human Kinetics, (1996).

12. BURSTRÖM L, The Influence of Biodynamic Factors on The Absorption of Vibration Energy in Human Hand and Arm, *Nagoya J Med Sci.,* 57, 159-167, (1994).

13. CALDWELL LS, Chaffin DB, Dukes-Dobos FN, Kroemer KH, Laubach LL, Snook SH, Wasserman DE, A proposed standard procedure for static muscle strength testing,*Am Ind Hyg Assoc J*, 35(4),201-6,(1974).

14. CANNON LJ, Bernacki EJ, Walter SD, Personal and Occupational Factors Associated with Carpal Tunnel Syndrome, *Journal of Occupational Medicine,* 23 (4), 255-258, (1981).

15. CAPITANI D, Beer S, Handlebar palsy – a compression syndrome of the deep terminal (motor) branch of the ulnar nerve in biking, *J Neurol,* 249, 1441–1445, (2002) .

16. CARDINALE M, Lim J, Electromyography Activity of Vastus Lateralis Muscle During Whole-Body Vibrations of Different Frequencies , *Journal of Strength and Conditioning Research*, 17,3, 621–624, (2003)

17. CARDINALE M, Wakeling J, Whole body vibration exercise: are vibrations good for you? , *Br J Sports Med*,39:585–589, (2005)

18. COLE S, Vibration and linear acceleration, The Body at Work, W. T. Singleton (ed.), Cambridge University Press, 201-234, (1982).

19. CUI J, Modeling of hand-arm-glove vibration system and testing and evaluating of anti vibration gloves, (PhD), Unîversity of Nevada, Las Vegas, (2001).

20. DE LORENZO DS, Hull ML, Quantification of structural loading during off-road cycling, *J Biomech Eng*, 121(4), 399-405, (1999).

21. DIMITROVA NA, Dimitrov GV, Interpretation of EMG changes with fatigue: facts, pitfalls, and fallacies, *J Electromyogr Kinesiol*, 13(1), 13-36, (2003).

22. DONG RG, Welcome DE, McDowel TW, Wu JZ, Measurement of biodynamic response of human hand-arm system, *J Sound and Vibration*, 294, 807-827,(2006).

23. DONG RG, Schopper AW, McDowell TW, Welcome DE, Wu JZ, Smutz WP, Warren C, Rakheja S, Vibration Energy Absorption (VEA) in Human Fingers-Hand-Arm System, *Medical Engineering and Physics,* 26 (6), 483-492, (2004).

24. FAIRLEY TE, Griffin MJ, The apparent mass of the seated human body: vertical vibration, *Journal of Biomechanics*, 22, 81–94,(1989).

25. FARD MA, Ishihara T, Inooka H, Identification of the head-neck complex in response to trunk horizontal vibration, *Biol Cybern*, 90(6), 418-26,(2004).

26. FAISS R, Praz M, Meıchtry A, Gobelet C, Derıaz O, The effect of mountain bike suspensions on vibrations and off-road uphill performance, *J Sports Med Phys Fitnes,* 47(2),151-158,(2007)

27. FINUCANE EV, *Definitions, Conversions, and Calculations for Occupational Safety and Health Professionals*, CRC Press (2006).

28. FREUND HJ, Motor unit and muscle activity in voluntary motor control, *Physiol Rev,* 63, 387–428, (1983).

29. FRITZ M, Fisher S, Bröde P, Vibration induced low back disorders—comparison of the vibration evaluation according to ISO 2631 with a force-related evaluation, *Applied Ergonomics,* 36, 481–488, (2005).

30. GOGLIA V, Gospodaric Z, Filipovic D, Djukic I, Influence on operator's health of hand-transmitted vibrations from handles of a single-axle tractor*, Ann Agic Environ Med*, 13, 33-38, (2006).

31. GRIFFIN MJ, *Handbook of Human Vibration*, London: Academic Press, (1990).

32. GRIFFIN MJ,A comparison of standardized methods for predicting the hazards of whole-body vibration and repeated shocks, *Journal of Sound and Vibration*, 215(4), 883-914, (1998).

33. GRIFFIN MJ, Bovenzi M, The Diagnosis of Disorders Caused by Hand-Transmitted Vibration: Southampton Workshop 2000. *International Archives of Occupational and Environmental Health,* 75 (1-2), 1-5, (2001).

34. HÄGG G, Luttman A, Jäger M, Methodologies for evaluating electromyographic field data in ergonomics, *J Electromyogr Kinesiol*, 10, 301-312, (2000).

35. HANSSON T, Magnusson M, Broman H, Back muscle fatigue and seated whole body vibrations: an experimental study in man, *Clin Biomech*, 6, 173–8, (1991).

36. HAZARIN B, Grzesik J, The transmission of vertical whole-body vibration to the body segments of standing subjects, *Journal of Sound and Vibration*, 215(4), 775-787, (1998).

37. HENNIG E M, Rosenbaum D, Milani TL, Transfer of tennis racket vibrations onto the human forearm, *Med Sci Sport Exerc*, 24 (10),1334-1340, (1992).

38. HINZ B, Seidel H, Menzel G, Bluthner R, Effects related to random whole-body vibration and posture on a suspended seatwith and without backrest, *Journal of Sound and Vibration,* 253, 265–282, (2002).

39. HSU WL, Krishnamoorthy V, Scholz JP, An alternative test of electromyographic normalization in patients, *Muscle Nerve*, 33, 232–241,(2006).

40. ISHII T, Influences of mountain bike suspension system on energy supply and performance, *Japanese J Biomech Sport Exerc*, 7,2-9,(2003)

41. ISO 2631-1,1997: Mechanical vibration and shock -Evaluation of human exposure to whole-body vibration -- Part 1: General requirements, International Organization for Standardization, Geneva, Switzerland, (2001).

42. ISO 5349-1, 2001: Mechanical Vibration-Measurement and Evaluation of Human Exposure to Hand-Transmitted Vibration-Part 1: General Requirements, International Organization for Standardization, Geneva, Switzerland, (2001).

43. JOHANSSON A, Nilsson L, Evaluation of discomfort using real-time measurements of whole body vibration and seat pressure distribution while driving trucks, Gothenburg, Sweden, Lulea University of Technology, Master of Science, (2006).

44. HENNİG EM, Rosenbaum D, Milani TL, Transfer of tennis racket vibrations onto the human forearm, *Med Sci Sports Exerc*, 24:10, 1134-1140, (1992).

45. KAULBARS U, Measurement and Evaluation of Coupling Forces When Using Hand-Held Power Tools, *Central European Journal of Public Health,* 4 (1), 57-58, (1996).

46. KIHLBERG S, Hagberg M, Hand-Arm Symptoms Related To Impact And Nonimpact Hand-Held Power Tools, *International Archives of Occup Environ Health,* 69(4), 282-288, (1997).

47. KIHLBERG S, Biodynamic Response of the Hand-Arm System to Vibration from an Impact Hammer and a Grinder. *International Journal of Industrial Ergonomics,* 16 (1), 1-8, (1995).

48. LATASH ML, *Neurophysiological Basis of Human Movement*, USA:Human Kinetics, (1998).

49. LEWIS CH, and Paddan GS, “Effects of vibration and posture on all-terrain bicycle ride,” UK Informal Group Meeting on Human Response to Vibration, England,(1990).

50. LINGS S, Leboeuf-Yde C, Whole-body vibration and low back pain: a systematic, critical review of the epidemiological literature 1992-1999, *International archives of occupational and environmental health*, 73,5, 290-7, (2000)

51. LIS AM, Black KM, Korn H, and Nordin M, Association between sitting and occupational LBP, *European Spine Journal*, 16, 283–298, (2007).

52. MARTIN BJ, Park HS, Analysis of the tonic vibration reflex: influence of vibration variables on motor unit synchronization and fatigue, *Eur J Appl Physiol Occup Physiol*, 75(6), 504-11, (1997).

53. MARTIN BJ, Roll JP, Gauthier GM, Inhibitory effects of combined agonist and antagonist muscle vibration on H-reflex in man, *Aviation, Space, Environ Med*, 57, 681–687, (1986).

54. MACRAE HS-H, Hise KJ, Allen PJ, Effects of front and dual suspension mountain bike systems on uphill cycling performance, *Med Sci Sports Exerc*, 32(7), 1276-80, (2000).

55. MANSFIELD NJ, *Human Response to Vibration*, Florida: CRS Press, (2004).

56. MANSFIELD NJ, Griffin MJ, Effect of magnitude of vertical whole-body vibration on absorbed power for the seated human body, *Journal of Sound and Vibration*, 215 (4), 813–825, (1998).

57. MATSUMOTO Y, Griffin MJ, Dynamic response of the standing human body exposed to vertical vibration: influence of posture and vibration magnitude, *J of Sound and Vibration*, 212(1), 85-107, (1998).

58. MCDOWELL TW, *An evaluation of vibration and other effects on the accuracy of grip and push force recall*, (PhD), West Virginia University, Morgantown, West Virginia, (2006).

59. MCGORRY RW, A System for the Measurement of Grip Forces and Applied Moments During Hand Tool Use, *Applied Ergonomics,* 32 (3), 271-279, (2001).

60. MERLETTI R, Parker PA, *Electromyography: Physiology, Engineering, and Noninvasive Applications*, New Jersey: John Wiley &Sons, (2004).

61. MESTDAGH KDV, Personal Perspective: in search of an optimum cycling posture., *Applied Ergonomics* ,29(5), 325-334,(1998).

62. MOGK JPM, Keir PJ, The effects of posture on forearm muscle loading during gripping, *Ergonomics*, 46(9), 956-75,(2003).

63. NAWAYSEH N, Griffin MJ, Tri-axial forces at the seat and backrest during whole body fore-and-aft vibration*, J Sound and Vibration*, 281, 921–42, (2005).

64. NISHIYAMA S, Uesugi N, Takeshima T, Kano Y, Togii H, Research on Vibration Characteristics Between Human Body and Seat, Steering Wheel, and Pedals (Effects of Seat Position on Ride Comfort), *J of Sound and Vibration*, 236(1), 1-21, (2000).

65. OUTCALD W, Bicycle-Friendly Rumble Strips. Colorado, Colorado Department of Transportation Research Branch. (2001).

66. PIVIT R, Vibrational Stress on Cyclists, *Human Power*, 7(2), 4-6, (1988).

67. POPE MH, Magnusson M, Wilder D, Low back pain and whole body vibration. *Clin Orthop*, 154,241-8, (1998).

68. PYNT J, Higgs J, and Mackey M, Milestones in the evolution of lumbar spinal postural health in seating, *Spine*, 27(19), 2180–2189 (2002).

69. RADWIN RG, Yen TY, Force Dynamometers and Accelerometers, ed: W Karwowski and WS Marras, The Occupational Ergonomics Handbook, CRC Press, Boca Raton, Florida, (1999).

70. RADWIN RG, Armstrong TJ, Chaffin DB, Power Hand Tool Vibration Effects on Grip Exertions, *Ergonomics,* 30 (5), 833-855, (1987).

71. RAMBARRAN KK, Roy JP, Variability of Muscle Activity During Off-Road Cycling. International Society of Biomechanics Congress XVIII. Zurich, Switzerland, (2001).

72. REYNOLDS DD, Keith RH, Hand-arm vibration, part I. Analytical model of the vibration response characteristics of the hand, *J Sound and Vibration*, 51(2), 235-252, (1977).

73. REYNOLDS DD, Standlee KG, Hand-arm vibration, part III:subjective response characteristics of individuals to hand-induced vibration, *J Sound and Vibration,* 51(2),267-282, (1977).

74. RIEDEL S, Consideration of Grip and Push Forces for the Assessment of Vibration Exposure, *Central European Journal of Public Health, Supp* 3, 139-141, (1995).

75. ROBERTS JR , Jones R, Mansfield NJ, Rothberg SJ, Evaluation of vibrotactile sensations in the 'feel' of a golf shot, *J Sound and Vib*, 285(1-2), 303-319, (2005).

76. ROHMERT W, Wos H, Norlander S, Helbig R, Effects of vibration on arm and shoulder muscles in three body postures, *European Journal of Applied Physiology*, 59, 243–248, (1989).

77. ROY JP, Robertson, DGE, Comparison of impact and shock attenuation between full-suspension and non-rear suspension bicycles. *Archives of Physiology and biochemistry*, 108,1-2, (2000).

78. SEIDEL H, Myoelectric reactions to ultra-low frequency and low-frequency whole body vibration, *Eur J Appl Physiol Occup Physiol*, 57(5), 558-62,(1988).

79. SEİDEL H, On the Relationship between Whole-body Vibration Exposure and Spinal Health Risk, *Industrial Health* 2005, 43, 361–377

80. SEIDEL H, Thner BR, Hinz B, Schust M, On the health risk of the lumbar spine due to whole-body vibration -theoretical approach, experimental data and evaluation of whole-body vibration, *Journal of Sound and Vibration*, 215, 723-741, (1998).

81. SEIFERT JG, Luetkemeier MJ, Spencer MK, Miller D, Burke ER, The effects of mountain bike suspension systems on energy expenditure, physical exertion, and time trial performance during mountain bicycling, *Int J Sports Med,* 18(3),197-200, (1997).

82. SILVERSTEIN BA, Fine LJ, Armstrong, TJ, Occupational Factors and the Carpal Tunnel Syndrome. *American Journal of Industrial Medicine,* 11(3), 343-358, (1987).

83. SÖRENSSON A, BURSTRÖM L. Transmission of Vibration Energy to Different Body Parts of the Human Hand-Arm System, *Int Arch Occup Environ Health,* 70: 199-204, (1997).

84. STARCK J, Jussi P, Ilmari P, Physical Characteristics of Vibration in Relation to Vibration-Induced White Finger, *American Industrial Hygiene Association Journal*, 51(4), 179-184, (1990).

85. STEWART JD, Ulnar neuropathies at the wrist and the hand, ed: Stewart JD, Focal peripheral neuropathies, Raven Press,New York (2.Baskı), 220–225, (1993).

86. STROEDE CL, Noble L, Walker HS, The effect of tennis racket string vibration dampers on racket handle vibrations and discomfort following impacts, *J Sports Sci*, 17:5, 379-385, (1999)

87. SUHR F, Brixius K, de Marées M, Bölck B, Kleinöder H, Achtzehn S, Bloch W, Mester J, Effects of short-term vibration and hypoxia during high-intensity cycling exercise on circulating levels of angiogenic regulators in humans, *J Appl Physiol*, 103(2), 474-83, (2007).

88. TITLESTAD J, Fairlie-Clarke T, Whittaker A, Davie M, Watt I, Grant S, Effect of suspension systems on the physiological and psychological responses to sub-maximal biking on simulated smooth and bumpy tracks, *Journal of Sports Science,* 24(2), 125-135, (2006).

89. TITLESTAD J, Fairlie-Clarke T et al, Experimental Evaluation of Mountain Bike Suspension Systems, *Acta Polytechnica*, 43, 5, 15-20, (2003).

90. TORBIC D, Ei-Gindyt M et al, Methodology for quantifying whole-body vibration experienced by bicyclists, *Int. J. of Vehicle Design*, 31, 4, 452-480, (2003).

91. TS-EN-ISO-5349-1, Mechanical vibration - Measurement and evaluation of human exposure to hand-transmitted vibration - Part 1 : General requirements (Vol. TS EN ISO 5349-1): Türk Standartları Enstitüsü, Aralık, (2005).

92. WAECHTER M, Zacharias N, Riess F, *Measurement and Simulation of the Vibrational Stress on Cyclis*", Proceedings of the 3rd European Seminar on Velomobile Design, ISBN 87-987188-0-0, Roskilde, Denmark, (1998).

93. WAECHTER M, Riess F, Zacharias N, A Multibody model for the simulation of bicycle suspension systems, *Vehicle System Dynamics*, 37(1), 3-28, (2002).

94. WANG EL, Hull MML, A Dynamic system model of an off-road cyclist, *J Biomech Engineering*, 119, 248-253, (1997).

95. ZATSIORSKY VM, Kraemer WJ, Science and practice of strength training, Ed: 2, Human Kinetics, ISBN 0736056289, (2006)

96. ZIMMERMANN CL, Cook TM, Effects of vibration frequency and postural changes on human responses to seated whole-body vibration exposure*, Int Arch Occup Environ Health,* 69,165-179(1997)

97. ZIMMERMANN CL,Cook TM, Goel VK, Effects of seated posture on erector spinae EMG activity during whole body vibration,*Ergonomics*, 36(6), 667-675,(1993).

APPENDIX A. INFORMED CONSENT FORM

1. Çalışmanın Açıklanması

O.D.T.Ü. Mühendislik Bilimleri Bölümü'nün yürütücülüğünde gerçekleştirilen bu araştırmanın konusu, el-kol titreşim iletimi sistemininin, uygulanan kuvvetler, kas kasılması kontrolü ve sergilenen biyodinamik yanıtlar bakımından incelenmesidir.

2. Ölçüm Yönteminin Açıklanması

Sizden alan ve laboratuvar ölçümleri için belirlenen günlerde ODTÜ Mühendislik Bilimleri Binasında bulunan Biyomekanik Laboratuvarına gelmeniz istenecektir. Alan ölçümleri kapsamında kampüs içerisinde farklı yüzey yapılarına sahip ve önceden belirlenen parkurlarda bisiklet ile sabit hızda sürüş yapmanız istenecektir. Laboratuvar ölçümleri ise platform üzerine monte edilen bisiklet üzerinde titreşim uyaranı verilerek gerçekleştirilecektir. Titreşimin vücuda iletimi ve kas kasılması paterni eş zamanlı olarak ölçülecektir.

3. Muhtemel Riskler ve Rahatsızlıklar

Uygulanacak testler süresince pedal çevirme yada devam eden statik kasılmalar sonucunda makul düzeyde yorgunluk hissi oluşabilecektir. Alt ve üst ekstremite ile ilşikili dokularda devam eden ya da daha önceden yaşadığınız bir rahatsızlık var ise ağrı hissedebilirsiniz. Böyle bir durum var ise çalışmaya katılmamanız önerilecektir.Ölçümler esnasında böyle bir durum ile karşılaşıldığı durumda testi sonlandırmanız sağlanacaktır. Ayrıca, kişi istediği an araştırma grubundan çıkarılabilecektir.

4. Beklenen Faydalar

Araştırma sonucunda, el-kol sisteminin maruz kaldığı titreşim düzeyi ve vücuda iletimi ölçülerek, titreşim dozu ile biyodinamik yanıt ilişkisine dair bilgi sunulabilecektir. Bu sayede bisiklet-sürücü el-kol titreşim iletimi modelinin oluşturulması için modele ait iskelet-kas sistemi dinamikleri ile titreşim dozu-biyodinamik yanıt ilişkisi detaylandırılacaktır.

5. Gizlilik

Katılımınız tamamen gizli tutulacaktır. Gizliliği korumak için analizler süresince isminiz yerine size verilmiş bir numara kullanılacaktır. Katılımcı bilgilerini içeren listelere ise sadece araştırmacılar ulaşabilecektir.

6. Yaralanmalar ve Tedavisi

Beklenmeyen acil bir durumun oluşması halinde ODTU Sağlık Merkezi Acil Servisine başvurulacaktır.

7. Sorular

Araştırmacılar çalışmanın mevcut riskleri ve bilgilendirilmiş onam formu hakkındaki her türlü sorunuza yanıt verecektir. Test yöntemleri hakkında soracağınız her soruya açıklıkla yanıt verilecektir. Eğer ilgileniyorsanız çalışmaya ait genel sonuçlar size gönderilecektir.

8. Katılım Özgürlüğü

Katılımda gönüllülük prensibine uyulacaktır. Katılımcılar istedikleri zaman çalışmadan ayrılma hakkına sahip olacaktır. Çalışmayı bırakmanız halinde herhangi bir yaptırım uygulanmayacaktır.

Eğer bu çalışmayı ilgilendiren daha başka sorularınız var ise veya sonuçların bir kopyasını isterseniz bizlere 210 41 75 no'lu telefondan ulaşabilirsiniz.

Bu formu okuyarak uygulayacağınız test prosedürlerini, içerebileceği riskleri ve rahatsızlıkları anlamış bulunuyorum. Bu riskleri ve rahatsızlıkları bilerek ve beni tatmin edecek şekilde cevaplandırılmış soru sorma ayrıcalığım tanınmış olarak bu çalışmada yer almayı kabul ediyorum.

Tarih   Katılımcının İmzası   Araştırmacının İmzası

APPENDIX B. ETHICAL APPROVAL FORM

ORTA DOĞU TEKNİK ÜNİVERSİTESİ
Fen Bilimleri Enstitüsü
1956

Sayı:B.30.2.ODT.O.CI.OO.OO/126/13 24.04.2007

GÖNDERİLEN : Prof.Dr. Gülin Birlik
Mühendislik Bilimleri EABD

GÖNDEREN : Prof.Dr.Canan Özgen
Fen Bilimleri Enstitüsü Müdürü

Canan Özgen

KONU : İnsan Araştırmaları Etik Kurulu onayı hk.

Enstitümüz Mühendislik Bilimleri EABD'da görev yapmakta olan Prof.Dr. Gülin Birlik ve arkadaşları tarafından yapılması planlanan "Ele İletilen Titreşim ve Submaksimal Kuvvet Üretiminin El-Kol Sisteminde Biodinamik Yanıt Üzerine Etkisinin İncelenmesi" başlıklı araştırma projesi ile ilgili olarak Üniversitemiz Laboratuvarlarında uygulama yapmak için görevlendirme başvurusu incelenmiş; adı geçenin isteği doğrultusunda görevlendirilmesine İnsan Araştırmaları Etik Kurulu onayı koşulu ile uygun görülmüştür.

Gereği için bilgilerinize saygılarımla sunarım.

Ek: YKK
EABD görüşü

İnsan Araştırmaları Etik Kurulu Onayı

Uygundur

24.04.2007

Canan Özgen

cc: Mühendislik Bilimleri EABD Başkanlığı.

ODTÜ Ankara 06531 Tel : (312) 210 22 91-2 Fax : (312) 210 11 13 E-posta : wwwfbe@metu.edu.tr

APPENDIX C. ADDITIONAL FIGURES OF RESULTS &DISCUSSION CHAPTER

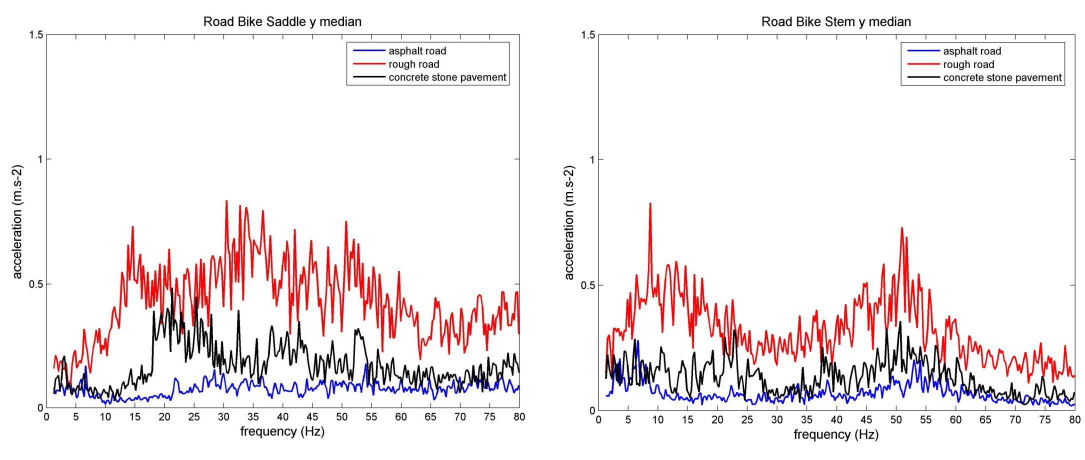

Figure C.1 Median a_y-f curves obtained at saddle and stem during the field measurements with road bike on asphalt road, rough road and concrete stone pavement

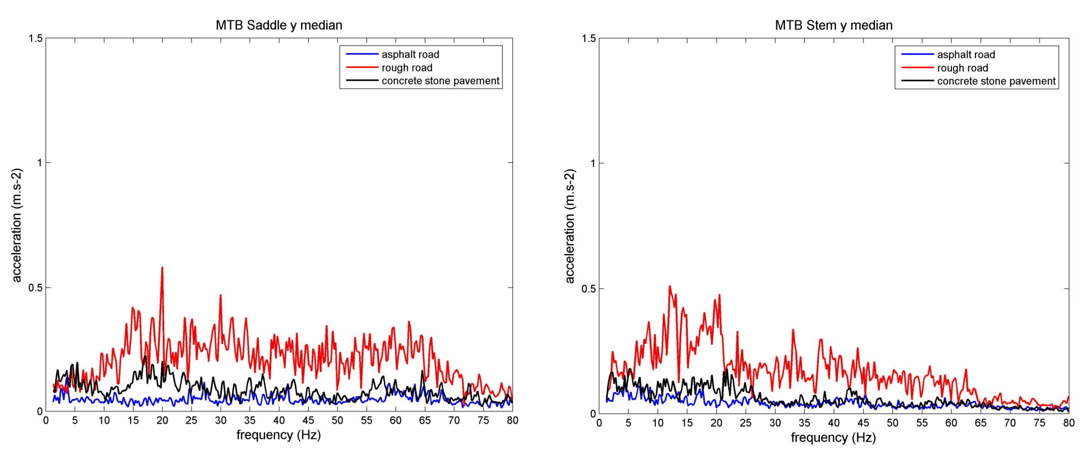

Figure C.2 Median a_y-f curves obtained at saddle and stem during the field measurements with MTB on asphalt road, rough road and concrete stone pavement

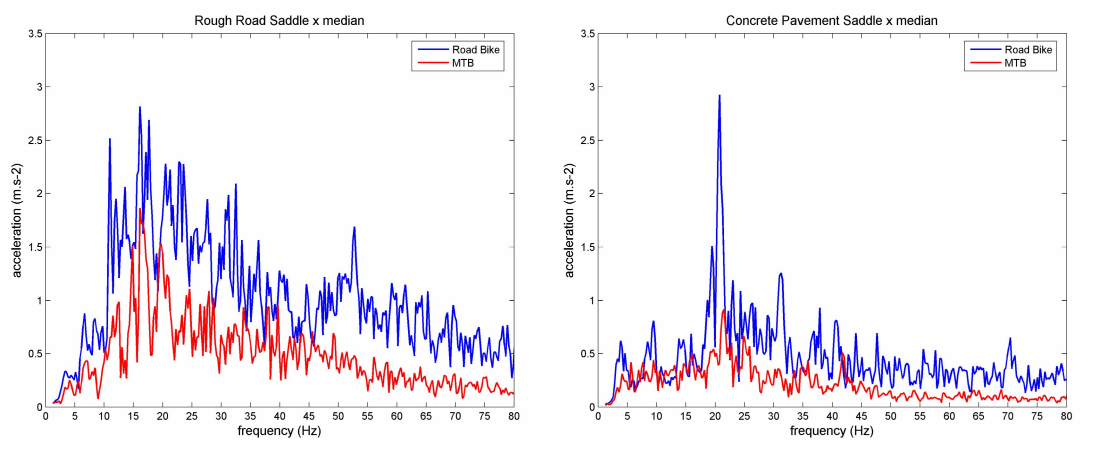

Figure C.3 Comparison of Road Bike and MTB in terms of Median a_x (saddle)-f curves for different test tracks (rough road and concrete stone pavement)

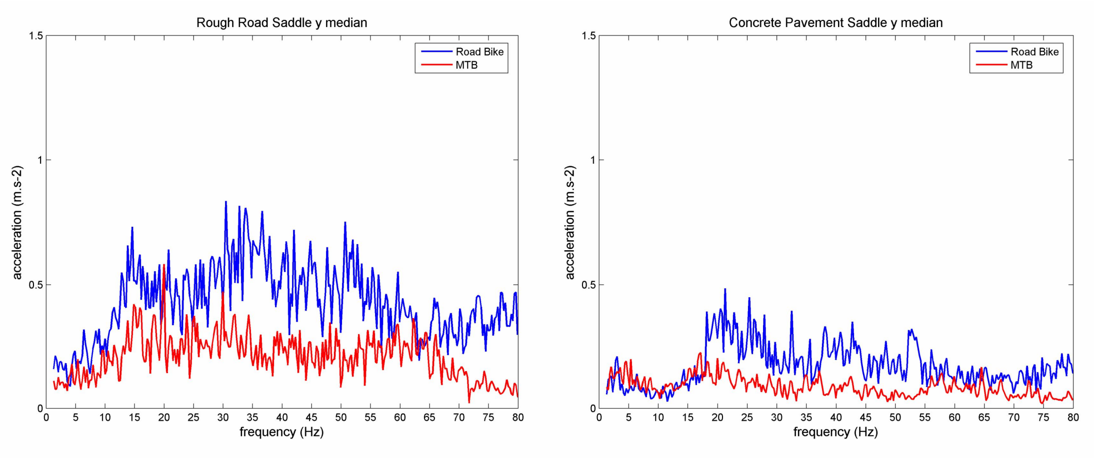

Figure C.4 Comparison of Road Bike and MTB in terms of Median a_y (saddle)-f curves for different test tracks (rough road and concrete stone pavement)

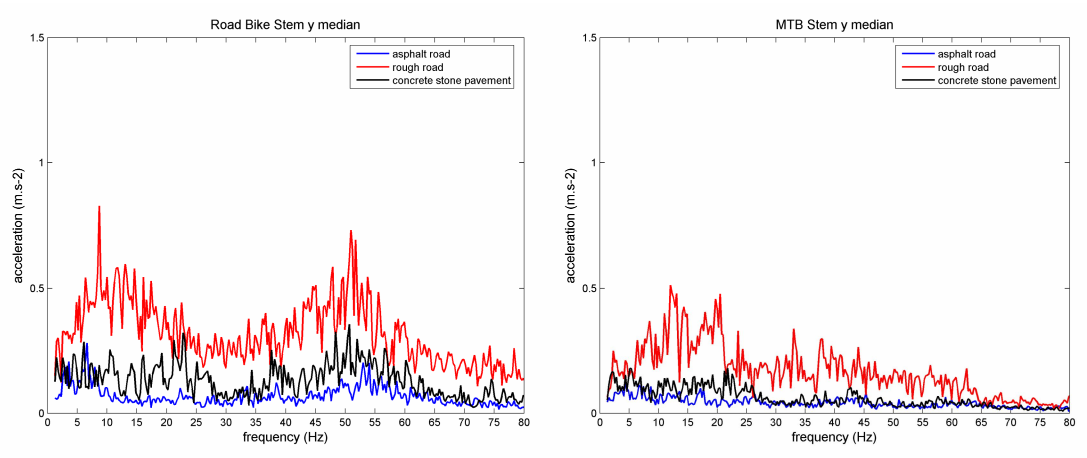

Figure C.5 Median a_y -f curves obtained at stem during the field measurements with road bike (left) and MTB (right) on asphalt road, rough road and concrete stone pavement

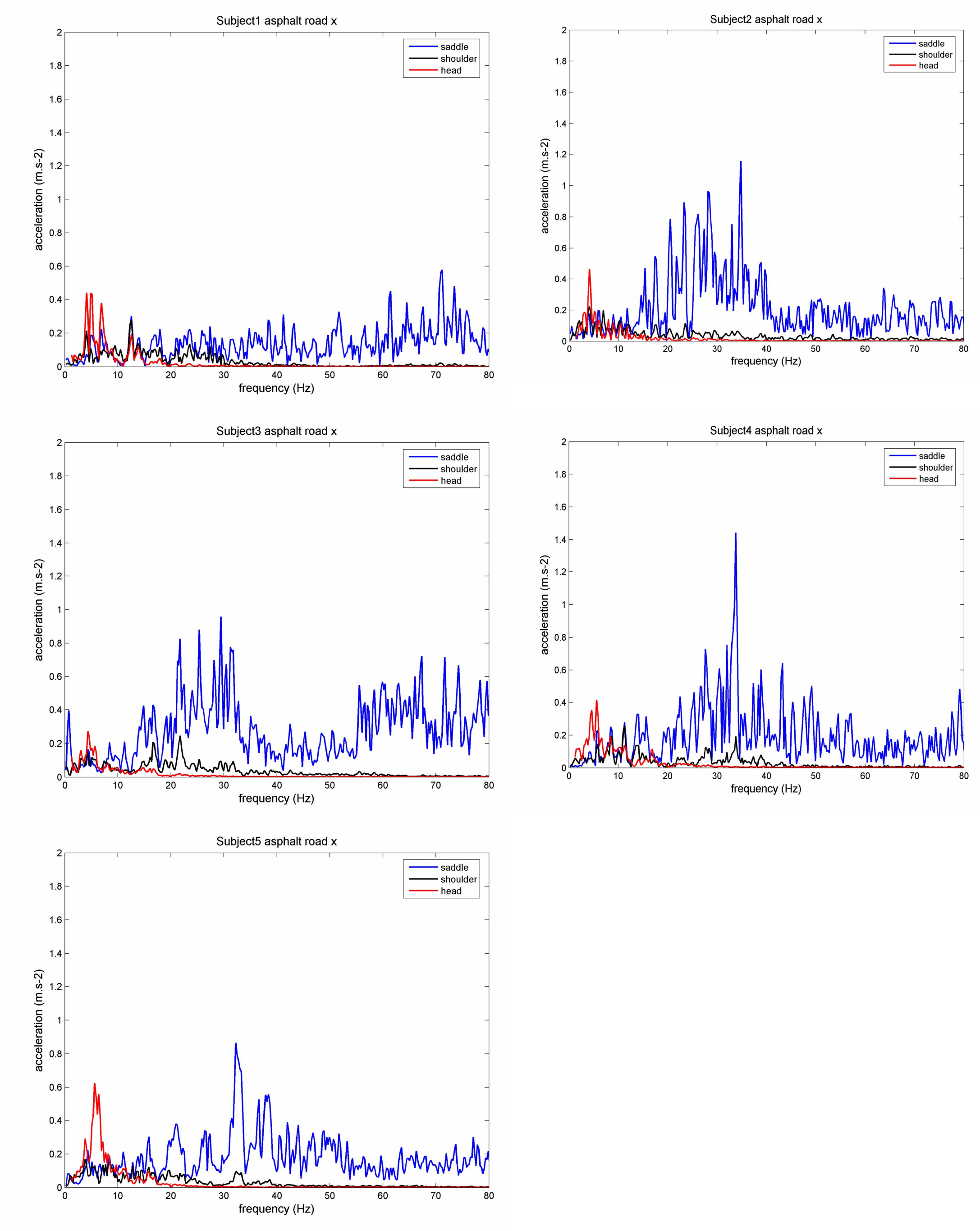

Figure C.6 Vibration transmitted, in x direction, to subjects on road bike while riding on asphalt road, through saddle-shoulder-forehead

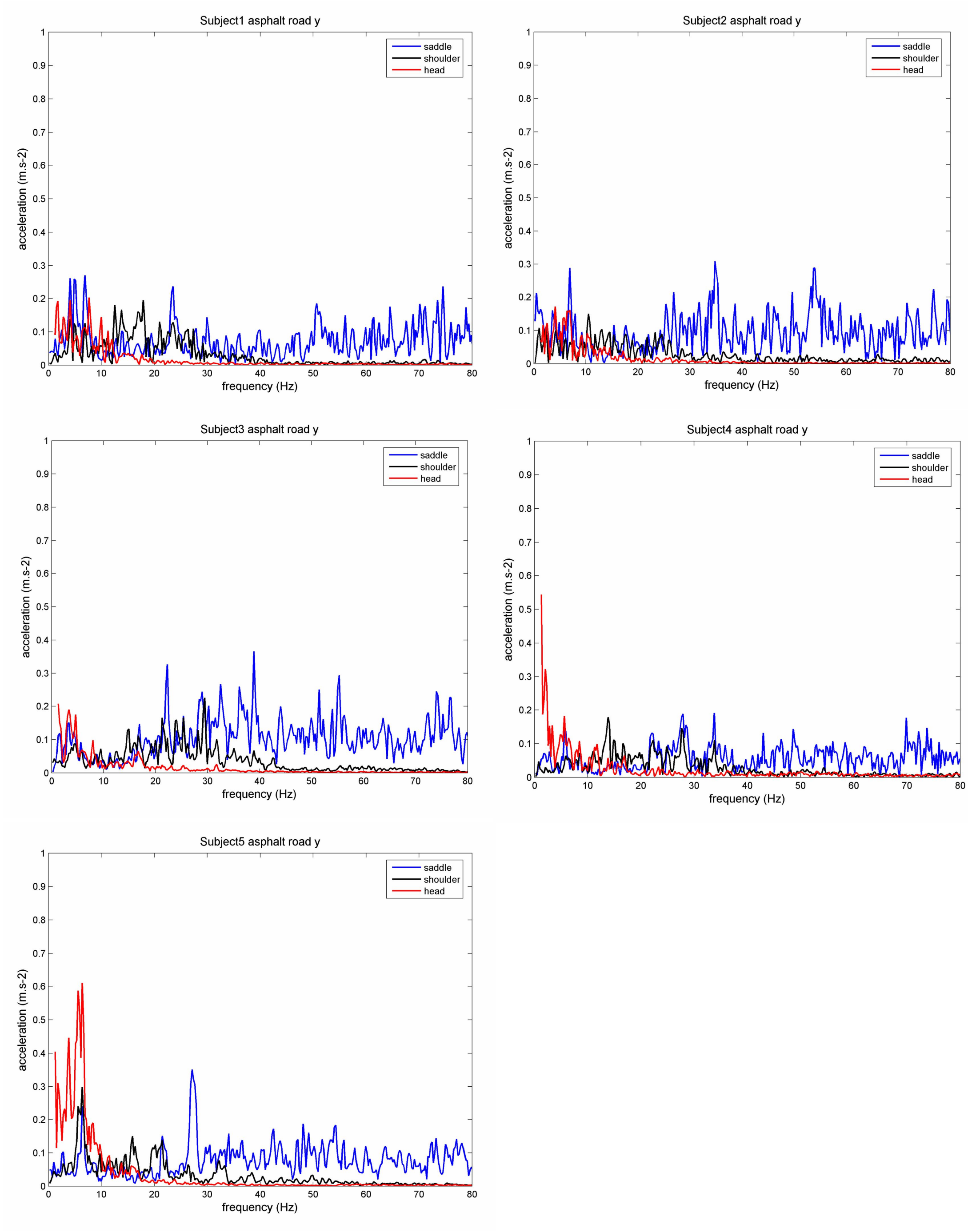

Figure C.7 Vibration transmitted, in y direction, to subjects on road bike while riding on asphalt road, through saddle-shoulder-forehead

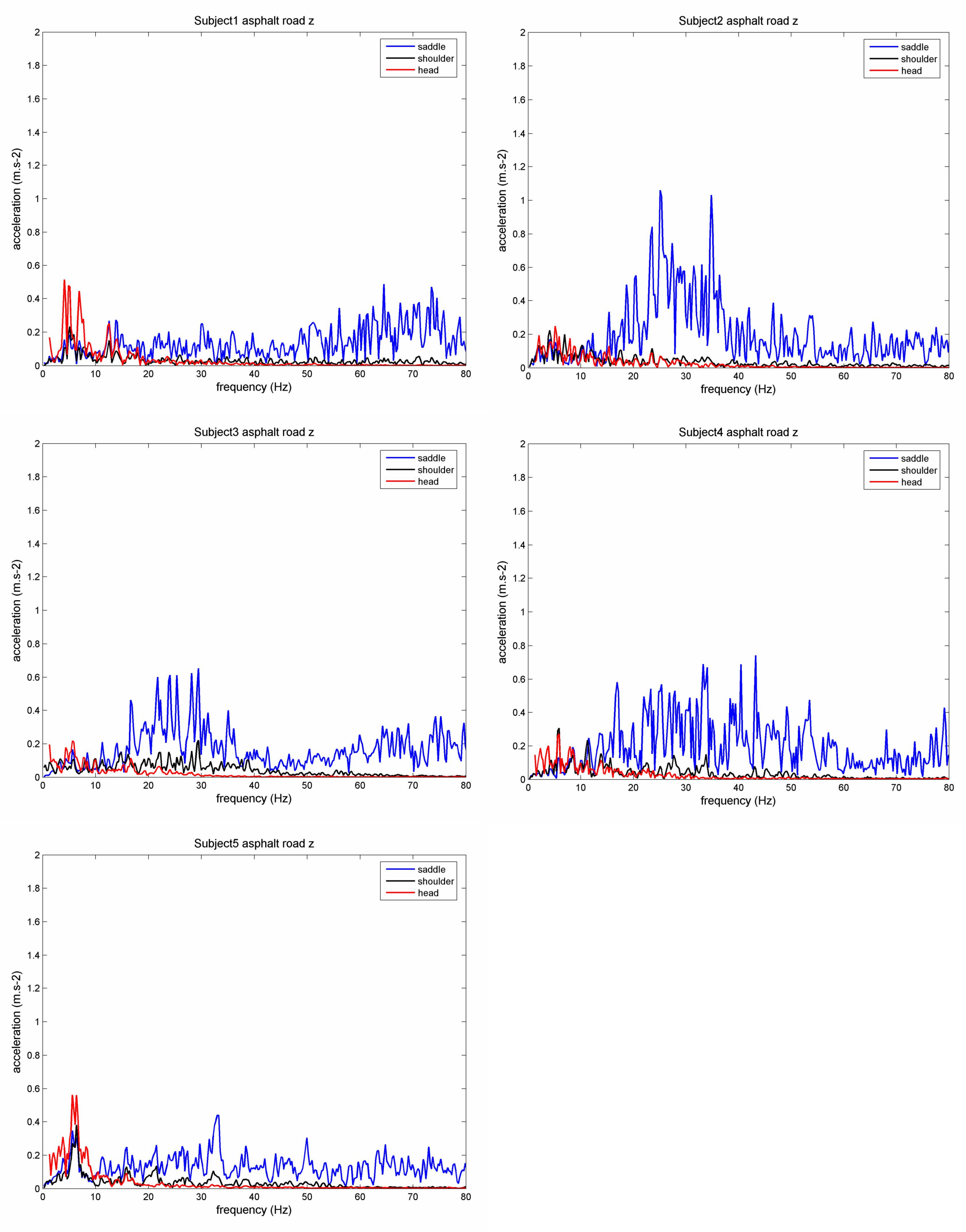

Figure C.8 Vibration transmitted, in z direction, to subjects on road bike while riding on asphalt road, through saddle-shoulder-forehead

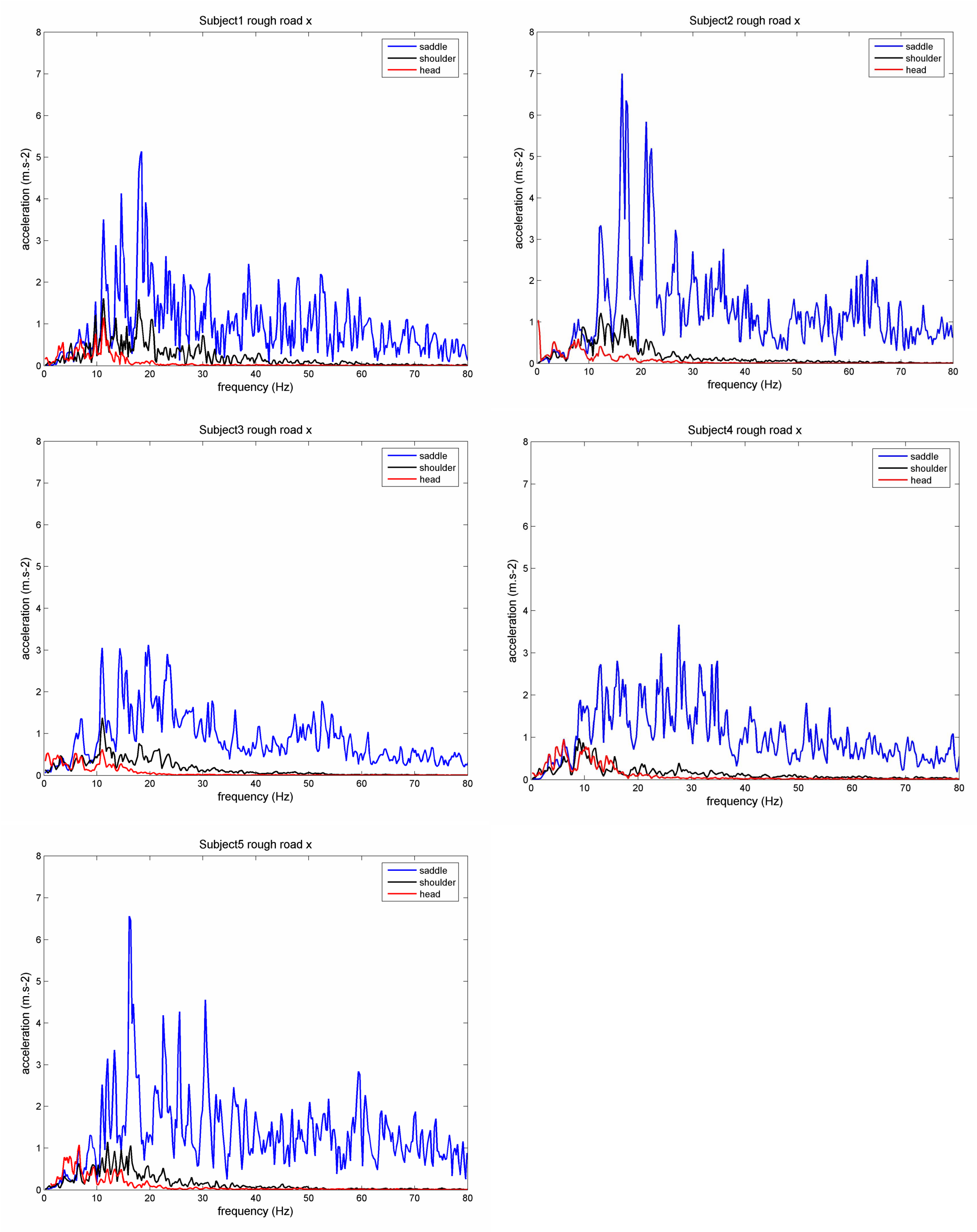

Figure C.9 Vibration transmitted, in x direction, to subjects on road bike while riding on rough road, through saddle-shoulder-forehead

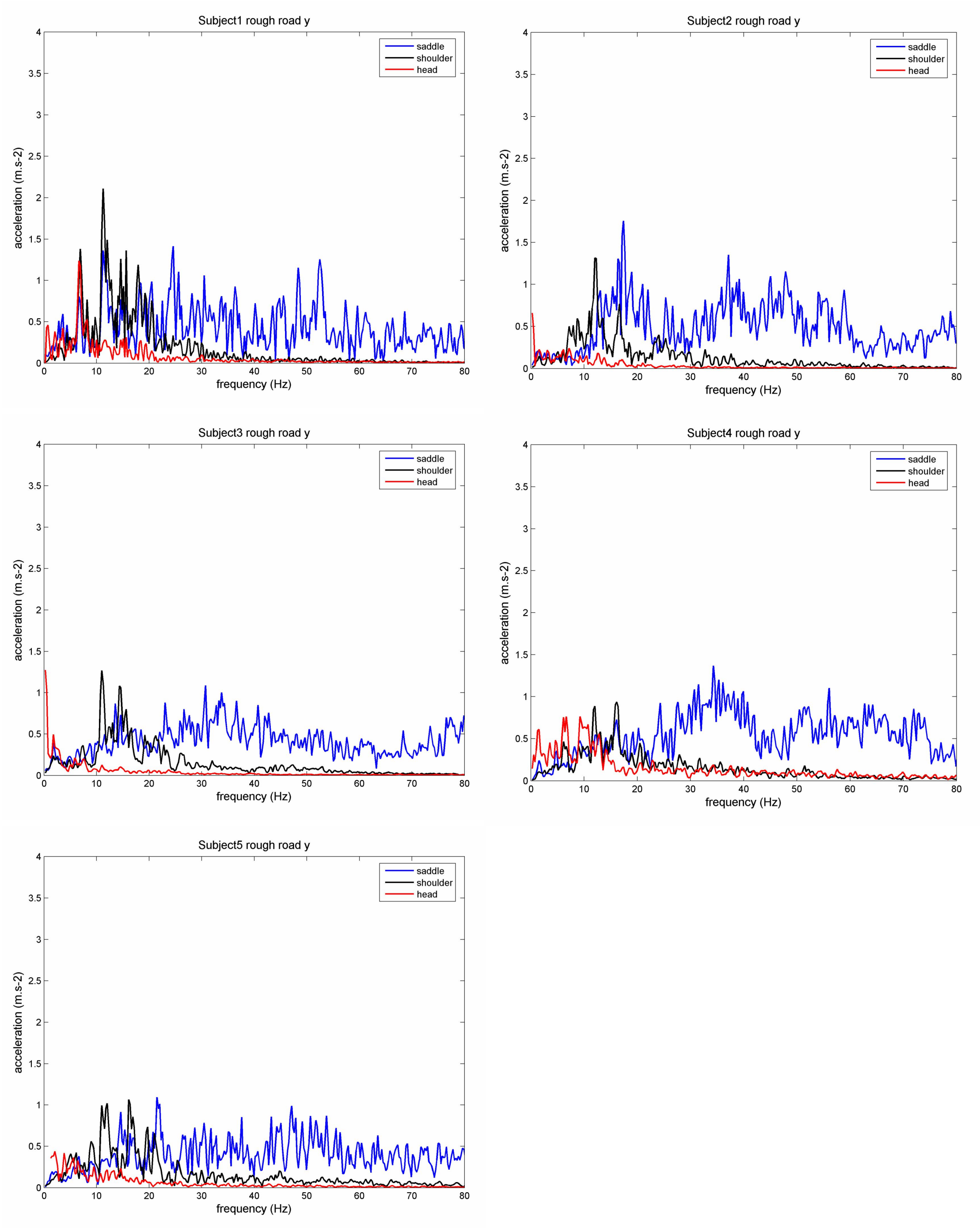

Figure C.10 Vibration transmitted, in y direction, to subjects on road bike while riding on rough road, through saddle-shoulder-forehead

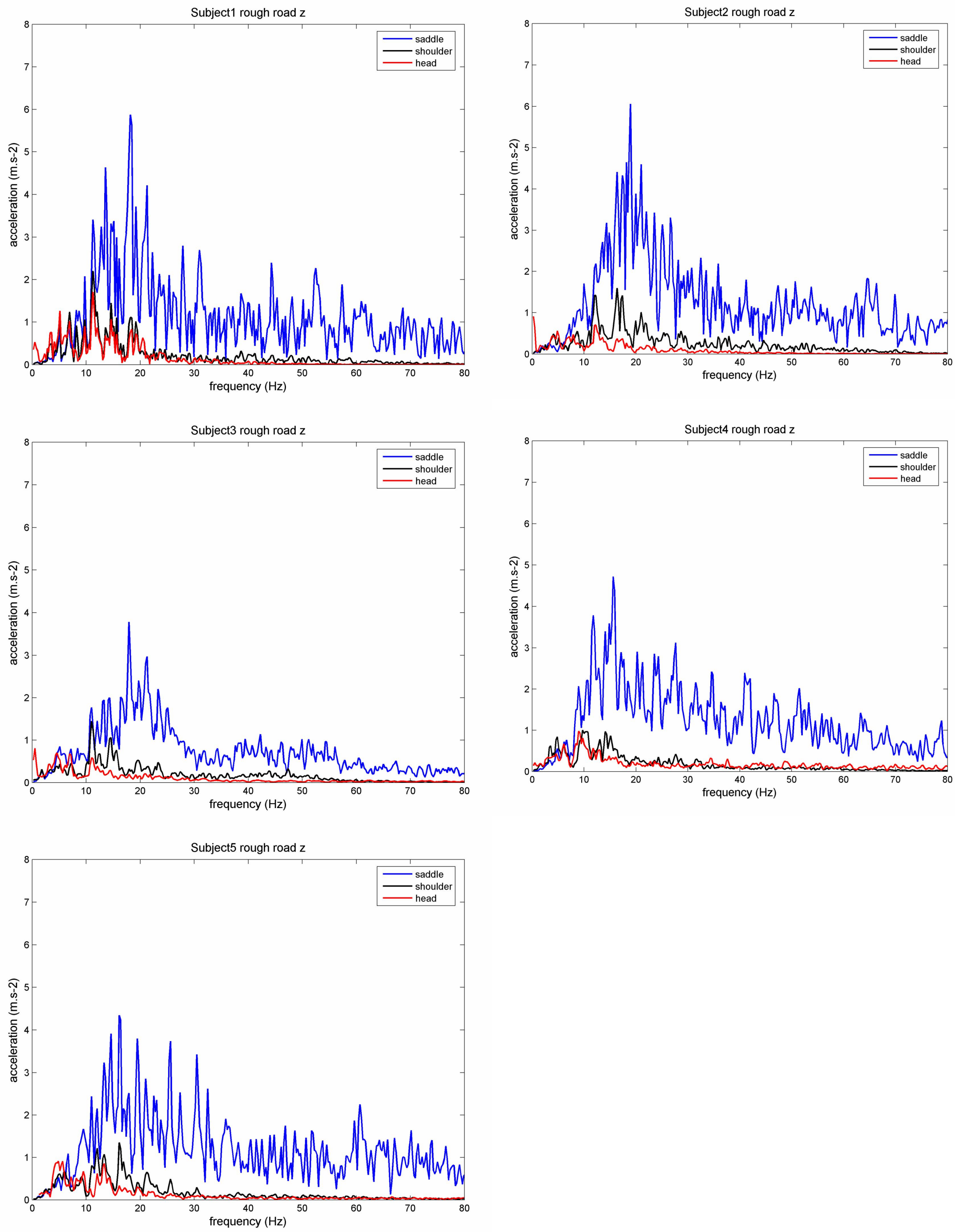

Figure C.11 Vibration transmitted, in z direction, to subjects on road bike while riding on rough road, through saddle-shoulder-forehead

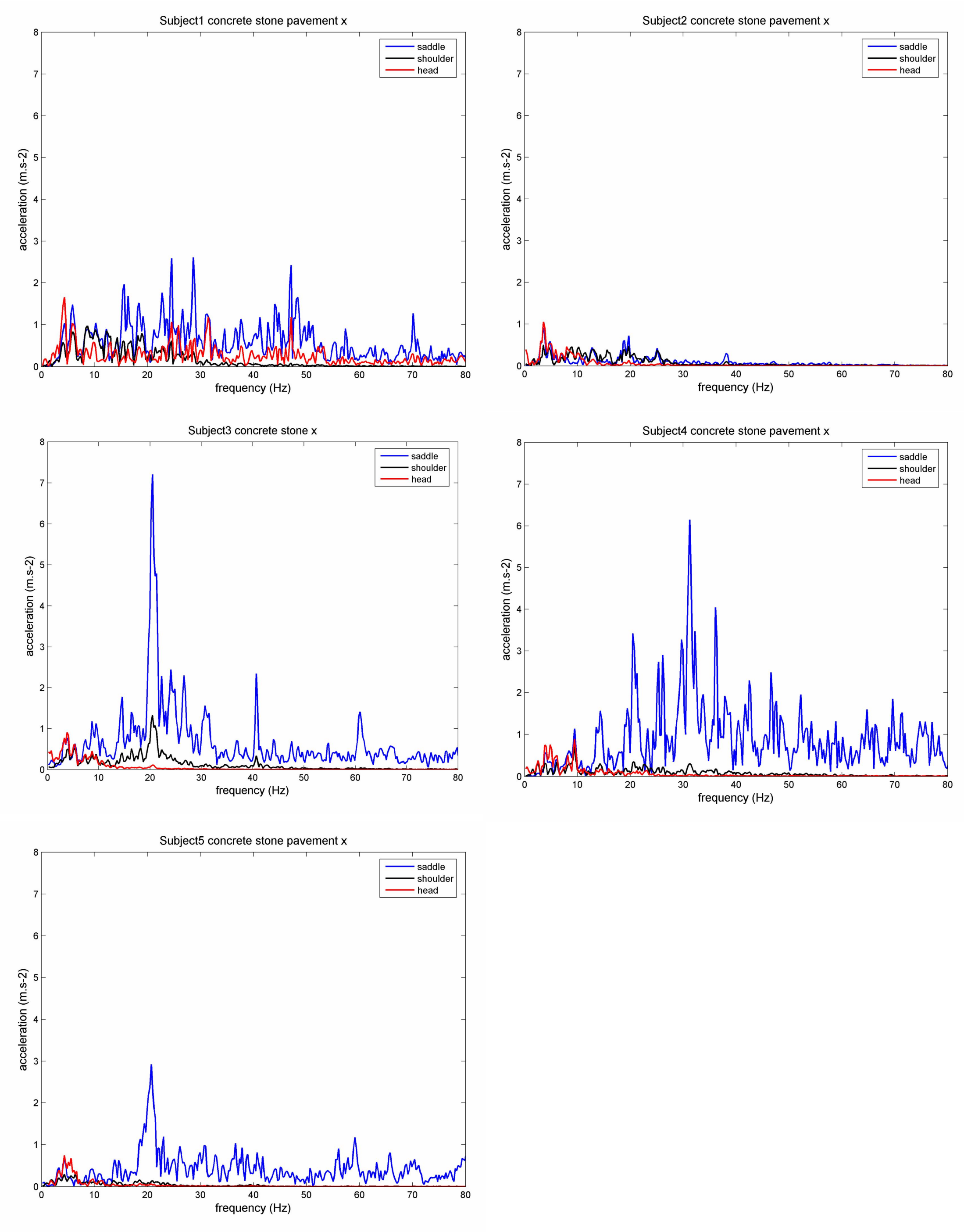

Figure C.12 Vibration transmitted, in x direction, to subjects on road bike while riding on concrete stone pavement, through saddle-shoulder-forehead

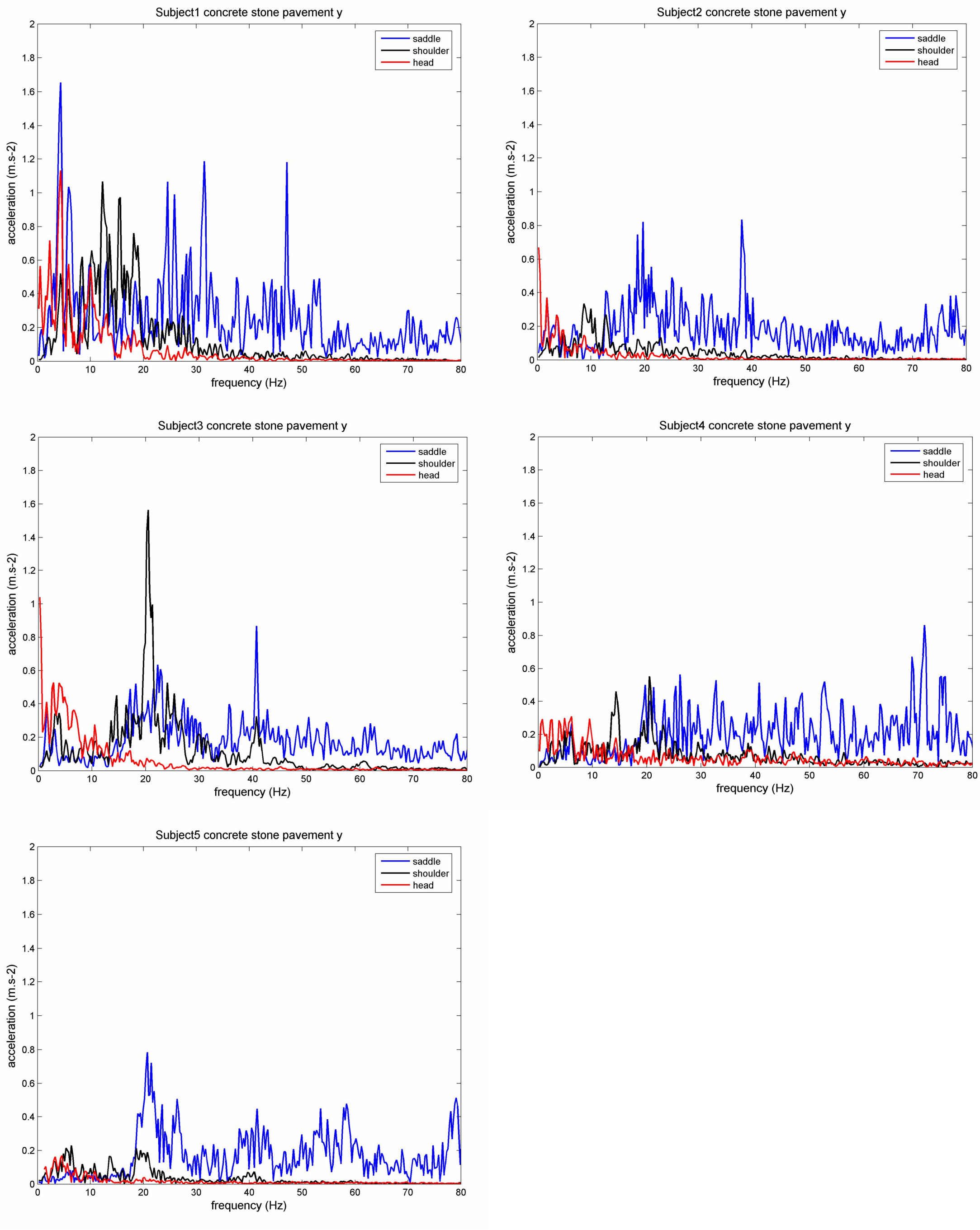

Figure C.13 Vibration transmitted, in y direction, to subjects on road bike while riding on concrete stone pavement, through saddle-shoulder-forehead

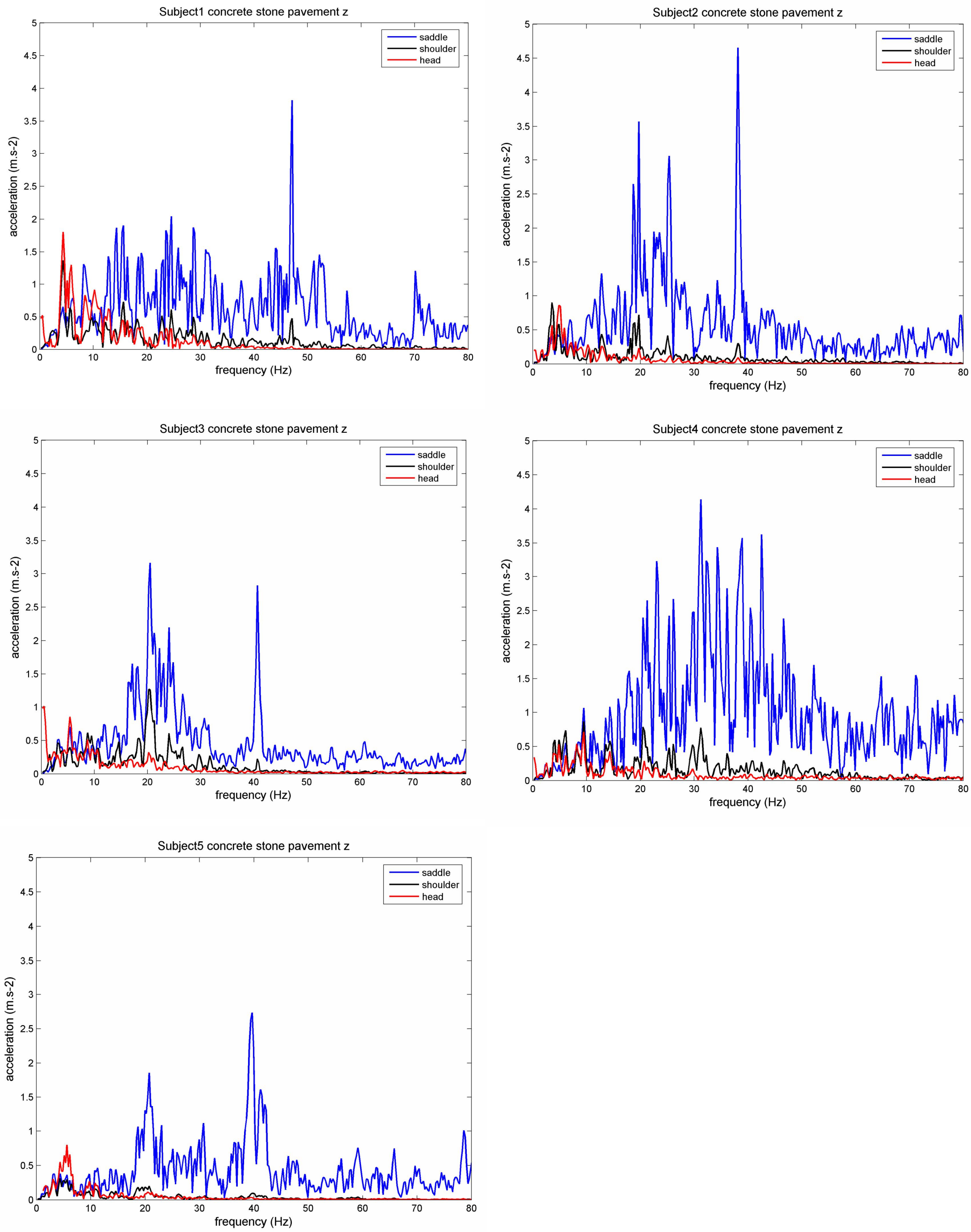

Figure C.14 Vibration transmitted, in z direction, to subjects on road bike while riding on concrete stone pavement, through saddle-shoulder-forehead

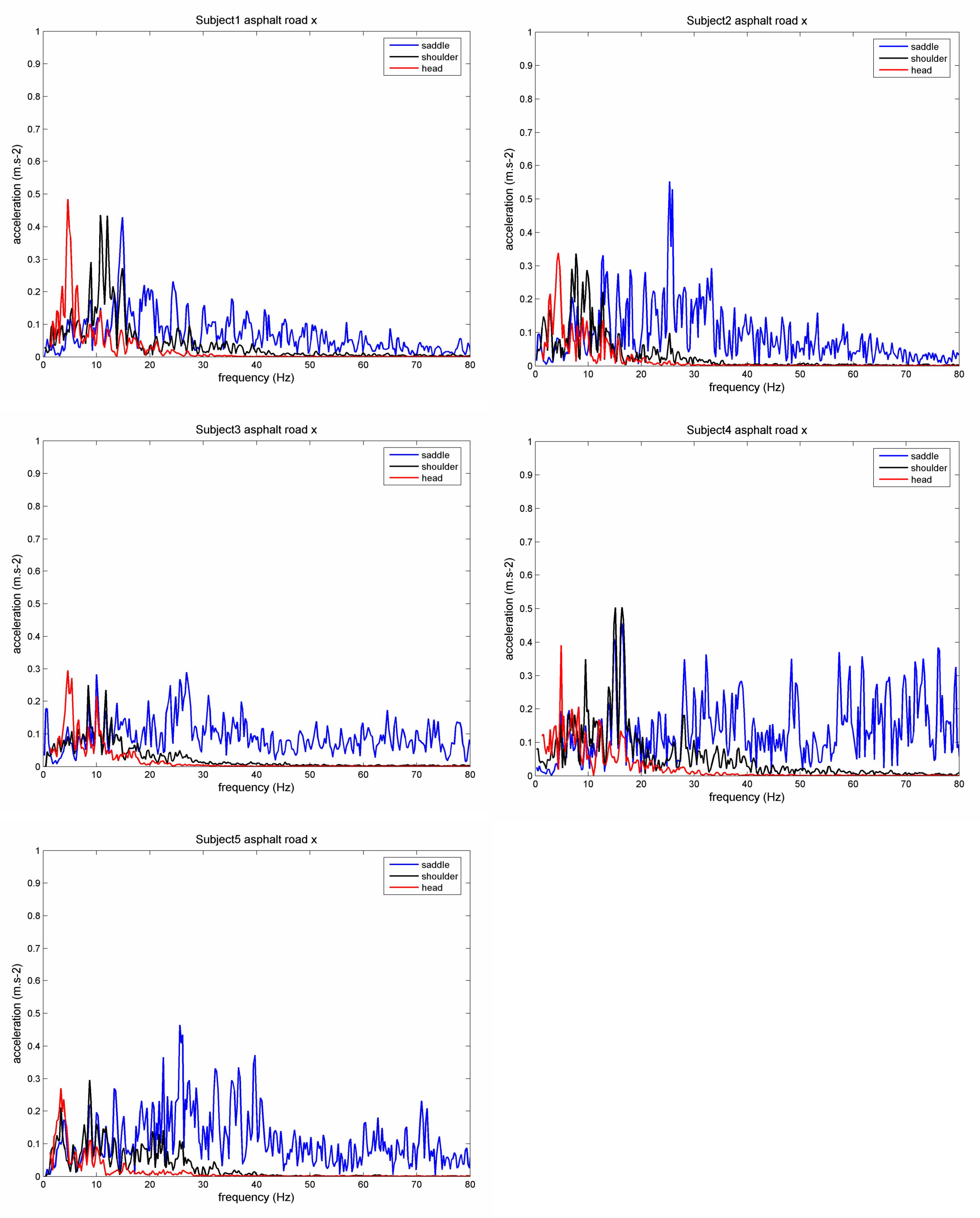

Figure C.15 Vibration transmitted, in x direction, to subjects on MTB while riding on asphalt road, through saddle-shoulder-forehead

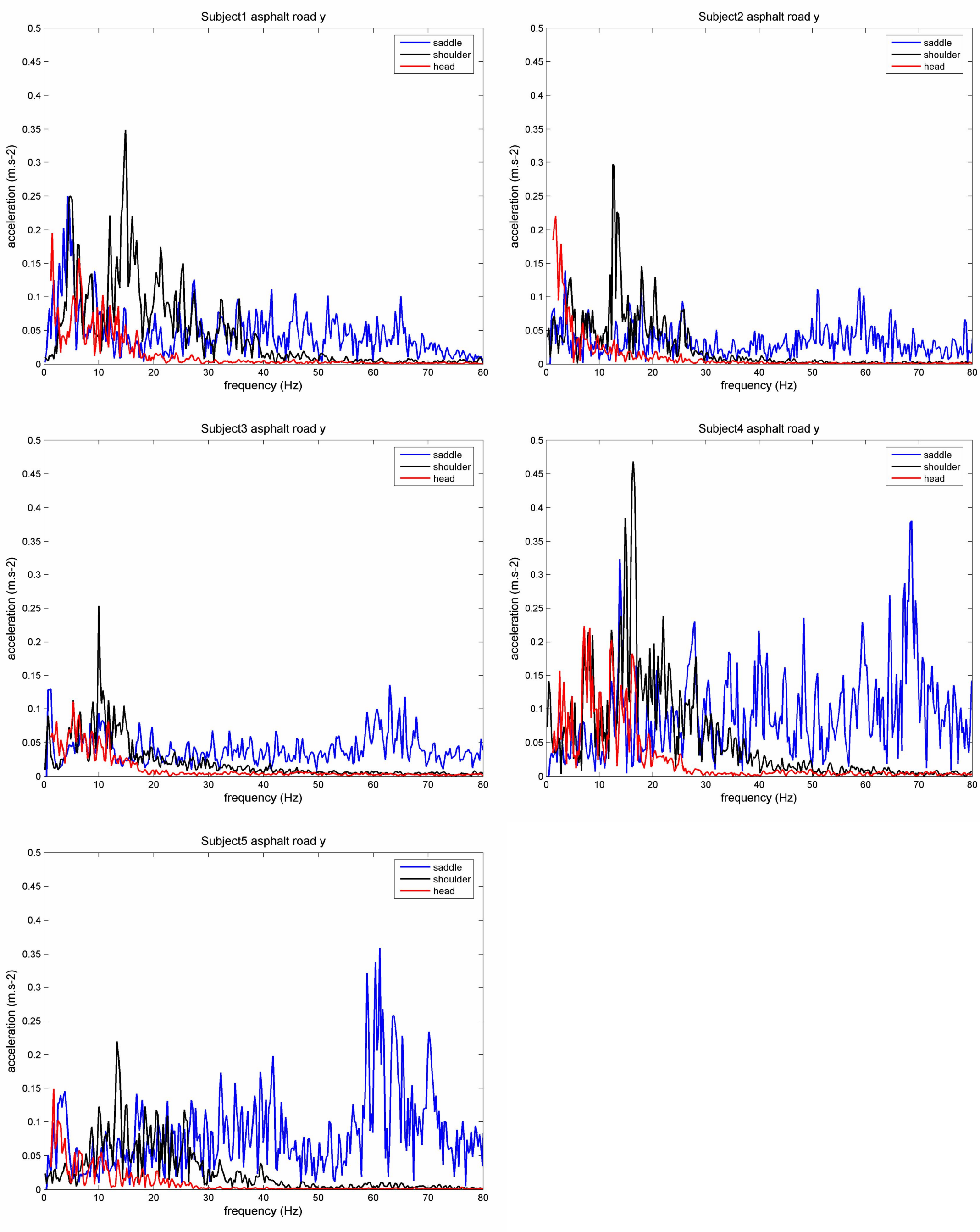

Figure C.16 Vibration transmitted, in y direction, to subjects on MTB while riding on asphalt road, through saddle-shoulder-forehead

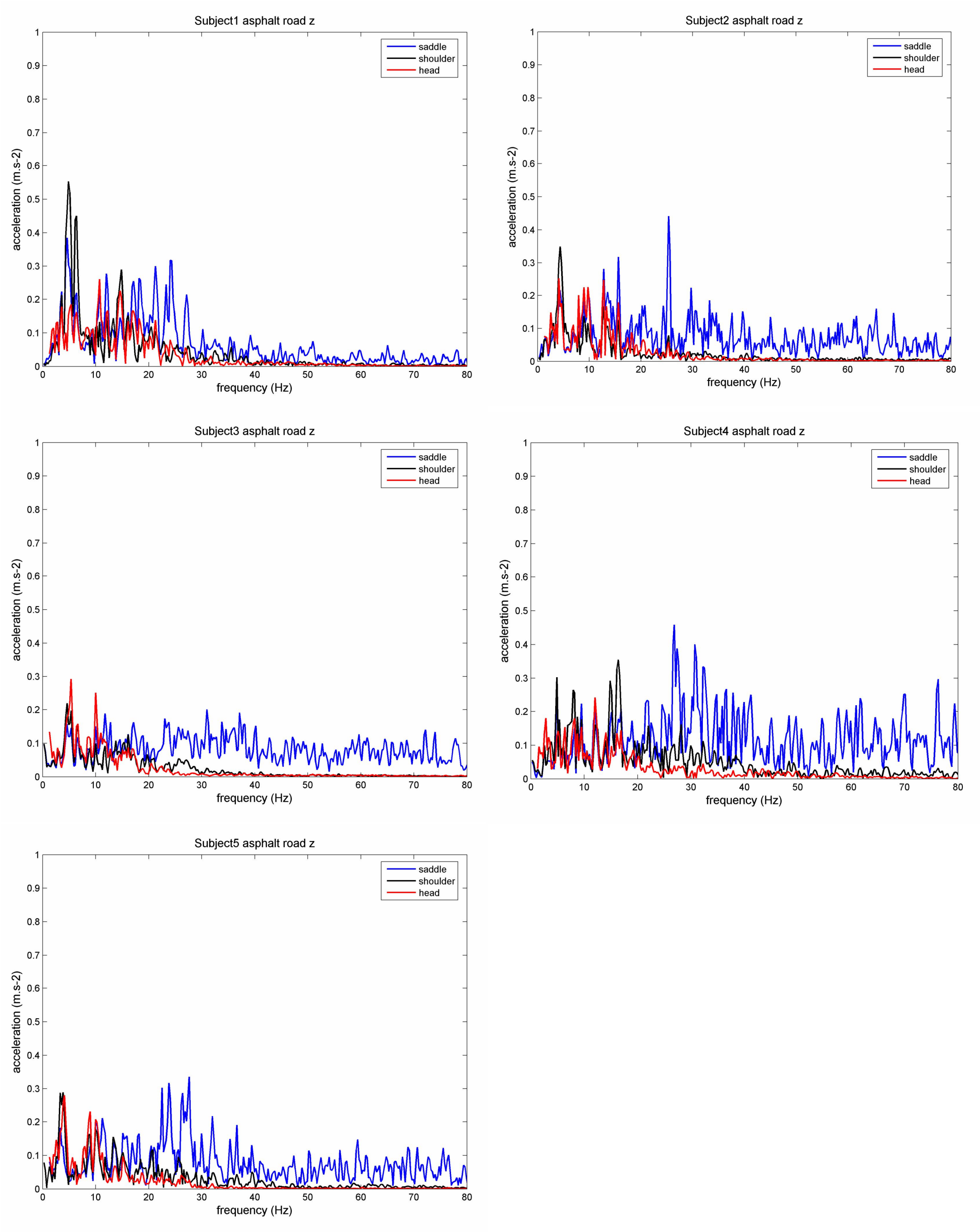

Figure C.17 Vibration transmitted, in z direction, to subjects on MTB while riding on asphalt road, through saddle-shoulder-forehead

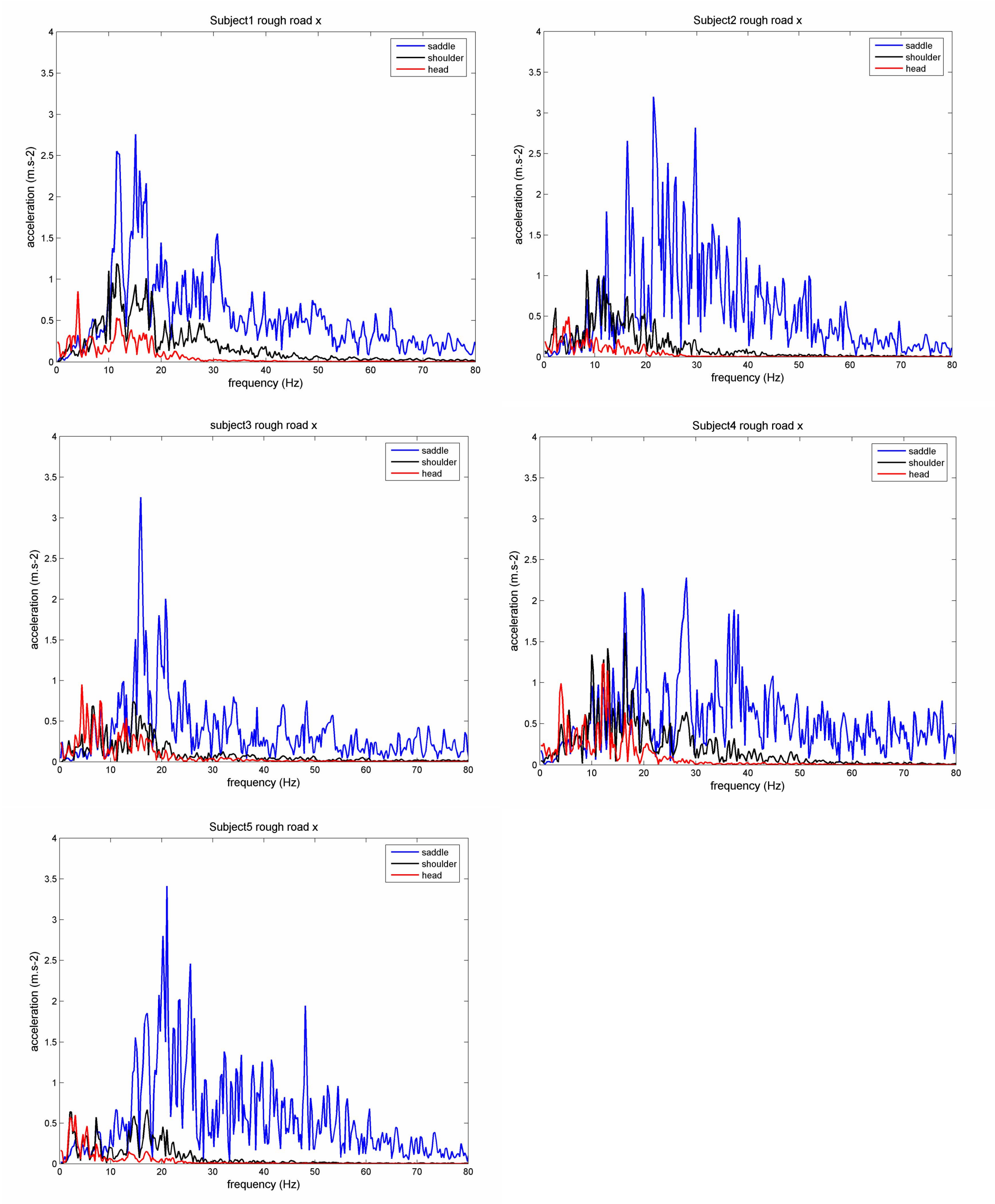

Figure C.18 Vibration transmitted, in x direction, to subjects on MTB while riding on rough road, through saddle-shoulder-forehead

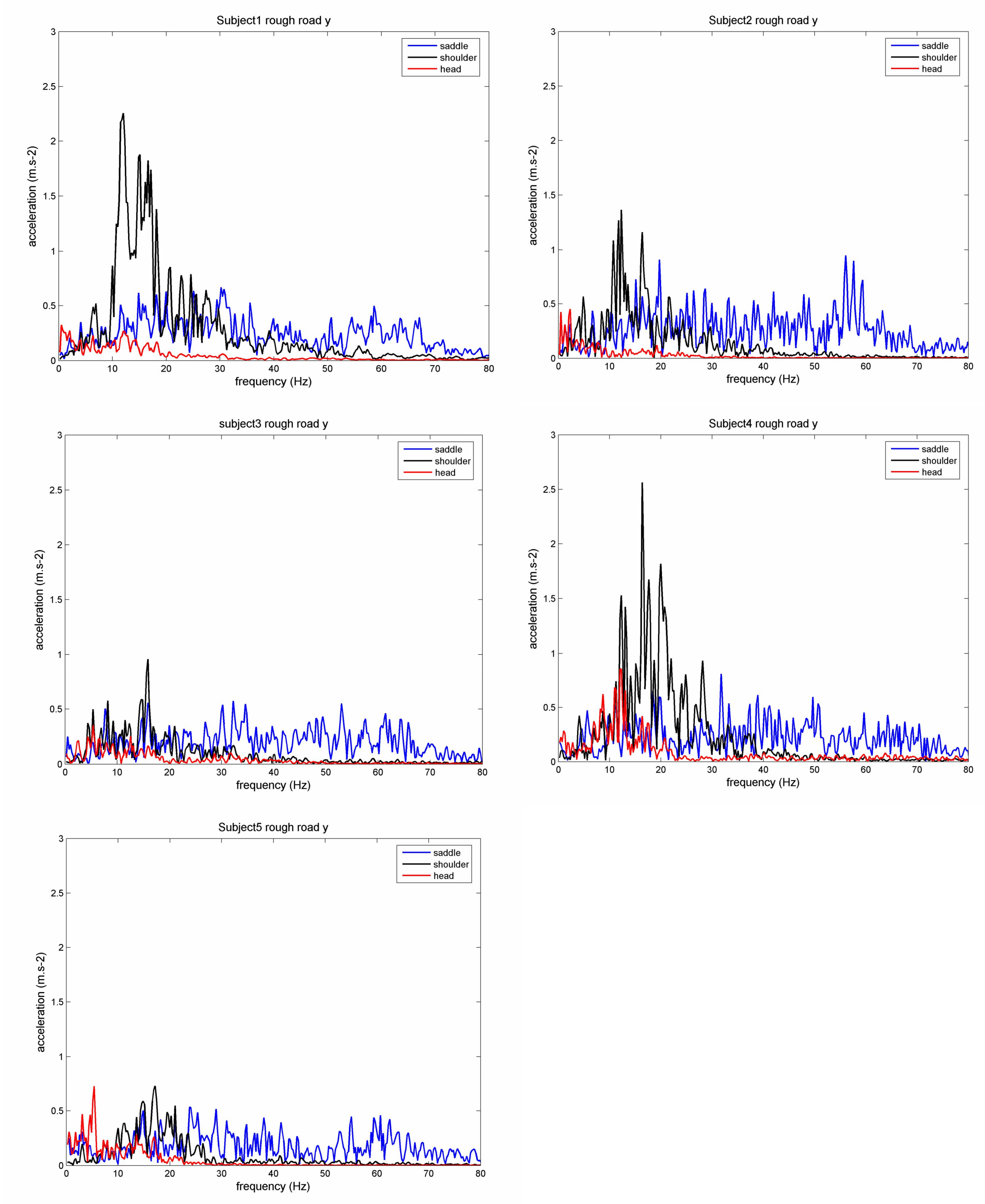

Figure C.19 Vibration transmitted, in y direction, to subjects on MTB while riding on rough road, through saddle-shoulder-forehead

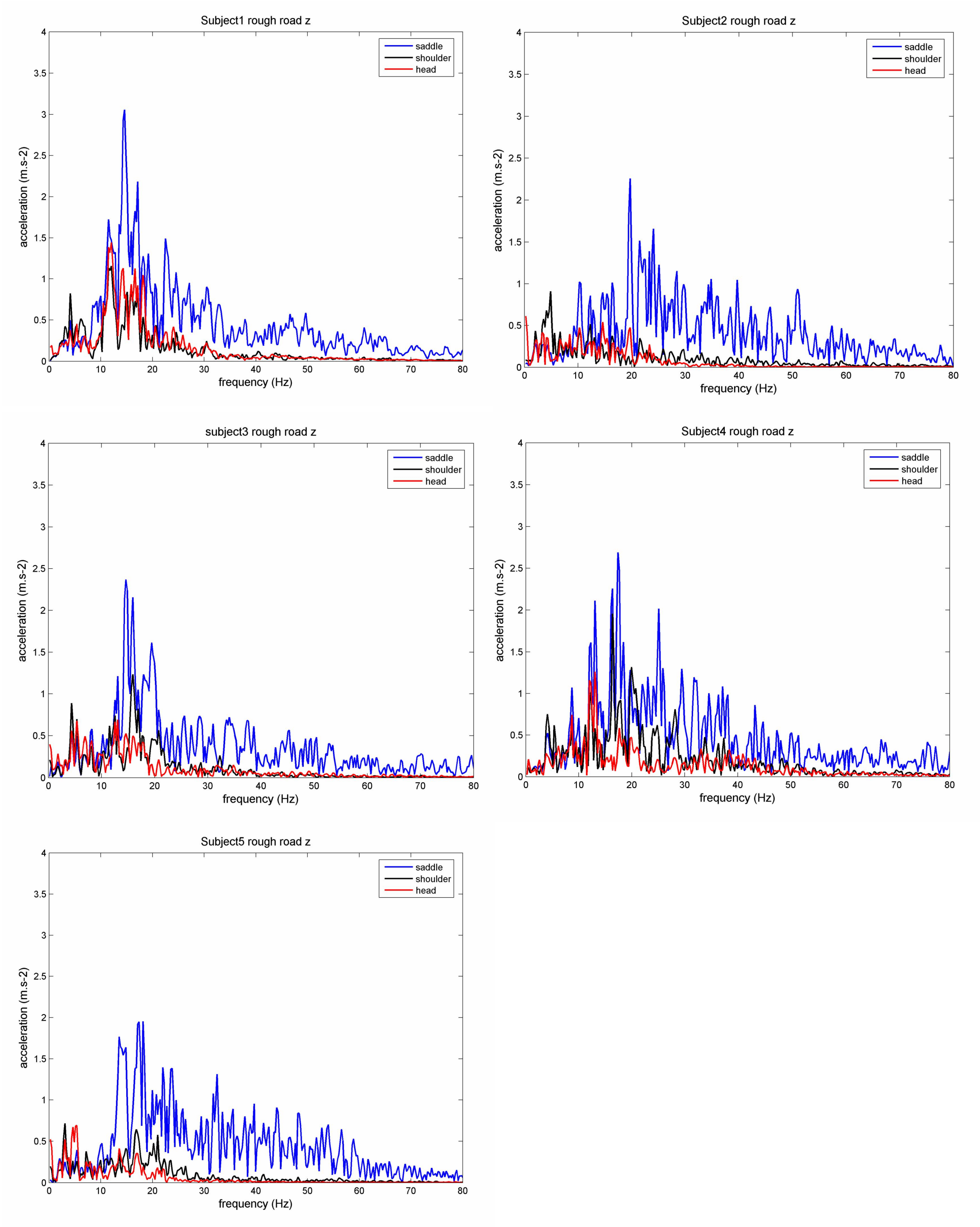

Figure C.20 Vibration transmitted, in z direction, to subjects on MTB while riding on rough road, through saddle-shoulder-forehead

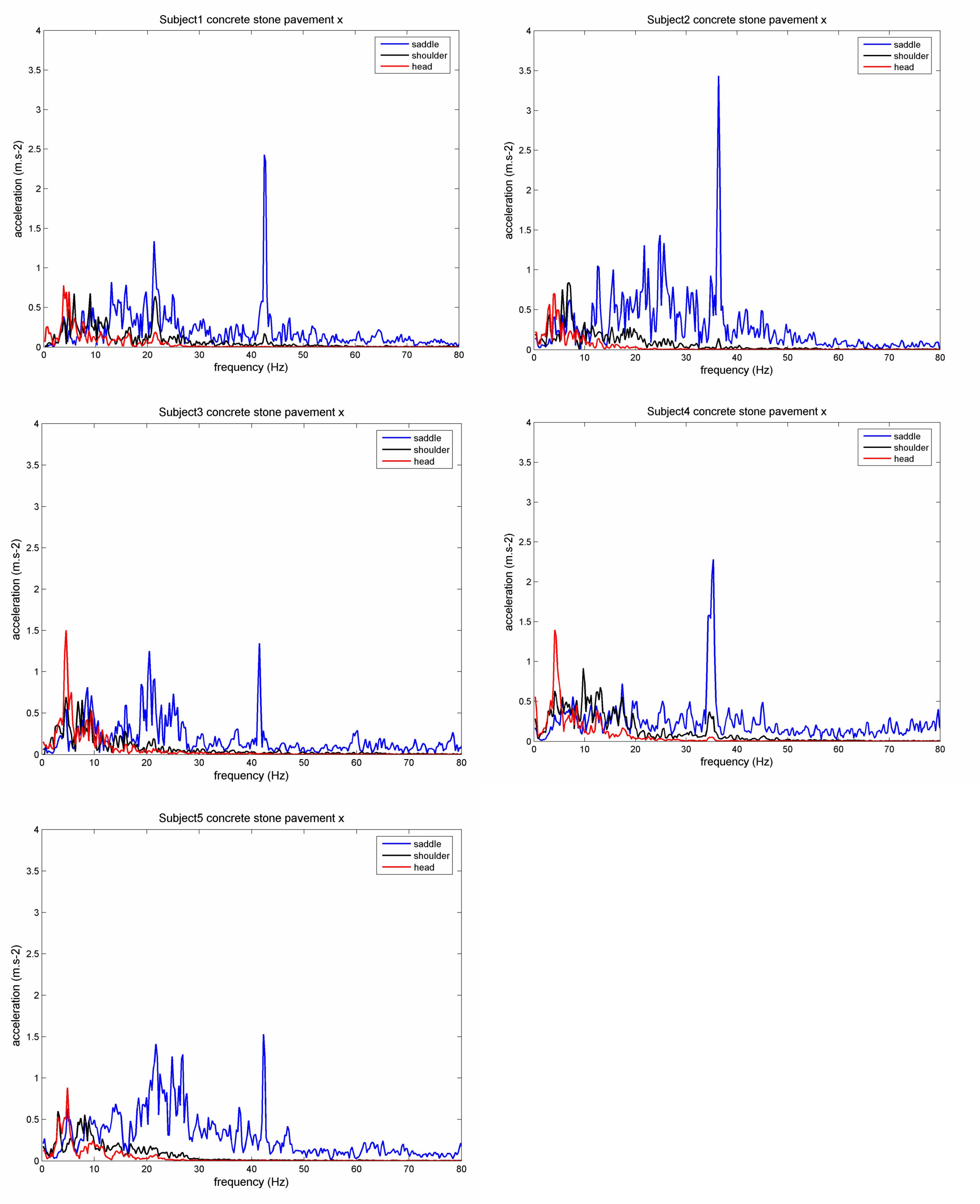

Figure C.21 Vibration transmitted, in x direction, to subjects on MTB while riding on concrete stone pavement, through saddle-shoulder-forehead

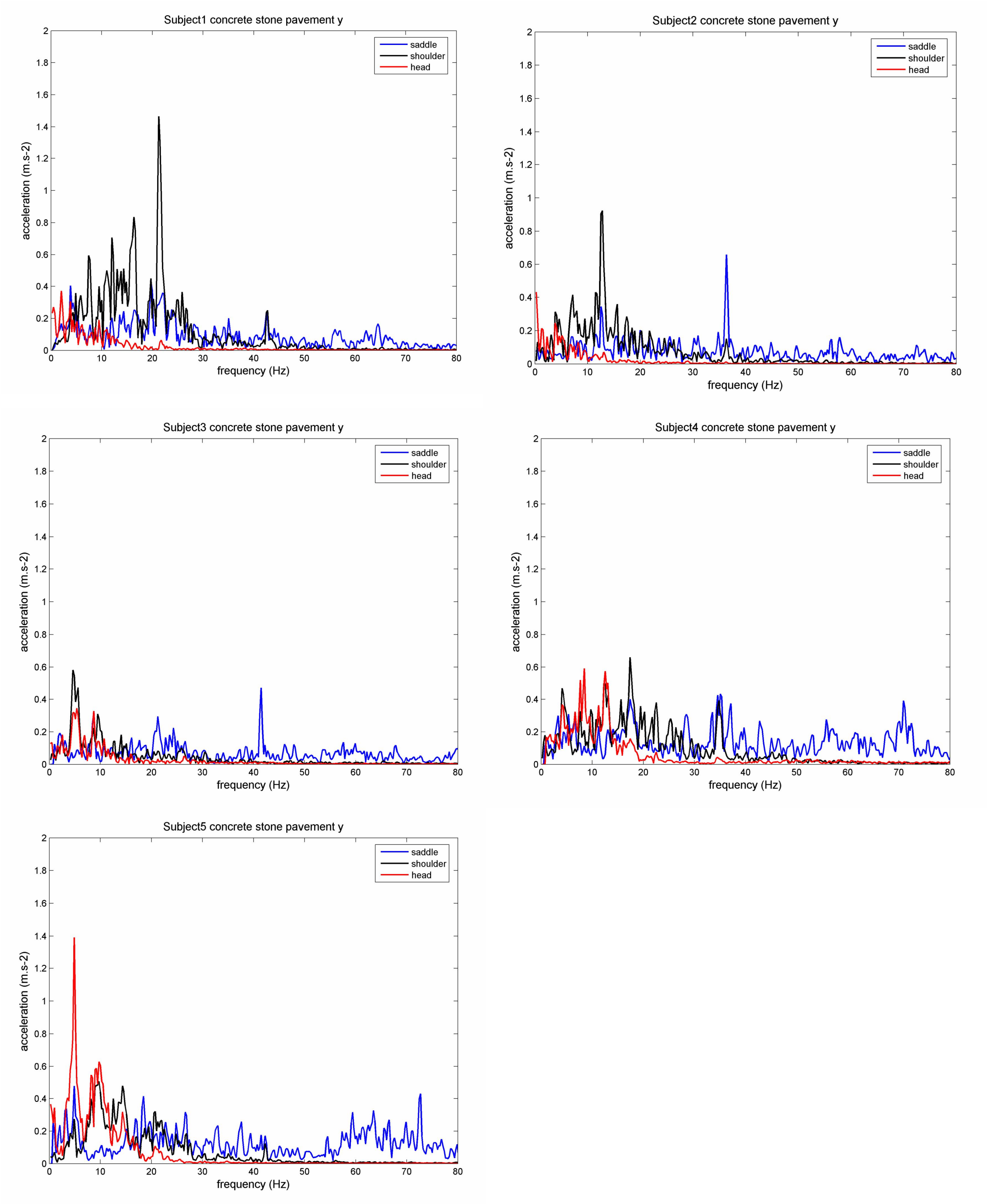

Figure C.22 Vibration transmitted, in y direction, to subjects on MTB while riding on concrete stone pavement, through saddle-shoulder-forehead

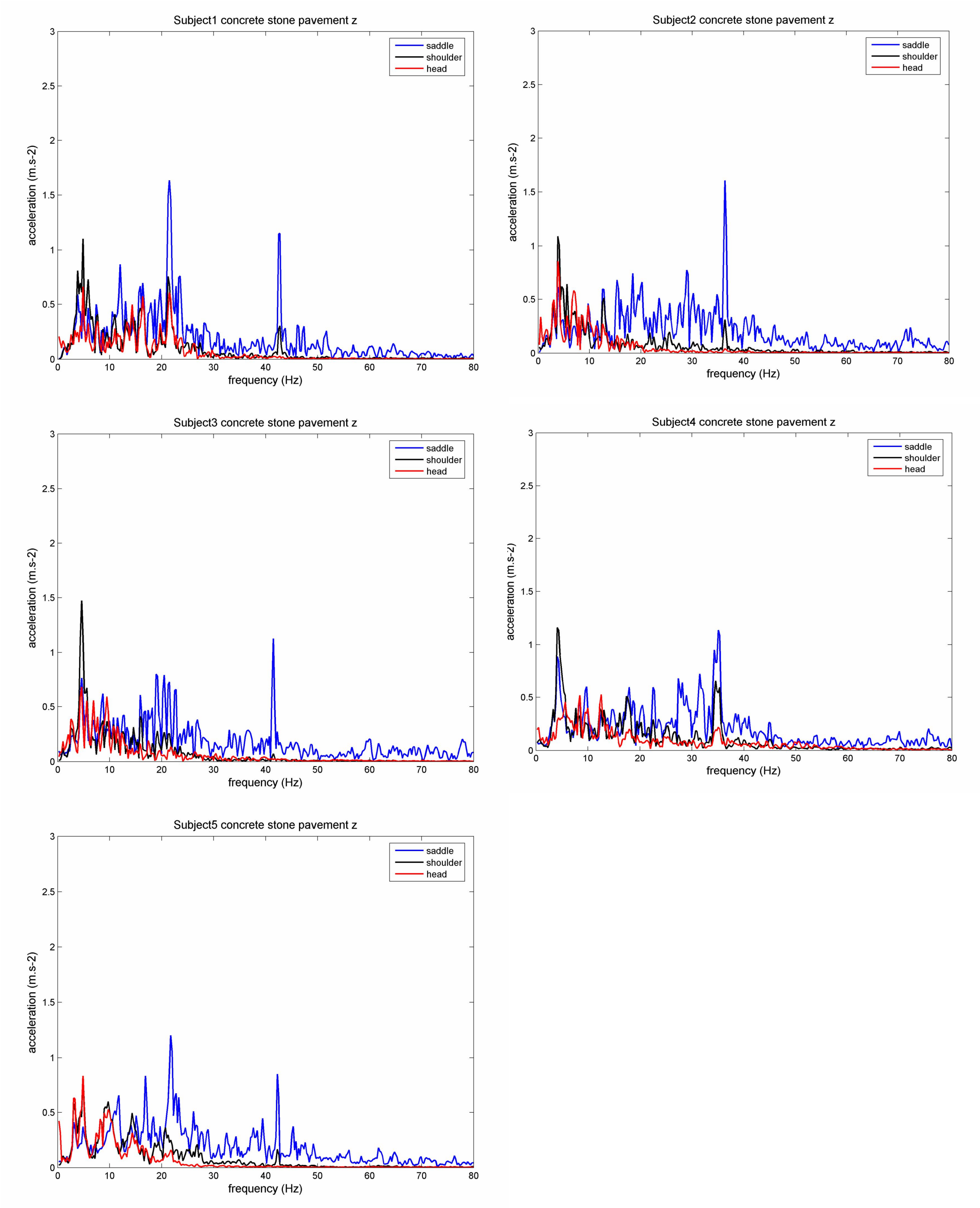

Figure C.23 Vibration transmitted, in z direction, to subjects on MTB while riding on concrete stone pavement, through saddle-shoulder-forehead

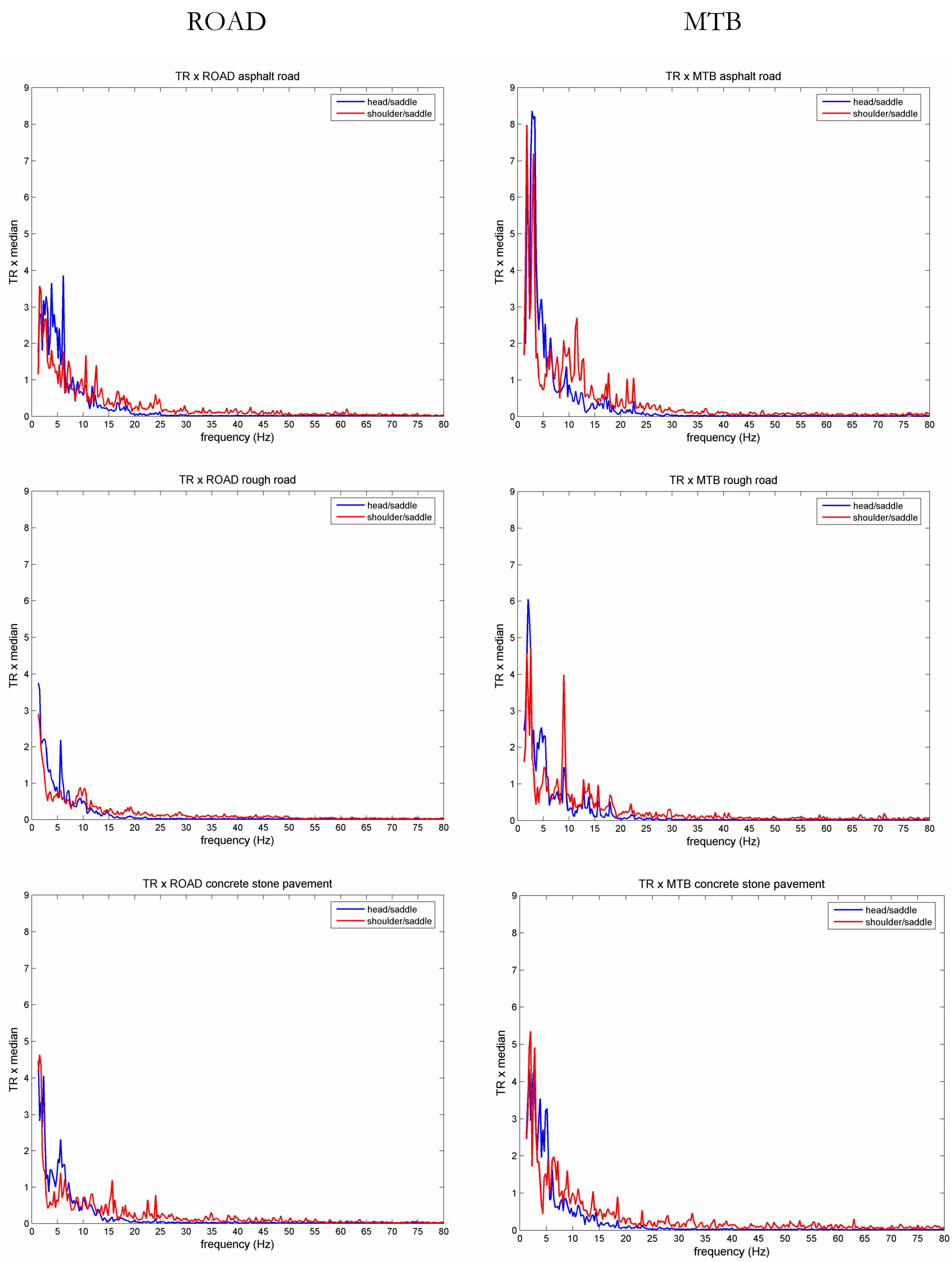

Figure C.24 TR_x-f curves for Road bike and MTB on different surfaces (Transmission path: saddle-shoulder-head)

ROAD MTB

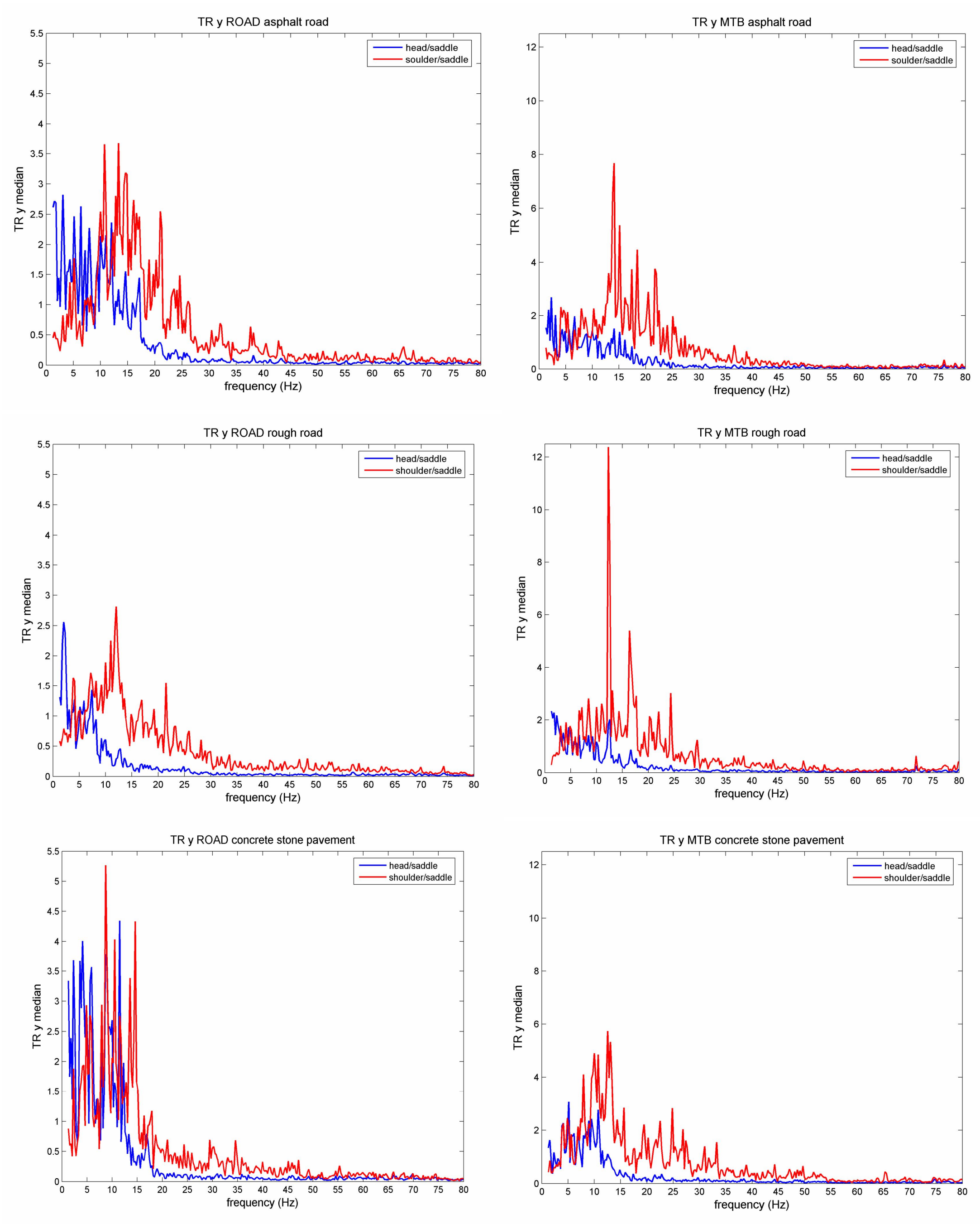

Figure C.25 TR_y-f curves for Road bike and MTB on different surfaces (Transmission path: saddle-shoulder-head)

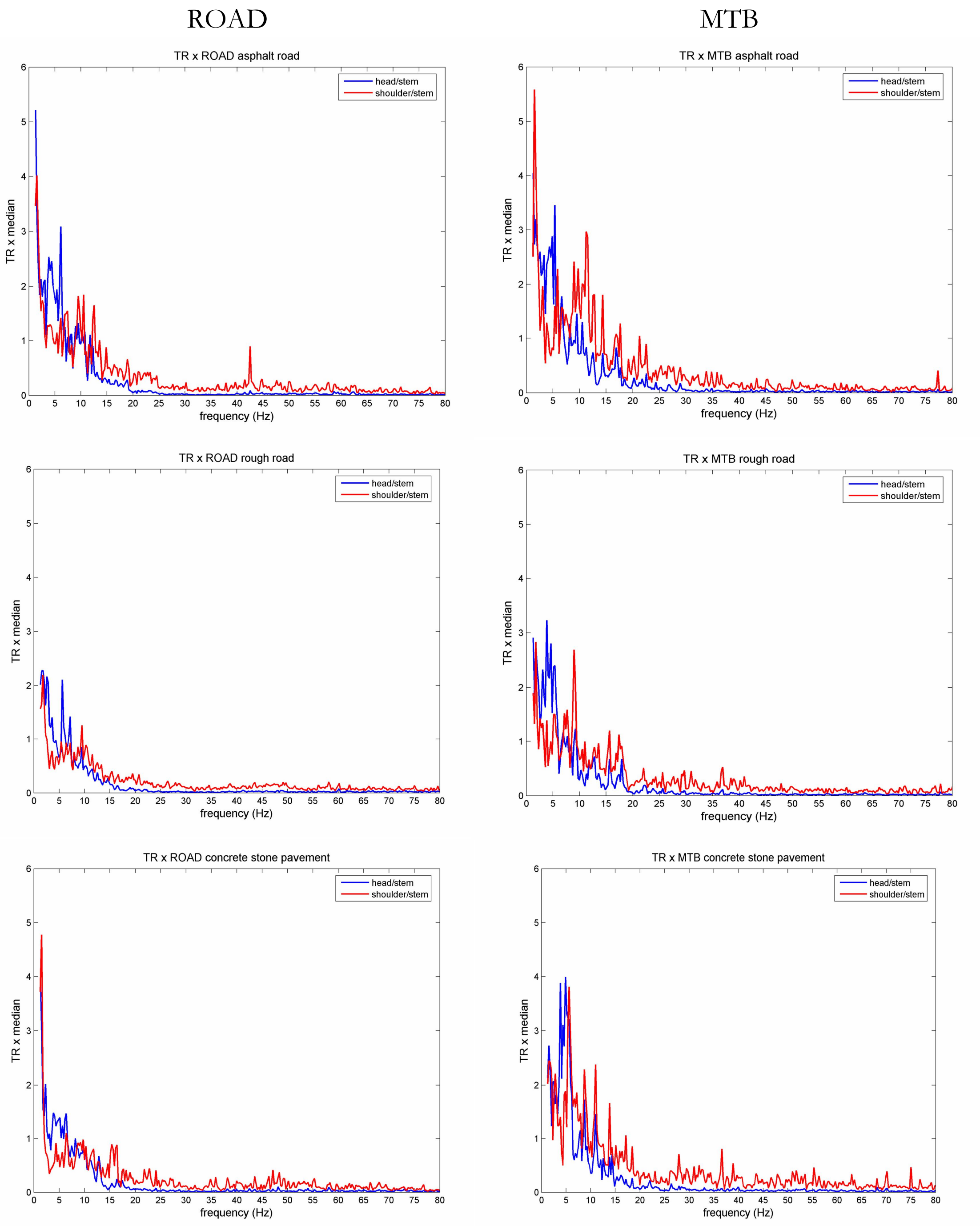

Figure C.26 TR_x-f curves for Road bike and MTB on different surfaces (Transmission path: stem-shoulder-head)

ROAD MTB

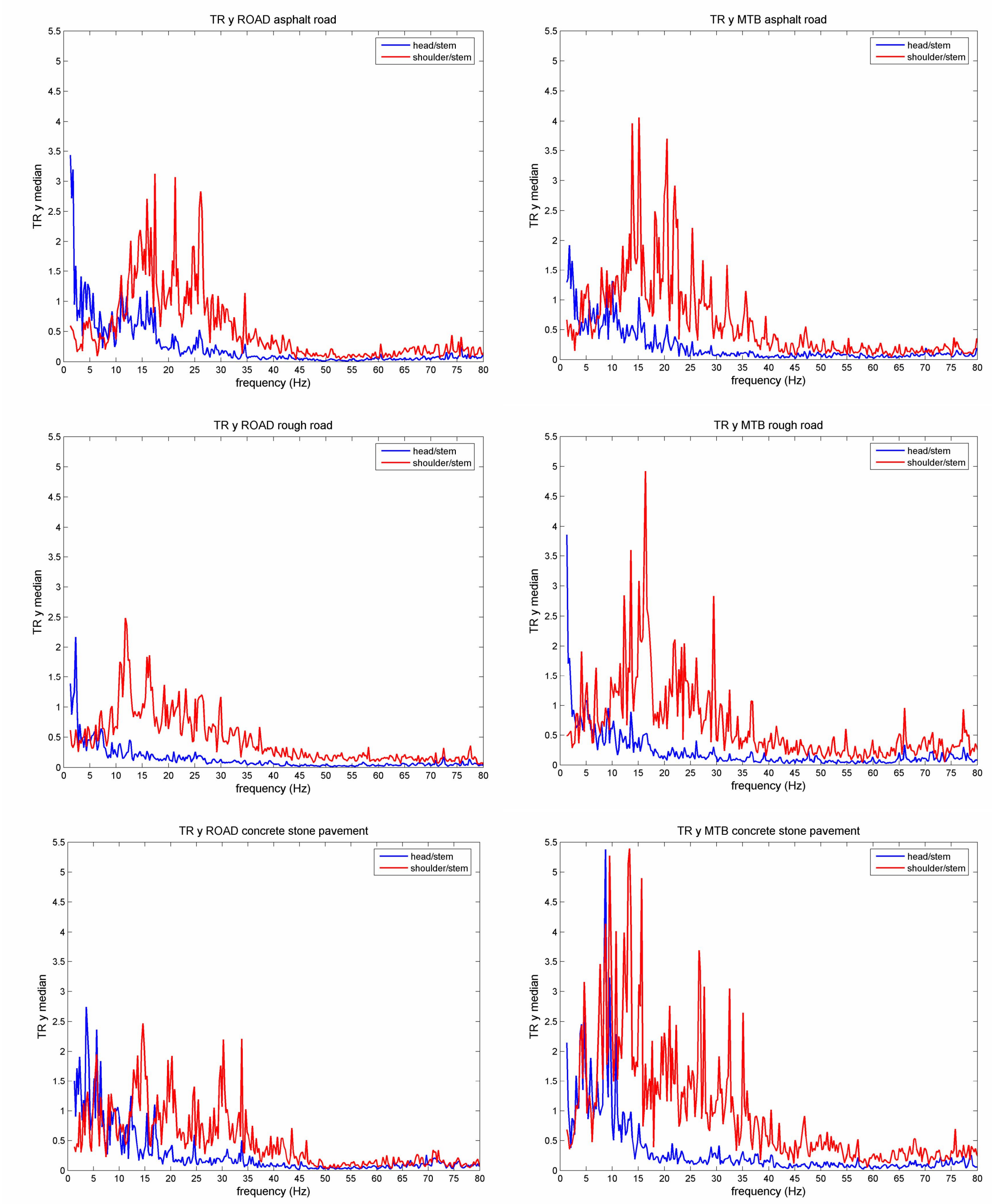

Figure C.27 TR_y-f curves for Road bike and MTB on different surfaces (Transmission path: stem-shoulder-head)

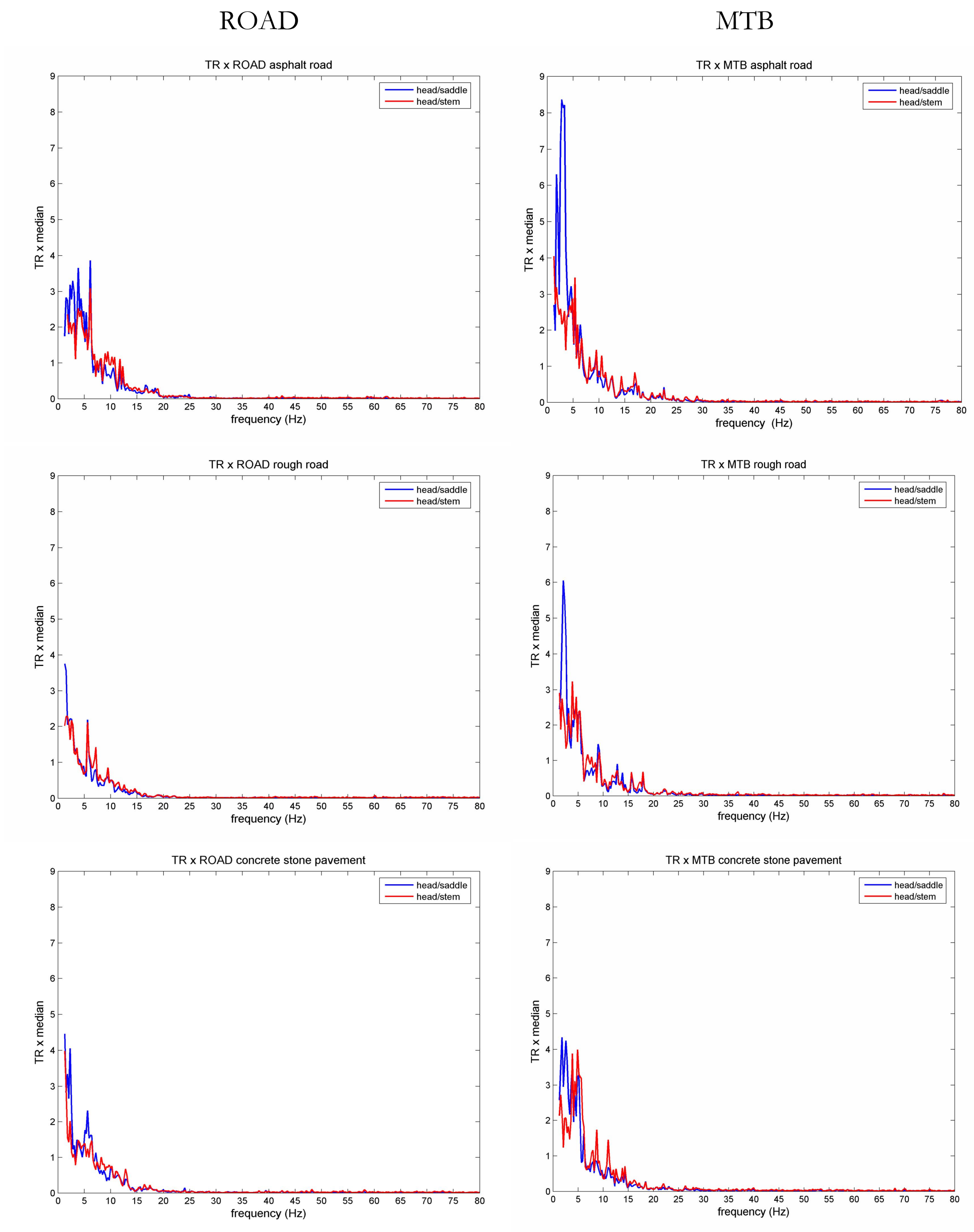

Figure C.28 Comparison of x axis transmission paths for head on road bike and MTB

ROAD MTB

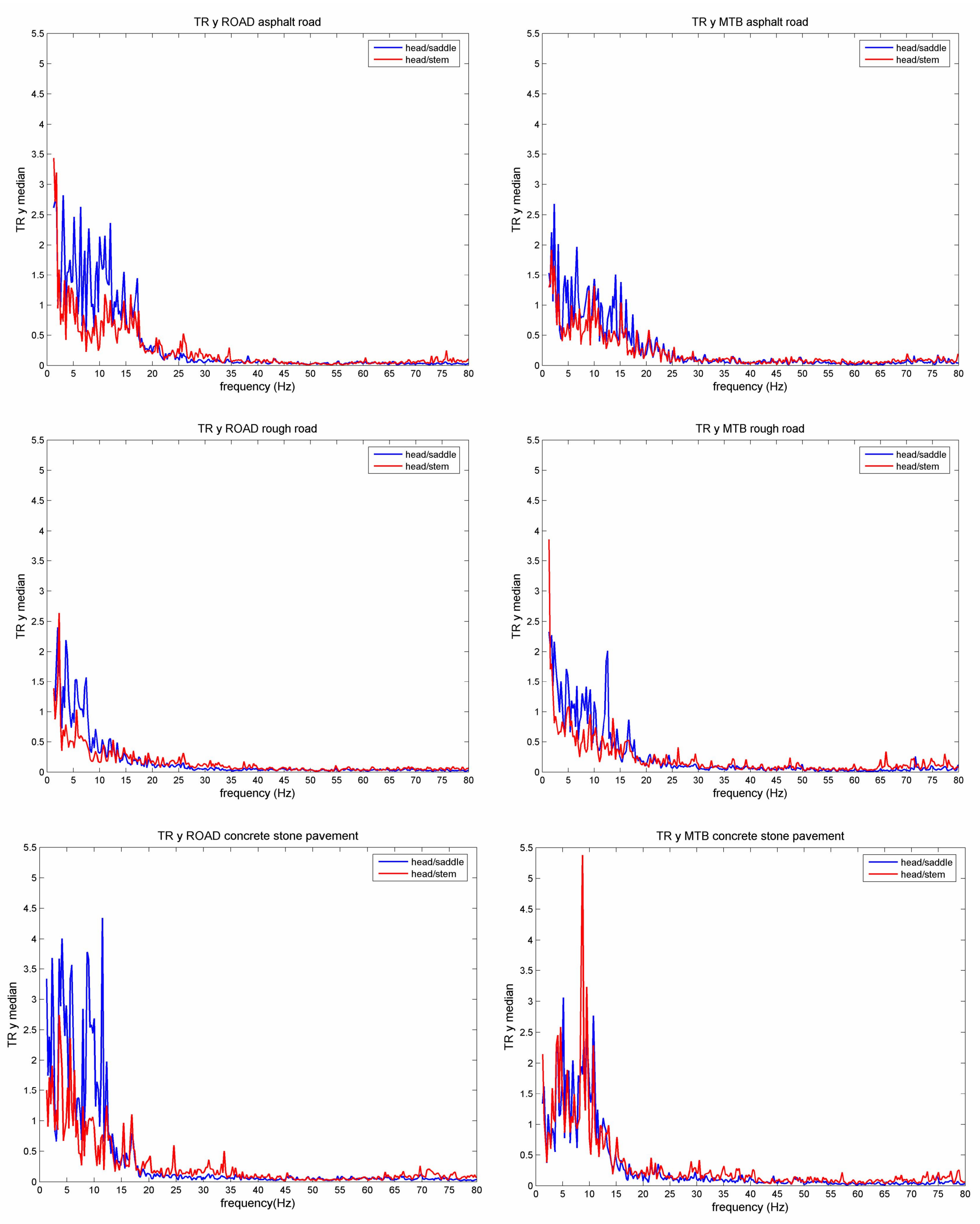

Figure C.29 Comparison of y axis transmission paths for head on road bike and MTB

ROAD MTB

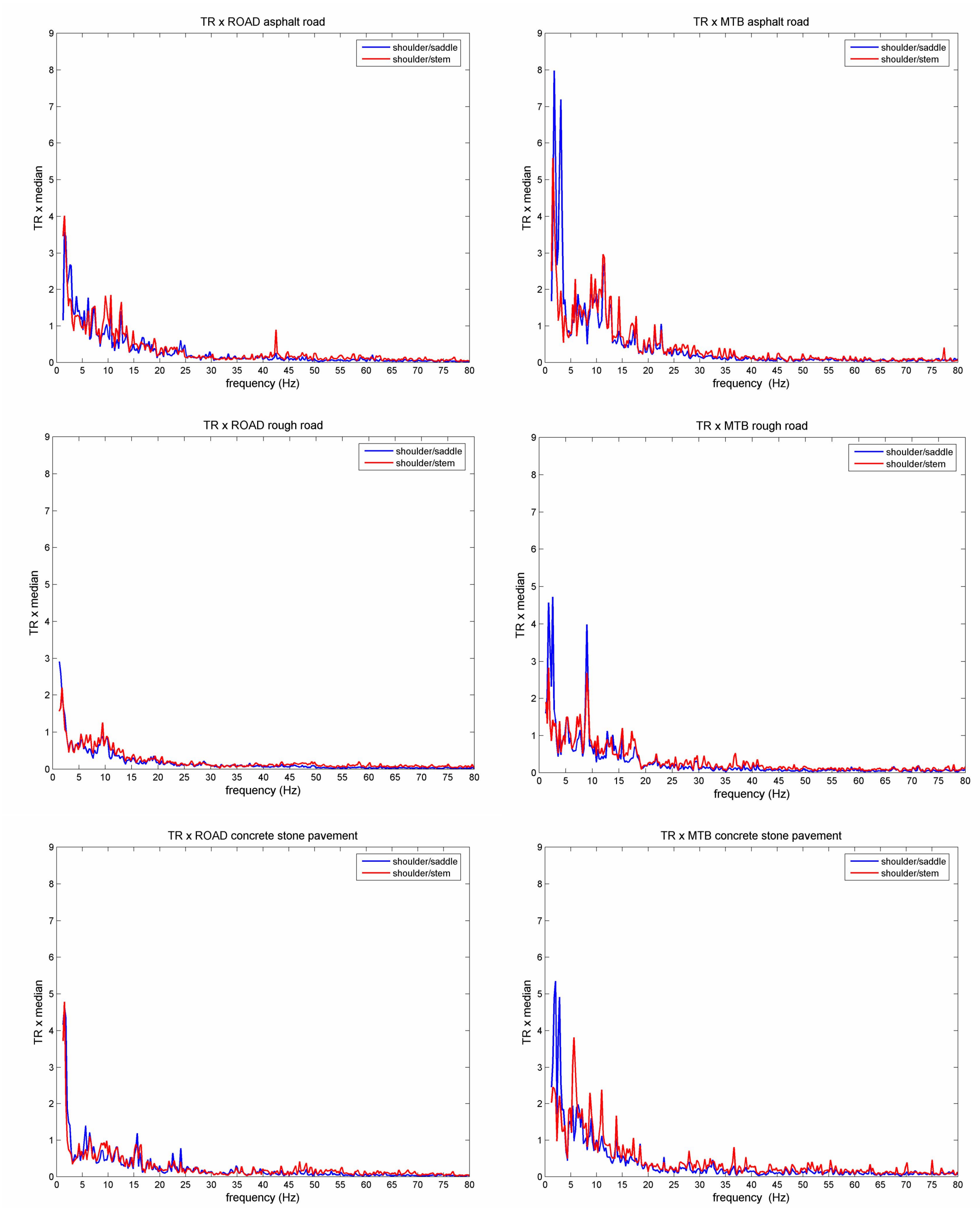

Figure C.30 Comparison of x axis transmission paths for shoulder on road bike and MTB

ROAD MTB

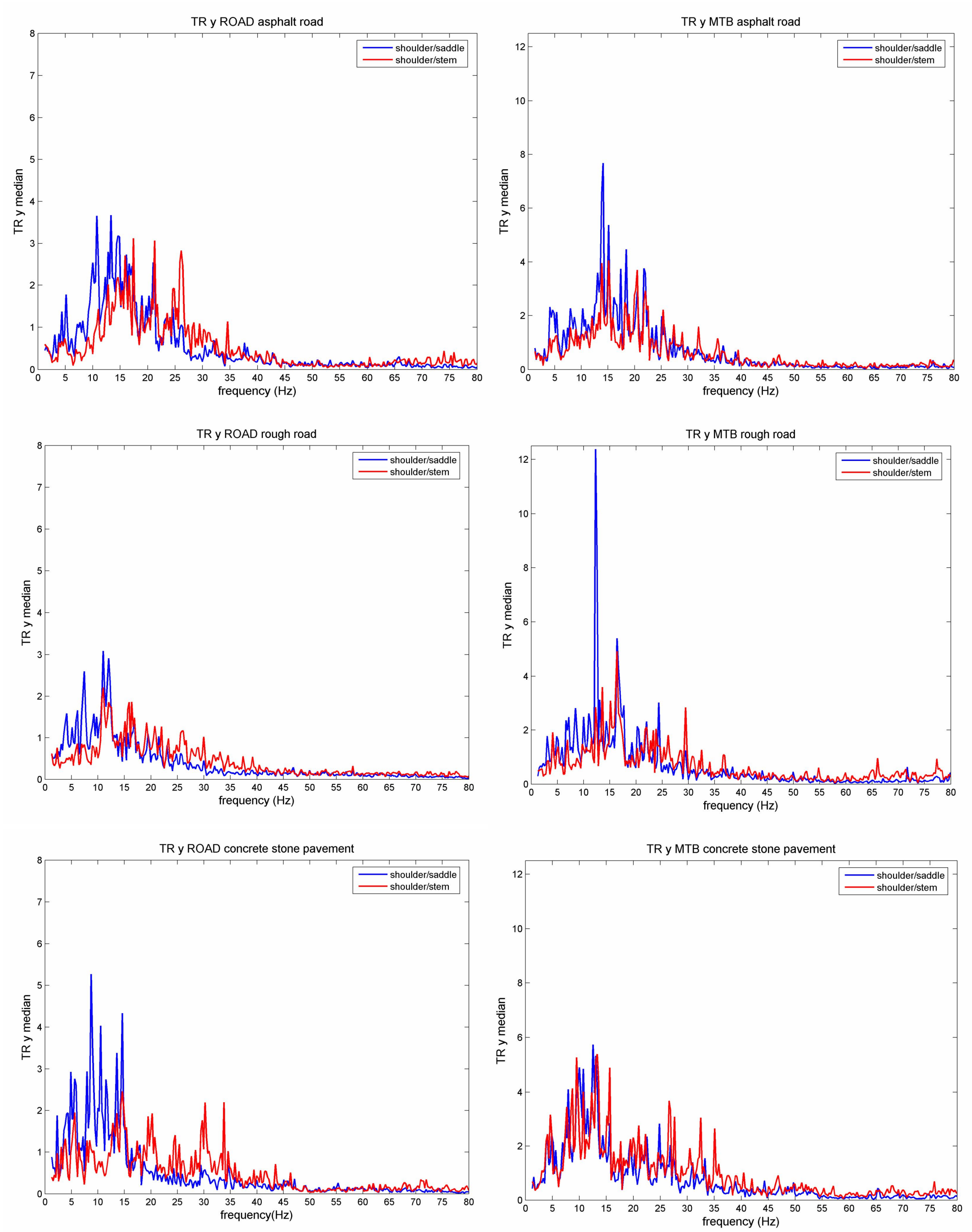

Figure C.31 Comparison of y axis transmission paths for shoulder on road bike and MTB

APPENDIX D. TÜRKÇE ÖZET

BİSİKLET VE SÜRÜCÜ ÜZERİNE TİTREŞİM İLETİMİ: ALAN VE LABORATUVAR ÇALIŞMASI

1.GİRİŞ

Araştırmanın amacı, bisiklet ve sürücünün maruz kaldığı titreşimin frekans ve büyüklüğü ile vücuda iletilen titreşimin iletim özelliklerinin araştırılmasıdır. Alan ve laboratuvar çalışması kapsamında yanıtı aranan araştırma soruları şunlardır: i) bisiklet ve sürücüye iletilen titreşimin büyüklük ve frekans aralığı nedir? ii) bu değerler farklı yol yüzeyleri ve bisiklet tiplerinden etkilenmekte midir? iii) farklı vücut pozisyonları için titreşim iletimi değerleri titreşim özelliklerinden etkilenmekte midir? iv) bisiklet ile sürüş esnasında el ve kola titreşim iletimi önkolda kassal aktiviteyi etkilemekte midir? v) yol eğimi ve titreşim frekansı submaksimal kuvvet üretimi esnasında el ve kola iletilen titreşimin büyüklüğünü etkilemekte midir? vi) submaksimal kuvvet üretimi esnasında titreşim frekansı önkolda kassal aktivite düzeyini etkilemekte midir?

2. MATERYAL VE METOD

2.1. TİTREŞİM İLETİMİ ÖLÇÜMLERİ

Bisiklet sürücü sistemi üzerinde farklı noktalarda ve laboratuvarda platform yüzeyinde titreşim ölçümleri üç eksenli ivme ölçerler kulanılarak gerçekleştirilmiştir. Laboratuvarda elektromekanik sarsıcı tarafından platform yüzeyine dikey dinamik uyaran uygulanmış ve bu platform üzerinde antrenman ünitesi ile sabitlenen bisiklet ve üzerinde oturur pozisyonundaki bisikletçiden oluşan sistemin belirli noktalarına yerleştirilen ivme ölçerler aracılığıyla titreşim verileri eş zamanlı olarak kaydedilmiştir. Alan ölçümleri esnasında veri toplama ünitesi batarya ile çalıştırılmıştır. Kullanılan ekipmanın güç kaynağına bağlı olarak kullanım süresinin sınırlı olması ve ard arda fazla sayıda denemenin doğuracağı olası yorgunluk etkisini elimine etmek amacıyla, ölçüm süresi alan ölçümleri için 4 sn ve laboratvur ölçümleri için 16 sn ile sınırlandırılmıştır. Titreşim verilerinin analizinde Pulse (B&K,Denmark) ve MATLAB yazılımları kullanılmıştır.

2.2. KUVVET ÜRETİMİ ÖLÇÜMLERİ

Laboratuvar ölçümlerinde kullanılan test bisikletinin bisiklet gidonu ile fren kolları arasına entegre edilen kuvvet ölçerler ile iki taraflı olarak kuvvet üretiminin ölçülmesi sağlanmıştır. Ölçümler öncesinde deneklerden 2 dk ara ile 3 kez çift taraflı maksimal izometrik kuvvet uygulamaları istenmiştir. Maksimal değerler indeks değer olarak alınmış ve her denek için %10 ve %20'lik submaksimal kuvvet düzeylerinin belirlenmesinde kullanılmıştır. Deneklerin istenilen kuvvet düzeyine ulaşmaları ve bu kuvveti sürdürmeleri amacıyla LCD monitor ile görsel geri bildirim sağlanmıştır.

2.3. KAS AKTİVİTESİ ÖLÇÜMLERİ

Yüzeyel ön kol fleksör (m.flexor carpi radialis) ve ekstensör kasları (m.extensor digitorum) kassal aktivitesi yüzeyel elektromyografi yöntemiyle, tekniğine uygun olarak hazırlanan deri yüzeyinden, Ag/AgCl elektrotlar kullanılarak iki taraflı olarak kaydedilmiştir. Analog EMG sinyalleri dijital forma çevrilmesi ardından 1000 Hz'de örneklenerek MATLAB yazımıyla 8-500 Hz aralığında filtrelenmiş ve sonraki hesaplamalar için kaydedilmiştir. En iyi maksimal istemli kasılma ölçümüne göre normalize edilen EMG verilerinin belirlenen zaman aralıkları için rms (root mean square) EMG değerleri hesaplanmıştır. Laboratuvarda EMG verileri sarsıcının input sinyali ve kuvvet ölçerlerden gelen sinyaller ile senkronize edilmiştir.

3. ARAŞTIRMA DİZAYNI

Yöneltilen araştırma sorularını yanıtlayabilmek amacıyla, tanımlanan farklı protokoller ile titreşim, kuvvet üretimi ve kassal aktivite ölçümleri gerçekleştirilmiştir. Çalışmada kullanılan protokoller Orta Doğu Teknik Üniversitesi Etik Komitesi tarafından onaylanmıştır.

3.1. ÖN ÇALIŞMA

Ölçümler öncesinde, alan ve labaratuvar koşullarında ayrı ayrı yapılan ön çalışma ile bisiklet-sürücü sistemine iletilen titreşim düzeyi hakkında bilgi toplanması ve araştırma sorularının yanıtlanmasında etkili parametrelerin belirlenmesi amaçlanmıştır. Bu nedenle farklı bisiklet tipleri ve farklı yol yüzeyleri ön çalışma kapsamına alınmıştır. Üç eksenli ivme ölçerler, bisiklet selesi ile bisikletçinin sırt bölgesine (L1-L3 seviyesinde) yerleştirilmiş ve titreşim iletimi incelenmiştir. Laboratuvarda ölçümlere alınan aynı bisikletçi üzerinde farklı tutuş pozisyonlarına bağlı olarak değişen postürler için iletim değerlerindeki olası değişimler araştırılmıştır. Platforma uygulanan 5 Hz frekanslı titreşim uyaranı altında alt gidon, fren kolu seviyesi ve üst gidondan tutuş için ölçümler tekrar edilmiştir. Alan ölçümü kapsamında ise aynı denek için üç farklı yol yüzeyinde titreşim iletimi değerleri kaydedilmiştir. Ölçümler yol ve dağ bisikleti için tekrar edilmiştir. Ölçümler esnasında hız 20 km/s olarak sabitlenmiştir. Deneğin bu hıza ulaşması ardından ölçüm boyunca pedal çevirmesine izin verilmemiştir.

3.1. ALAN ÖLÇÜMLERİ

Bisiklet ve sürücüye iletilen titreşim büyüklük ve frekans aralığının belirlenmesi ve farklı yol yüzeyleri ve bisiklet tipleri arasındaki olası farklılıkları belirlemek amacıyla alan ölçümleri gerçekleştirilmiştir.

3.1.1.TİTREŞİM İLETİMİ ÖLÇÜMLERİ: BİSİKLET TİPLERİ VE YOL YÜZEYLERİ

Düz asfalt yol, bozuk toprak yol ve beton parke yol yüzeyleri üzerinde gerçekleştirilen ölçümler yol bisikleti ve ön süspansiyonlu dağ bisikletleri için tekrar edilmiştir. Alan ölçümlerine en az 2 yıl bisiklet antrenmanı deneyimine sahip, yaşları 19-33 yıl aralığında 10 sağlıklı erkek bisikletçi (dağ ve yol bisikleti için 5'er kişi) katılmıştır. İvme ölçerler bisiklet-sürücü koordinat sistemi referans alınarak bisiklet üzerinde sele bisikletçi ara yüzü ve gidon orta noktasına, bisikletçinin vücudu üzerinde ise omuzda scapula üzerinde acromion alt yüzeyine ve alın orta noktasına yerleştirilmiştir. Veri toplama ünitesi bisikletçi ile aynı hızda ilerleyen araç içerisine konumlandırılmış ve 3 uzunluğundaki kablolar ile ölçüm bilgisayarlarına veri aktarımı sağlanmıştır. Ölçüm esnasında sürüş hızı 20 km/s olarak sabitlenmiştir. Deneklerden ölçüm esnasında pedal çevirmemeleri, her iki ayaklarını yere paralel olarak sabit konumda tutmaları istenmiş ve görsel kontrolü sağlanmıştır. Deneklerden yol bisikleti üzerinde ellerini alt gidon üzerinde ve dağ bisikletinde ise işaret parmakları fren ile temas edecek şekilde konumlandırmaları istenmiştir.

3.1.2.TİTREŞİM İLETİMİ ve KAS AKTİVİTESİ ÖLÇÜMLERİ

El-kol sistemine iletilen titreşim düzeyinin ön kol kassal aktivitesi üzerine etkisini belirlemek amacıyla çift taraflı olarak ön kol fleksör ve ekstensör kasları kassal aktivitesi titreşim ölçümleri ile eş zamanlı olarak kaydedilmiştir. Ağırlığı 400 gr olan EMG ölçüm ünitesi sırt çantası şeklinde bisikletçi tarafından takılarak taşınmış ve hareketlerini etkilemeyecek yada herhangi bir rahatsızlığı sebep olmayacak şekilde sabitlenmiştir. Verilerin iletiminde titreşim ölçümleri ile benzer şekilde 3 m uzunluğunda kablo kullanılarak araç içerisindeki veri toplama bilgisayarına veri aktarımı sağlanmıştır.

3.2. LABORATUVAR ÖLÇÜMLERİ

Kontrollü koşullar altında, titreşim frekansı ve büyüklüğü ile farklı tutuş pozisyonlarının bisiklet-sürücü sistemine iletilen titreşim üzerine etkisi araştırmak ve maruz kalınan titreşimin ön kol kassal aktivitesi üzerine etkilerini araştırmak amacıyla laboratuvar ölçümleri gerçekleştirilmiştir. Laboratuvar ölçümlerine üç ayrı protokole katılmak üzere toplam 14 denek katılmıştır.

3.2.1. TİTREŞİM İLETİMİ: TİTREŞİM BÜYÜKLÜĞÜ, KUVVET ÜRETİM DÜZEYİ VE TUTUŞ POZİSYONU ETKİLERİ

Farklı tutuş pozisyonları neticesinde değişen gövde ve üst ekstremite eklem açılarının titreşim iletimi üzerine etkisinin araştırılması amaçlanmıştır. Titreşim uyaranının simule edildiği platform üzerine yerleştirilen yol bisikleti üzerinde oturan denekler üç farklı tutuş pozisyonu için (alt tutuş, fren kollarından tutuş ve üst tutuş), rastgele sıra ile 1,1.5 ve 2 ms^{-2} rms büyüklüğünde 5 v 7.5 Hz olarak belirlenen iki farklı frekansta sinüsoidal titreşim uyaranına maruz bırakılmıştır. Üç eksenli ivme ölçerlerin yerleştirildiği ölçüm noktaları bisiklet üzerinde gidon ve sele yüzeyi, vücut üzerinde omuz ve dirsek ile sarsıcının bağlı olduğu platform yüzeyi olarak belirlenmiştir.

3.2.2. TİTREŞİM İLETİMİ: TİTREŞİM FREKANSI, KUVVET ÜRETİM DÜZEYİ VE YÜZEY EĞİMİ ETKİLERİ

Titreşim frekansı ve bisikletin üzerinde bulunduğu platformun yüzey eğiminin el-kol sistemine ieltilen titreşim düzeyi üzerine olası etkileri laboratuvar koşullarında, ön kol kasları tarafından üretilen farklı submaksimal kuvvet düzeyleri için araştırılmıştır. Platform üzerine 5^o eğim ile yerleştirilen bisiklet üzerindeki denekler 5 ve 7.5 Hz frekansta sinüsoidal titreşim uyaranına maruz bırakılmışlardır. Ölçümler, ön kol kasları tarafından sürdürülen %0, %10 ve %20 şiddette submaksimal kuvvet düzeyleri çin tekrar edilmiştir.

3.2.3. ÖN KOL KASSAL AKTİVİTESİ

Titreşim frekansının ön kolda kassal aktivite üzerine etkileri ön kol tarafından uygulanan farklı submaksimal kuvvet düzeyindeki kasılmalar için sorgulanmıştır. Kassal aktivite ölçümleri fleksör ve ekstensör kaslar üzerinden yapılırken, submaksimal kuvvet üretim düzeyi %10 ve %20 olarak belirlenmiştir. Titreşim uyaranı büyüklüğü $2ms^{-2}$ rms ve titreşim frekansı 5 ve 7.5 Hz olarak seçilmiştir. Titreşim ve kasılma uyaranının olmadığı ölçümler de kontrollü koşulların sağlanması için çalışmaya dahil edilmiştir. Kuvvet, titreşim ve kassal aktivite verileri eş zamanlı olarak kaydedilmiştir.

4. **BULGULAR**

4.1. ÖN ÇALIŞMA BULGULARI

Ön çalışma kapsamında gerçekleştirilen labatuvar ölçümlerinde seleye iletilen titreşimin x ekseninde iki kata kadar artış gösterdiği gözlenmiştir. Ayrıca z ekseninde bisikletçinin vücuduna iletilen titreşim büyüklüğü her üç tutuş pozisyonu içinde oldukça yüksek değerlere ulaştığı belirlemiştir. Ön çalışma alan ölçümleri esnasında da bisikletçinin özellikle bozuk toprak yol üzerinde oldukça yüksek düzeyde titreşime maruz kaldığını ve bunun da hem x hem z yönünde bisikletçinin vücuduna iletilen titreşim düzeyinde artışa neden olduğunu göstermiştir. İletim oranları hem yol hem dağ bisikleti için 5-10 Hz aralığındaki frekanslarda maksimal değerlere ulaşmıştır. İletim bozukluğu yol bozukluğundaki artışa bağlı olarak artmıştır.

4.2. ALAN ÖLÇÜMLERİ BULGULARI

4.2.1 BİSİKLET-SÜRÜCÜ SİSTEMİ VE TİTREŞİM İLETİMİ: YOL YÜZEY YAPISI VE BİSİKLET TİPİ ETKİSİ

Alan ölçümleri sonucunda elde edilen bulgular bisiklet-sürücü sisteminde belirlenen ölçüm noktalarında (sele, gidon, omuz ve alın) maruz kalınan titreşimin x (hareket yönünde) ve z (hareket yönüne dik) eksenlerinde etkili olduğunu göstermektedir. İletim değerleri yol bozukluğu arttıkça artış göstermiş, düz asfalt yolda en düşük ve bozuk toprak yolda en yüksek değerlerine ulaşmıştır.

Waechter ve ark (2002) ile benzer şekilde hem yol hem dağ bisikleti (MTB) ile gerçekleştirilen ölçümlerde sele ile karşılaştırıldığında gidonda ölçülen titreşim düzeyleri bir miktar daha yüksek bulunmuştur. Omuza iletilen titreşim düzeyleri düşükten yükseğe asfalt yol, beton parke yol ve bozuk toprak yol sırlamasını izlemiştir. Bozuk toprak yolda omuza iletilen titreşim alında ölçülen değerlerden de yüksek bulunmuştur. Şaşırtıcı şekilde, farklı vücut noktalarına iletilen titreşim, yol bozukluğuna bağlı olarak artma eğilimi gösterirken, iletim oranı iki bisiklet tipi arasındaki farklılıktan etkilenmemiştir. Asfalt yol ölçümlerinde dominant eksenlerde (x ve z) ölçülen maksimal titreşim iletimi değerlerinin dağ bisikleti için ~5-40 Hz ve yol bisikleti için ~20-70 Hz gibi daha geniş bir frekans aralığında olduğu gözlenirken, yol bozukluğunun artmasıyla her iki bisiklet için de 15-30 Hz aralığına gerilediği belirlenmiştir. Benzer şekilde, önceki araştırmalarda da etkin frekans aralığının 0-50 Hz aralığında olduğu bildirilmiş (Waechter ve ark,2002; Faiss ve ark,2007; De Lorenzo and Hull,1999) ve maksimal değere ulaşılması ardından frekans spectrumunda titreşimin sönümlendiği gözlenmiştir (Lewis and Paddan,1990; Waechter ve ark,2002; Faiss ve ark,2007).

Omuz ve alına iletilen titreşim, iletilen titreşimin büyüklüğüne bağlı olmaksızın 3-12 Hz aralığında maksimal değerlere ulaşmıştır. Yol bisikletinde ise bu değerlerin 3.5-7 Hz gibi daha düşük frekanslarda olduğu gözlenmiştir.

4.2.2. GİDON HAREKETLERİNİN KONTROLÜNDE ÖN KOLDA KASSAL AKTİVİTE: YOL YÜZEY YAPISI VE BİSİKLET TİPİ ETKİSİ

Ön kol ekstensör kasları rms EMG değerleri dağ biskleti denemelerinde titreşim iletimi ile benzer şekilde yol bozukluğunun artmasıyla artış eğilimi göstermiştir. Bozuk toprak yol ölçümlerinde kassal aktivite, maksimal istemli kasılma esnasında ulaşılan değerlerin %50'sine kadar artış göstermiştir. Yol bisikleti ölçümlerinde fleksör kaslara ait rms değerleri bozuk toprak yol denemelerinde en yüksek değerine ulaşmıştır. Bisiklet üzerinde maruz kalınan titreşim düzeyinin artmasıyla gidon hareketlerini kontrol etmek üzere ön kol kasları kassal aktivitesi de artış göstermiştir.

4.3. LABORATUVAR ÖLÇÜMLERİ BULGULARI

4.3.1. BİSİKLET-SÜRÜCÜ SİSTEMİ TİTREŞİM İLETİMİ: TİTREŞİM BÜYÜKLÜĞÜ VE İLETİM NOKTASI ETKİLERİ

Normalize edilmiş titreşim iletimi değerleri 7.5 Hz titreşim uyaranı ile karşılaştırıldığında 5 Hz frekans altında üç farklı titreşim büyüklüğü için sele ve gidonda en yüksek değerine ulaşmıştır. Seleye iletilen titreşimin platforma iletilen titreşim ile aynı büyüklükte olduğu gözlenirken gidona titreşim iletimi oranı %80 olarak bulunmuştur. 5 Hz ile karşılaştırıldığında 7.5 Hz frekanslı sinüsoidal titreşim uyaranı için sele ve gidona iletim değerleri sırasıyla ~%20 ve %40 daha düşük bulunmuştur. Omuz ve dirseğe iletilen titreşim düzeyleri de 5 Hz frakenslı uyaran altında daha yüksek değerlere ulaşmıştır. Her iki frekans için de omuza titreşim iletimi titreşim kaynağına göre %20-25 aralığında bulunurken, dirseğe iletilen titreşim özellikle 5 Hz titreşim frekansı için 3 kata kadar artış göstermiştir. Gidona iletilen titreşim değerine göre normalize edildiğinde bu oran 4 kat civarında bulunmuştur. Buna karşın, omuza iletilen titreşimin iletim noktasından etkilenmediği gözlenmiştir.

4.3.2. BİSİKLET-SÜRÜCÜ SİSTEMİ TİTREŞİM İLETİMİ: TUTUŞ POZİSYONU, TİTREŞİM FREKANSI, KASILMA ŞİDDETİ VE YÜZEY EĞİMİ ETKİSİ

Bisiklet üzerinde tutuş pozisyonuna bağlı olarak değişen vücut pozisyonunun sele ve gidona aktarılan vücut ağırlığı dağılımında farklılığa neden olacağı bilinmektedir. Daha dik oturma pozisyonları için seleye iletilen titreşim artarken, gidona iletilen titreşim azalma eğilimi göstermiştir. Gidonda ölçülen titreşim değerinin titreşim büyüklüğü arttığında frekansa bağımlı olmadığı gözlenmiştir. Yüzey eğimine bağlı olarak vücut pozisyonu değiştiğinde gidona aktarılan vüut ağırlığının artması, özellikle 5 Hz frekansta dirseğe iletilen titreşim düzeyinde artışı beraberinde getirmiştir. Omuza iletilen titreşim ise her iki frekans için 5^o eğimin olduğu ölçümlerde daha düşük bulunmuştur.

Eğimin olmadığı durumda, %20 kuvvet üretim düzeyinde omuza ve dirseğe iletilen titreşim %10 kuvvet düzeyine göre daha yüksek bulunmuştur. Artan ivme büyüklükleri ile paralel şekilde, rms EMG değerleri de aynı kuvvet çıktısını sürdürebilmek üzere 5 Hz lik titreşim frekansı altında fleksör ve ekstensör kas aktivitesinin artığına işaret etmektedir. Titreşimin olmadığı ölçümler ile karşılaştırıldığında, 5 ve 7.5 Hz lik titreşim uyaranı artan kas aktivitesi ile sonuçlanmıştır.

4.3.3. TİTREŞİM İLETİMİ VE ÖN KOL KASSAL AKTVİTESİ: KASILMA ŞİDDETİ VE TİTREŞİM FREKANSI ETKİSİ

Titreşim uyaranının olmadığı ölçümler ile karşılaştırıldığında, titreşime uyaranı altında fleksör ve ekstensör kaslar için ölçülen rms EMG değerleri her iki titreşim frekansı için de uygulanan submaksimal kuvvet düzeyi ile orantılı olarak artış göstermiştir. Özelikle 5 Hz frekansta %20 lik submaksimal kuvvet düzeyi için kassal aktivitedeki artış sağ kol fleksör ve ekstensör kasları için belirgindir.

5. SONUÇ

Araştırmanın bulguları, bisiklet ve sürücüye titreşim iletiminin x ve z eksenlerinde etkin olduğunu göstermiştir. Yol bozukluğunun artmasıyla, sele ve gidon üzerinde ölçülen titreşimin etkin olduğu frekans aralığı yol ve dağ bisikleti için 15-30 Hz gibi daha düşük frekaslara gerilemiştir. Bisiklet üzerine iletilen titreşim düzeyi yol bisikletinde çok daha yüksek değerlere ulaşmıştır (bozuk yolda 25 m.s-2 rms'e kadar). Farklı vücut

noktaları üzerinde ölçülen iletim değerlerinin 0-30 Hz arasında etkin olduğu ve iletilen titreşim düzeyine bağlı olmaksızın 3-12 Hz arasında maksimum değerlere ulaştığı gözlenmiştir. Yol bozukluğuna bağlı olarak ivme değerleri artarken, önkola ait rmsEMG değerleri MTB ölçümlerinde ekstensör kaslarda, yol bisikletinde ise fleksör kaslarda %50 düzeyinde bir artış göstermiştir. Titreşim uyaranının olmadığı ölçümler ile karşılaştırıldığında, titreşim uyaranı altında aynı kuvvet çıktısını sürdürebilmek için rms EMG değerleri artmıştır. Vücuda iletilen titreşim artan kuvvet üretimi ile birlikte artma eğilimindedir. İletim değerleri düşük frekaslarda yüksek değerlere ulaşmıştır. 5 Hz'lik titreşim uyaranı için dirsekte ölçülen ivme büyüklüğü 3 ila 4 kata kadar artmıştır. Omuzda ölçülen titreşim değerleri oturma pozisyonları dikleştikçe artma eğilimi göstermektedir. Titreşim büyüklük ve frekansının bozulan solunum paterni, artan kas tonusu gibi vücut fonksiyonları üzerine bilinen bazı olumsuz etkileri sebebiyle, bisiklet ile sürüş esnasında vücuda iletilen titreşimin sürüş konforunu, bisikletin kontrolünü ve bisikletçinin genel olarak sağlığını etkileyebileceği düşünülmelidir.

APPENDIX E. CURRICULUM VITAE

PERSONAL INFORMATION

Surname, Name: Arpinar-Avsar, Pınar
Nationality: Turkish
Date and Place of Birth: 6 February 1979 , İzmir-Turkey
E-mail: parpinar@gmail.com

EDUCATION

Degree	Institution	Year of Graduation
PhD	Middle East Tehnical University, Ankara Department of Physical Education & Sport	2009
MS	Ege University, İzmir School of Physical Education & Sport	2003
BS	Ege University, İzmir School of Physical Education & Sport	1999

WORK EXPERIENCE

Degree	Institution	Enrollment
2003-2009	Middle East Tehnical University, Ankara Department of Physical Education & Sport	Research Assistant
2000-2003	Ege University, İzmir School of Physical Education & Sport	Research Assistant

FOREIGN LANGUAGES

Advanced English