The Effects of Surface-Induced Loads on Forearm Muscle Activity during Steering a Bicycle

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Abstract

On the bicycle, the human upper extremity has two essential functions in steering the bicycle and in supporting the body. Through the handlebar, surface-induced loads are transmitted to the hand and arm of the bicycle rider under vibration exposure conditions. Thus, the purpose of the study was to investigate the effect of vibration exposure on forearm muscle activity for different road surfaces (i.e. smooth road, concrete stone pavement, rough road) and for different bicycles. Ten subjects participated in experiments and two types of bicycles, i.e. Road Bike (RB) and Mountain Bike (MTB) are compared. The acceleration magnitudes were dominant along x and z-axes. The r.m.s acceleration values in the z direction at the stem of MTB were at most 2.56, 7.04 and 10.76 m·s^{-2} when pedaling respectively on asphalt road, concrete pavement and rough road. In the case of RB the corresponding values were respectively 4.43, 11.75 and 27.31 m·s^{-2}. The cumulative normalized muscular activity levels during MTB trials on different surfaces had the same tendency as with acceleration amplitudes and have ranked in the same order from lowest to highest value. Although road bike measurements have resulted in a similar trend of increment, the values computed for rough road trials were higher than those in MTB trials. During rough road measurements on MTB, rmsEMG of extensor muscles reached a value corresponding to approximately 50% of MVC (Maximum Voluntary Contraction). During RB trials performed on rough road conditions, rmsEMG (%MVC) values for the forearm flexor muscles reached 45.8% of their maximal. The level of muscular activity of forearm muscles in controlling handlebar movements has been observed to be enhanced by the increase in the level of vibration exposed on the bicycle**.** Since repeated forceful gripping and pushing forces to a handle of a vibratory tool can create a risk of developing circulatory, neurological, or musculoskeletal disorder, a bicycle rider can be considered vulnerable to developing vibration related overuse injuries and/or performance diminishing consequences.

Key words: Vibration transmission, electromyography, cycling, road bike, mountain bike.

Introduction

Humans are exposed to vibration during daily activities, e.g. while travelling in vehicles and in contact with vibrating tools. It is well known that, when it is prolonged and repetitive, vibration exposure may cause undesired physiological changes as a function of magnitude (m·s^{-2}), frequency (Hz) and duration (time) of the vibration (Griffin, 1990). In the light of numerous researches and well documented adverse effects associated with vibration expo-

sure to the human body, international guidelines have been developed to set the health and safety requirements for humans exposed to either whole body vibration (WBV) (ISO 2631) or hand arm vibration (HAV) (ISO 5349-1).

The topic of vibration exposure in sports has also received attention in the fields of ergonomics, biomechanics, sports engineering, physical therapy etc. by focusing on exposure levels' possible effects related to the human body functioning (Games and Sefton, 2011; Rittweger, 2010). Vibration transmitted to the bicycle and the rider has also gained interest from several researchers after the first report published by Pivit (1988). Studies on vibration transmission to the bicycle and the rider can be categorized in two main groups. The first group of studies have focused on the physiological and psychological responses of the cyclist while being exposed to vibration (Berry et al., 2000; Faiss et al., 2007; Filingeri et al., 2012; Mac Rae et al, 2000; Rambarran and Roy, 2001; Seifert et al., 1997; Suhr, 2007; Titlestad et al., 2006) whereas the second group of studies have focused on the vibration transmitted to the bicycle and the rider (Chiementina et al., 2011; Faiss et al., 2007; Lewis and Paddan, 1990; Outcald, 2001; Pivit, 1988; Torbic et al., 2003; Waechter et al., 1998; 2002). Available information on vibration transmission characteristics related with the type of the bicycle, surface condition and riding speed have provided considerable insights into possible physiological effects of vibration exposure based on our knowledge of human body resonance characteristics. However, vibration induced physiological effects need to be investigated in a broad sense to get a complete picture of underlying physiological mechanisms associated with the loads acting on a bicycle-rider system.

A bicycle rider is in contact with a bicycle at multiple points, and vibration is transmitted to the body through the handlebar, saddle and pedals. When cyclists are riding on uneven surfaces that cause continuous intolerable vibration levels, it can be observed that they may either stop pedaling or they may stand up from the saddle (Burke, 1996). Because the human upper extremity has two essential functions in steering the bicycle and in supporting the body, it is not usual for them to remove their hands from the handlebar. So, it is likely that the controlling handlebar which serves as an interface between the rider and the steering system (i.e. front wheel, fork, headset, stem, handlebars, and handlebar grips) that transmits surface-induced loads to the hand and arm is fundamental

in proper steering under vibration exposure. Although, the damping properties vary for different types of bicycles (e.g. road bike versus mountain bike) with different mechanical properties (e.g. aluminum or carbon frame, with or without suspension system, with different tyre properties), it is well known that the bicycle-rider system is affected by vibration to some extent for any bicycle having any of the configurations (Pivit, 1988; Torbic et al., 2003; Waechter et al., 2002).

Since repeated forceful gripping and coupling forces at the interface of the hand-arm system and the vibrating tool can be at risk of developing circulatory, neurological, or musculoskeletal disorders (Griffin and Bovenzi, 2002; NIOSH, 1997) which have been collectively grouped as hand–arm vibration syndrome (HAVS) (Gemne and Taylor, 1983), a bicycle rider can be considered vulnerable to develop vibration related overuse injuries and/or performance diminishing consequences. Available literature that reported traumatic and non-traumatic overuse injuries pertaining to bicycle riding proves that contact-point interaction between bicycle and rider results in discomfort, pain, dysfunction, or pathology in relation to anatomical regions (De Bernardo et al., 2012; Dettori and Norvell, 2006; Kronisch and Pfeiffer, 2002). For instance, clinically reported cases show the existence of distal nerve compression caused by prolonged cycling, known as "cyclist's palsy" (Capitani and Beer, 2002; Eckman et al.,1975; Patterson et al., 2003). Chronic repeated trauma and pressure, which are the well-known extrinsic causes of ulnar neuropathy, at the cyclists' wrist or hand with resultant numbness and tingling into fingers are likely to be amplified with the vibration when exposed for long periods of time (Capitani and Beer, 2002). Although wearing cycling gloves, ensuring proper bicycle fit, and frequently changing hand position have been proposed to decrease the incidence of the symptoms, their effects on vibration transmitted to the body have not been well documented.

Besides mechanical compression on anatomical structures (arteries, veins, nerves), increased muscular contraction can also be thought to affect the vibration transmission to the bicycle rider by increasing tissue stiffness through two mechanisms. Firstly, the amount of vibration transmitted to the body depends on musculoskeletal stiffness and damping (Rittweger, 2010). When a muscle is activated, it generates muscle tension. Theoretically, muscular effort increases the number of motor units recruited and level of activation which results in increased tension and intramuscular pressure. Bovenzi (2006) has suggested that force applied by the hand may alter the transmission of vibration due to the fact that increased force will tend to stiffen the tissues which causes change in resonance frequencies and tends to increase the transmission of vibration from the area of contact with vibration. Rohmert et al. (1989) have pointed out that as the intensity level of contraction increases, vibration exposure can become more severe. Secondly, vibration itself results in increased muscle activation. It is well known that vibration, applied to a muscle belly or a tendon, elicits a muscle contraction, involving a spinal reflex mechanism known as tonic vibration reflex (TVR)

(Lance, 1966). If a muscle is initially moderately active, vibrating its tendons causes small length changes in muscle fibers, and its spindles activate neural pathways via primary afferent fibers causing agonist muscle contraction while reciprocally inhibits antagonist muscle (Hagbarth and Eklund, 1966). It has been reported that while maintaining a weak or moderate contraction, vibration causes an enhancement of EMG activity as well as contraction force (Bongiovanni et al., 1990). Mester et al. (1999) have also stated that muscle tension and stiffness which are increased in response to vibration is characterized by increased muscular activity. This physiological consequence is also supported by a number of electrophysiological studies which found greater rms (root mean square) EMG levels in muscles in response to vibration stimuli (Aström et al., 2009; Bosco et al., 1999; Krol, 2011; Radwin, 1987).

Considering the limited knowledge regarding muscular activity in the upper extremity in response to vibration exposed on a bicycle, this study aimed to investigate forearm muscle activity depending on the surface irregularities and the type of the bicycle.

From the reviewed literature, it was hypothesized that surface induced loads will result when vibration is transmitted to hand and arm of the bicycle rider and in parallel with the level of vibration exposure forearm muscle activity will be affected. Accordingly, the following research questions were tried to be answered: i) Does vibration transmitted to the hand-arm-system affect forearm muscle activity during steering a bicycle? ii) Do types of bicycles and surface irregularities affect forearm muscle activity due to the possible changes in amplitude of vibration? Therefore, forearm flexor and extensor muscle activity in response to vibration exposure and the vibration transmitted to the bicycle's stem were investigated.

Methods

Participants

Two groups of subjects participated in experiments designed to test the effect of different types of bicycles, i.e. Road Bike (RB) and Mountain bike (MTB). Each group consisted of 5 right-handed healthy volunteer male cyclists between the ages of 19 and 33 with at least 2-year regular training background. Subjects had no history of neurological or musculoskeletal pathology. Subjects were tested on their own bicycles during the measurements. Descriptive characteristics of the subjects and the main properties of the bicycles are presented in Table 1.

The material of the frames of the MTBs was aluminum-carbon, and except the bicycle of subject 1 and 5, the frames of the RBs were of aluminum. With the exception of subject 1's bicycle in MTB group, all handlebars and forks were made of aluminum. Wheel diameters for MTBs and RBs were 26 (66.4 cm) and 28 inch (71.12 cm), respectively. During the measurements, each subject wore their own cycling jersey, cycling shoes with clipped pedals, padded cycling tight, gloves and helmet. The weight of the helmets ranged from 230 to 300 gr. After being informed both verbally and in writing about the

**Table 1. Characteristics of the bikes and the riders participated in the field measurements.**

	MTB						RB					
Subject No	**1**	**2**	**3**	**4**	**5**	**Mean (SD)**	**6**	**7**	**8**	**9**	**10**	**Mean (SD)**
Age (years)	24	22	18	21	25	22.0 (2.7)	32	23	20	33	25	26.6 (5.7)
Body Height (m)	1.68	1.70	1.68	1.76	1.83	1.73 (.06)	1.81	1.79	1.80	1.73	1.82	1.79 (.04)
Body Weight (kg)	57	70	52	63	80	64.4 (11.0)	83	73	68	65	73	72.4 (6.8)
Bicycle Weight (kg)	11	11.5	11.5	12	12.5	11.7 (.57)	8.5	9.5	10.5	9	9	9.3 (.8)
Frame Size (inch)	42	43	42	42	42	42.2 (.5)	56	54	54	56	55	55.0 (1.0)
Tyre Pressure (psi)	45	45	45	45	45	45 (0)	90	90	90	90	90	90 (0)

method and the possible risks of the study, all participants signed an informed consent form. The protocol was approved by the Middle East Technical University's Ethics Committee.

Experimental procedures
Measurement of vibration at bicycle's stem and data analysis

A Tri-axial accelerometer (ENDEVCO®, Model 7253C-10) was used to measure the level of vibration on the bicycle. The accelerometer was mounted by double-sided adhesive foam tape on mid-point of the stem where it is attached to the handlebar to provide connection to the steering system. The acceleration data was collected in all three orthogonal axes, with the x-axis positioned to measure vibration in the anterior-posterior direction, the y-axis in the medial-lateral direction, and the z-axis in the vertical direction. The reference coordinate system for the placement of the accelerometer is shown in Figure 1.
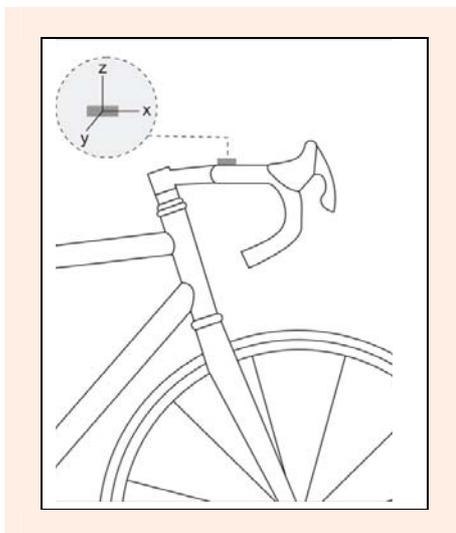
Figure 1. The placement of the accelerometer and adopted reference coordinate system.

The measurements consisted of three trials for each subject on each of the road surfaces, i.e. smooth asphalt road, concrete stone pavement and rough road. Measurements were performed on flat road sections that are approximately 250 m long having no curve and were in the order of asphalt road, rough road and concrete stone pavement. When the subjects arrived at the reference point, they were instructed to stop pedaling and to maintain a sitting position by placing the right foot forward on the pedal with the crank arms parallel to the road surface. The head was in a forward looking position toward the

direction of locomotion while the arms supported on the handlebar in an extended position. For the road bike trials (RB), subjects were asked to place their hands on the drop of the handlebar, whereas with Mountain bike trials (MTB) the hands were placed on top of the handlebar on both sides. Subjects were also instructed not to pedal or stand up from the saddle during the measurement period and verbally informed just before the recording was initiated.

The bicycle-rider model presented by Torbic et al. (2003) postulates that the combined effect of vibration magnitude and vibration frequency is greatest at the bicycle speeds near 19-20 km·h^{-1} and is likely to cause moderately high comfort and control problems for cyclists whereas it decreases as speeds increase beyond 20 km·h^{-1}. Therefore, the speed of the bicycle was decided to be 20 km·h^{-1} during the measurements. Data recordings were initiated when the bicycle passed the reference point on each course, while maintaining a constant driving speed of 20 ± 2 km·h^{-1}. Measurement duration was set at 4 seconds for data collection. 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.

As a measure of severity of vibration transmission, root-mean-squared acceleration, a(rms), values measured at the stem were calculated using the below given formula (Equation 1):

$$a(r.m.s) = \left[\frac{1}{T}\int_{0}^{T} a^2 dt\right]^{\frac{1}{2}} \qquad \text{Eq 1}$$

where T is the duration of measurement and a stands for the frequency of acceleration.

Measurement of muscle activity and data analysis

In order to determine the effects of vibration transmitted to the bicycle stem on the level of forearm muscular activity, surface electromyography signals (sEMG) were recorded bilaterally from a forearm flexor (m.flexor carpi radialis) and an extensor muscle (m.extensor digitorum) which are the superficial forearm muscles involved in force production during gripping and grasping movements.

sEMG recordings were performed simultaneously with the vibration measurements. The portable EMG data acquisition unit was designed to be worn back-pack style and was fixed to the subject's body with shoulder and abdominal straps causing no respiratory restriction or discomfort to the rider. A 3-m long USB cable was used to establish the connection with the portable computer. EMG measurements were repeated for both RB and MTB trials for each of the aforementioned road surfaces. Before

Table 2. Individual un-weighted rms acceleration values.

	Stem Acceleration (m·s⁻² rms)	Smooth asphalt		Concrete Stone		Rough Road	
		x	z	x	z	x	z
MTB	Subject 1	1.08	1.58	3.71	4.74	6.75	10.10
	Subject 2	1.89	2.22	4.14	5.19	7.60	9.37
	Subject 3	1.75	2.56	4.14	7.04	6.23	10.76
	Subject 4	1.40	1.66	3.60	4.18	7.16	7.86
	Subject 5	1.55	2.37	3.30	5.30	6.00	10.17
	Mean	**1.53**	**2.08**	**3.78**	**5.29**	**6.75**	**9.65**
	SD	**.32**	**.44**	**.36**	**1.07**	**.66**	**1.12**
RB	Subject 6	2.84	3.21	10.69	9.97	16.24	19.12
	Subject 7	3.58	3.85	8.60	9.42	13.15	13.68
	Subject 8	3.69	4.43	9.54	11.12	18.31	27.31
	Subject 9	4.37	4.21	7.61	8.52	13.71	18.12
	Subject 10	3.08	3.38	10.25	11.75	18.06	23.58
	Mean	**3.51**	**3.82**	**9.34**	**10.16**	**15.89**	**20.36**
	SD	**.59**	**.52**	**1.25**	**1.30**	**2.40**	**5.24**

the trials, subjects underwent three consecutive bilateral maximal voluntary isometric gripping tasks (MVC) with 2 min rests between each.

While sitting on their own bike, they were asked to start gripping the bar as hard as possible without changing the position of the body. MVC values were achieved by increasing the force level gradually from rest to maximal effort within 2 seconds and by sustained steady maximal exertion for subsequent 3 seconds as described by Caldwell et al. (1974). The muscular activity levels attained by the subjects were recorded in order to use in the normalization procedures and to determine the percentage of muscular contraction.

Ag/AgCl electrodes were used in sEMG measurements. Prior to electrode placement, all electrode sites were shaved to remove any hair, cleaned after mildly abraded with 70% alcohol and allowed to dry before the electrode placement. Experiments were performed between August and September when there was no rain. The temperature and humidity were between 19 to 22 ºC and 25 to 60%, respectively.

The active area of the electrodes was positioned at 2 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 500 Hz (low-pass). EMG values were then normalized with respect to peak amplitude of sEMG of the respective muscles attained in the best MVC trial. Then, the root mean square EMG activity (r.m.s EMG) was calculated for the selected time periods in MATLAB.

It has to be noted that unexpected changes in the handlebar direction during steering a bicycle may result in muscle contraction (involuntary manner) in both flexor and extensor muscles and in both sides. Therefore, in order to make comparisons between road surfaces and types of the bicycles, cumulative summation of normalized muscle activity levels are calculated as the sum of muscle activity levels (rmsEMG of %MVC) of both right and left flexor and extensor muscles (EMG_T). Besides, EMG normalization gives an access to the relative level of activation of a given muscle (Hsu et al, 2006) by ex-

pressing the absolute amplitude of the signal measured during the exercise as a percentage of a meaningful reference EMG value. The cumulative normalized activity levels were also calculated for right (EMG_R) and left (EMG_L) forearm as the sum of flexor and extensor muscle activity to make a comparison for hand dominance.

Non-parametric tests were chosen to assess the differences between the pairs of data studied since normal distribution could not be verified because the small sample sizes. Wilcoxon Rank-Sum test (Mann-Whitney U) and Wilcoxon Signed-Rank Test were conducted in order to compare i) EMG_T values for two types of bicycles (two independent sample) and ii) EMG_R and EMG_L values for different road surfaces (paired sample), respectively.

Results

Vibration transmitted to the bicycle

The results of the field measurements revealed that the vibration levels measured at the stem were effective in the x-axis (in the line of motion) and z-axis (perpendicular to the line of motion) in both groups (Table 2). Higher values were observed in the z-axis. At the stem of MTB, the values were at most 2.56, 7.04 and 10.76 m·s⁻² when pedaling on smooth asphalt road, concrete stone pavement and rough road, respectively. In the case of RB the corresponding values were 4.43, 11.75 and 27.31 m·s⁻².

It can be seen that acceleration magnitudes increased as the road roughness increased. It is clear that the values were highest on the rough road and lowest on the asphalt road for both types of bicycles. There was also a difference in the exposure levels of the two types of bicycles. With respect to MTBs, the level of vibration in the RBs was higher for each surface, and the values were approximately two fold higher. The highest level of accelerations occurred in the road bike trials, whereas the lowest values were observed pedaling on asphalt road.

Forearm muscle activity in controlling handlebar movements

Figure 2 was presented as an illustration of the simultaneously collected sEMG signal from the forearm flexor muscle (upper trace) and the acceleration signal (lower trace) during a rough road trial. The effect of road
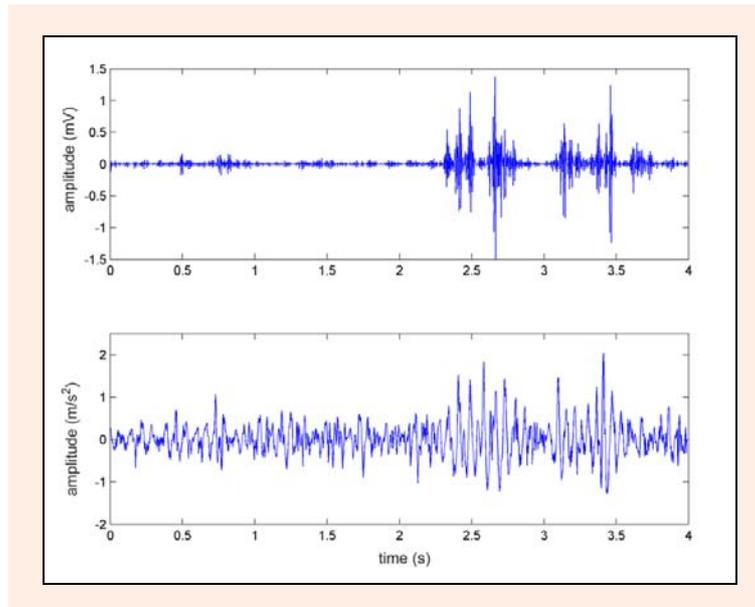
Figure 2. A time domain illustration of a simultaneously recorded EMG of extensor muscle (upper trace) and an acceleration (lower trace) signal (z-axis) recorded on the stem during a RB trial on the rough road.

roughness was detected in the acceleration signal with random acceleration peaks, while the roughness dependent rise in muscular activity of forearm flexor muscle was observed in the EMG signal. In the present study, rmsEMG of extensor muscles during MTB trials had the same tendency with acceleration amplitudes that increased towards higher values with the increasing order of roughness (i.e., asphalt road, concrete stone pavement and rough road, respectively) (Figure 3a). During rough road measurements it even reached to a value corresponding to approximately 50% of MVC. During the RB trials performed in rough road conditions, rmsEMG (%MVC) values for the forearm flexor muscles tended to be higher

than that of the other muscles (Figure 3b). As it is shown in both Figure 3 and 4, dominant hand (right for all subjects) was more responsive in controlling handlebar movements in both RB and MTB trials.

Cumulative summation of normalized muscle activity levels were also shown in Figure 4 due to the change in handlebar direction towards unknown directions (fore or aft) which requires muscular contraction of both flexor and extensor muscles in both arms. It is clear that RB trials tend to have slightly higher total muscle activation levels (EMG_T). However, the difference between two bicycles is only significant in rough road trials (Table 3). Dominant hand reached higher muscle
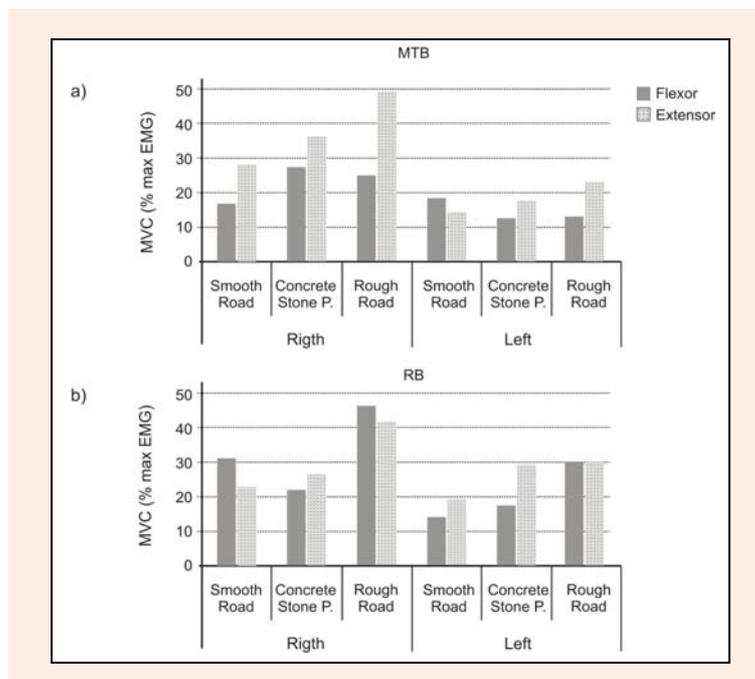
Figure 3. The percentage of max EMG values for right and left flexor and extensor muscles calculated for MTB (a) and RB (b) trials on different road surfaces.
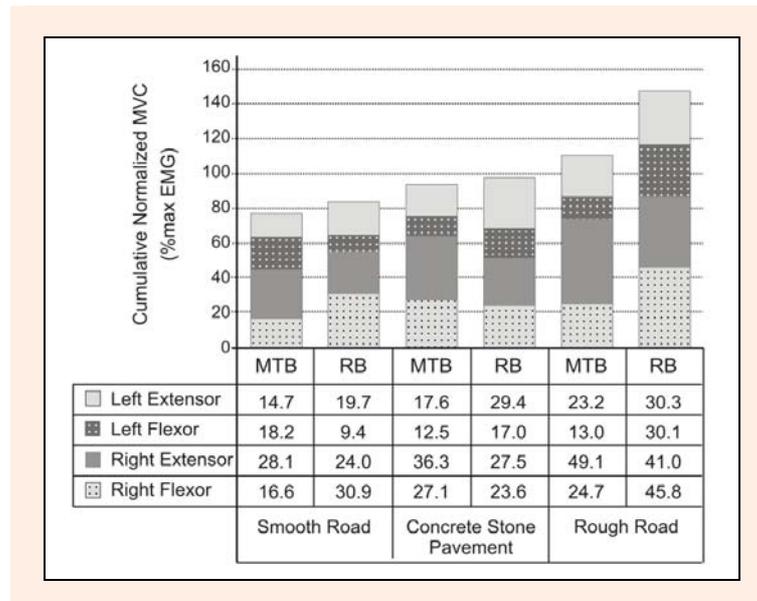
Figure 4. Cumulative summation of normalized muscle activity levels, calculated as the summation of both flexor and extensor muscles in both left and right arms. Average values of the r.m.s EMG as a function of the percentage of the maximal voluntary contraction (%MVC) presented for each muscle.

activation levels in all conditions. Table 3 also shows that the difference between right and left total muscle activity (EMG_R vs. EMG_L) is statistically significant for all surface conditions in both bicycle types, with the exception of RB trials on rough road surfaces which also resulted in statistically higher EMG_T.

Discussion

The purpose of this study was to capture the muscular activity in the forearm while steering a bicycle to investigate the effect of surface irregularities and the type of the bicycle. In the literature, vibration transmission studies have focused extensively on the mechanical transmission of vibration to different parts of the bicycle and body segments of interest. So far, the only study focusing on effects of vibration exposure on biodynamic response of the rider's body has been conducted by Rambarran et al. (2001) who has investigated muscular activity (i.e. erector spinae, vastus lateralis and biceps femoris) during simulated shock exposure conditions for two different types of MTB. However, the muscular activity of the upper extremity in response to vibration exposure on a bicycle has yet to be studied. In accordance with the aim of the research, the forearm muscles were selected to investigate

the effect of vibration transmission. Therefore, the level of representative muscular contraction measured for different types of bicycles and on different road surfaces has provided common ground for discussion.

The study has revealed the following results in clarifying the research questions. The cumulative normalized muscular activity levels during MTB trials on different surfaces had the same tendency with acceleration amplitudes and have ranked in the following order from lowest to highest value: asphalt road, concrete stone pavement and rough road. Although RB trials have resulted in a similar trend of increment, the values computed for rough road trials were higher than those in MTB trials. It is clear that road roughness amplified the amplitude of transmission and translated into higher muscle activity levels. In particular, during rough road measurements on MTB, rmsEMG of extensor muscles reached to a value corresponding to approximately 50% of MVC. During the RB trials performed in rough road conditions, rmsEMG (%MVC) values for the forearm flexor muscles have reached their highest levels.

The fatter tires and existence of front suspension system may explain the lower values in MTB trials. The other possible factors creating the difference between bicycles have been reported as being the geometry and the

Table 3. Statistical significance for selected comparisons (Wilcoxon Signed-Rank Tests: EMG_R vs. EMG_L for both RB and MTB, Mann-Whitney U Test: RB vs. MTB for EMG_T values) (NS: non-significant difference).

		MTB	RB
EMG_R vs. EMG_L	**Smooth Road**	p < 0.01	p < 0.001
	Concrete Stone P.	p < 0.01	p < 0.01
	Rough Road	p < 0.001	NS (p=0.083)
EMG_T	**Smooth vs Rough**	p < 0.01	p < 0.01
	Smooth vs Concrete	NS (p = .934)	NS (p = .095)
	Concrete vs Rough	NS (p = .107)	p < 0.001
		MTB vs RB	
EMG_T	**Smooth Road**	NS (p = .950)	
	Concrete Stone P.	NS (p = .934)	
	Rough Road	p < 0.001	

material of a bicycle frame and existence of the shock absorption system. For instance, tyre pressure (Torbic et al., 2003) as well as the type of shock absorption system (Faiss et al., 2007; Ishii et al., 2003; Rambarran and Roy, 2001; Roy and Robertson, 2000) 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. It has been shown that the type of suspension system results in different dampening characteristics of the MTBs in terms of impact forces and shock attenuation (Rambarran and Roy, 2001; Roy and Robertson, 2000), as well as vertical displacement (Titlestad et al., 2006) 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).

The recruitment of forearm muscles during steering a bicycle can be explained by the functions of these muscle groups. Firstly, when riding a bicycle on uneven road surfaces, even in a straight path, the arms, and consequently the forearm muscles, are of importance in providing postural stability by supporting the body and controlling handlebar movements. The handlebar movements, caused by irregularities on the surface and oscillations as a result of body movements to generate propulsive forces on the pedals, are controlled through co-contraction of the extensor and flexor muscles. Secondly, on a bicycle, some of the body weight is transferred to the handle through the arms while coupling forces are also applied by the hands. So, while a bicycle rider generates propulsive forces on the pedals and keeps the posture, arm muscles actively participate in maintaining balance on the bicycle by co-contracting isometrically. Since the vibration transmitted to the bicycle was effective in both the x and z-axis in both groups, bi-directional influence of vibration exposure on stability of the body and rotation around the vertical axis of the handlebar is likely to increase muscle activity in both flexor and extensor forearm muscles. Unsurprisingly, the results showed that the level of muscular activity of forearm muscles in controlling the handlebar movements has also been observed to be enhanced by the increase in the level of vibration exposed on the bicycle. In general, whole body vibration exposure is characterized by increased amplitude of EMG signals. There exist studies which found higher levels of muscular activity in vibration exposure conditions compared with no vibration trials in trunk muscles (Pope et al., 1998; Zimmermann and Cook, 1997), lower extremity muscles (Cardinale and Lim, 2003) and in upper extremity muscles (Aström et al., 2009). Since the severity of transmitted vibration to the bicycle was found to be considerably higher in RB trials, increased vibration amplitudes can explain the higher rmsEMG values in RB than that of MTB trials. In addition to amplitude difference in vibration transmission between the two bicycle types, road roughness resulted in increased muscular activity in both RB and MTB trials.

In respect to hand dominance, where dominant hand resulted in higher muscle activation levels in all conditions, RB trials tended to have slightly higher total muscle activation levels (EMG_T). It seems that increased surface irregularities result in higher contribution of dominant hand in controlling the handlebar. It may be explained by the fact that all the subjects are right-handed and it has been consistently shown that dominant hand is actively participating in the movement as a manipulating hand while the non-dominant hand is mostly responsible for ensuring the stability (Sainburg, 2005).

On the other hand, the amount of vibration transmission to the hand-arm system which is shown to affect the level of muscular activation is known 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 (Kaulbars, 1996; Radwin et al., 1987; Riedel, 1995). In the case of cycling, one might suggest that forearm muscle activity is enhanced as a result of a considerable portion of body weight transferred to the handlebar through the arms while coupling forces are applied by the hands. Because of the fact that when exposed to repetitive shocks and vibration, riders make an effort to support and keep themselves in balance with body movements including upper extremity by producing isometric muscle contractions to stabilize the bicycle against surface induced impact forces (Seifert, 1997). However, due to the study's limitations in conducting field experiments with the cabled measurement devices in the current experimental setup, the coupling forces have not been provided and the measurements could be performed with a limited number of subjects.

Another limitation of the study, which warrants discussion, was the apparent differences in physical characteristics of the subjects, specifically the differences in their body weights. Even though the rider's body is the biggest part of the rider-bicycle system (Waechter et al., 2002), Torbic et al. (2003) claim that the mass of bicycle rider does not affect the whole-body vibration characteristics. They have reported a wide range of body weight of their experimental group between 54-107 kg. However, the increased amount of body weight transferred to the handlebar through the hand-arm system due to different sitting postures and slope of the road can be thought to influence the magnitude of vibration experienced by the bicycle rider (Capitani and Beer, 2002). It was reported that approximately 30% of the rider's mass is supported by the hands and the rest is distributed over the saddle and the pedals while riding in seated position on a smooth surface (Wang and Hull, 1997). This distribution may change from one bicycle type to another. It is a known fact that MTB cyclists maintain a more upright sitting posture compared to RB cyclists. This in turn may result in a higher percentage of body weight of a MTB rider to be supported by the saddle instead of handlebar.

To the extent of our knowledge, the vibration exposure experienced by a bicycle rider is likely to be influenced by other factors such as material properties of the bicycle components, tyre pressure and the riding speed (Torbic et al., 2003). As they have the potential to affect

the biodynamic response of the bicycle rider, further research might investigate the possible effects of the aforementioned factors on muscular activity of forearm muscles in response to different vibration characteristics.

Conclusion

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 the bicycle in the field settings. The findings of the study revealed that increased surface irregularities amplify the severity of vibration transmission to the bicycle. Thus, it translated into increased muscle activity levels in forearm flexor and extensor muscles with higher values in dominant hand. The values have been ranked in increasing order as asphalt road, concrete stone pavement and rough road. With respect to type of bicycle, RB trials showed higher values compared to MTB.

To the best of our knowledge, the level of muscular contraction is of interest to vibration studies in two ways. Numerous studies have elicited that i) the severity of vibration exposure increases parallel with the increase in level of muscular contraction and ii) vibration applied to a muscle elicits a sustained muscular contraction through tonic vibration reflex (TVR). There is thus a "chicken-and-egg" problem: does muscle activity increase in response to vibration transmission? Or, does vibration transmission increase as a result of increased muscle activity? Or, do we observe an interaction effect for two independent variables? These questions and the study's limitations require further investigations under controlled conditions in future research.

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Key points

- The muscular activity level in the forearms increases in response to random vibration transmitted to the bicycle to control handlebar movements.
- The level of vibration transmission depends on irregularities on road surface and bicycle type.
- A bicycle rider can be considered vulnerable to developing vibration related overuse injuries and/or performance diminishing consequences.

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