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EXECUTIVE SUMMARY OF THE THESIS

Foot-transmitted vibration in cycling: a preliminary study

TESI MAGISTRALE IN MECHANICAL ENGINEERING – INGEGNERIA MECCANICA

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1. Introduction

The study of the effects of vibration on the human body in occupational settings is well established due to the need to prevent long-term physical disorders associated with prolonged exposure. However, vibration exposure is present not only in occupational settings; for example, in cycling, riders are continuously exposed to mechanical vibrations originating from the interaction between the rider, the bike and the riding surface. Despite this, no comprehensive synthesis of the existing evidence of the effects of vibration on the different types of human responses is available to date. The main findings obtained after systematically reviewing the existing literature on the effects of cycling-induced vibration on the rider showed that the exposure limits to hand-arm vibration (HAV) and whole-body vibration (WBV) imposed by the European Directive 2002/44/EC are easily reached also in not highly demanding conditions [1], [2]; in addition, the body parts in contact with the bike have been observed to be the most exposed to vibration [2], [3], [4], [5]. Overall, it has to be considered that all the fields investigated in the systematic review are characterized by a methodological heterogeneity that doesn't permit to draw definitive conclusions, highlighting the need for further investigation to strengthen the evidence. Moreover, vibration exposure to HAV and WBV in cycling has been already investigated, while none of the studies has specifically examined foot-transmitted vibration (FTV) in cycling. Considering that the body parts in contact with the bike, namely hands, lower back and feet, are the most exposed to vibration, it is important to better understand the mechanism of FTV in cycling. Since no specific standard has been developed for the evaluation of FTV exposure, the standard used for WBV (ISO 2631) has to be used.

This thesis focuses on the characterization of FTV in cycling in real-world conditions, to guarantee ecologically valid vibration exposure. The specific objectives of the work are to: evaluate vibration exposure at the foot following ISO 2631 guidelines, assess the suitability of ISO 2631 to analyse FTV exposure, identify the main frequencies at which vibrations are transmitted to the feet and compare them with the resonance frequencies reported for human foot in standing position, and analyse vibration transmission in the different phases of the pedalling cycle.

2. Materials and methods

2.1. Population

The experimental trials involved three healthy female subjects, each subject performed two acquisition sessions, one with a road bike and one with a mountain bike, for a total of six trials used in the analysis. The subjects had a mean height of 1.65±0.13 m, a mean weight of 67±4 kg, and a mean age of 25.6±1.5 years. Subjects were considered eligible for the experimental trials if they had no contraindications to ride a bicycle, and if they were accustomed to road bike and mountain bike rides, no competitive background was necessary.

2.2. Experimental set-up and protocol

Two Blue Trident IMU sensors (Vicon, UK) were used to collect the acceleration data from the pedal and the foot during the pedalling. One sensor was attached to the bottom part of the pedal to acquire the input acceleration, the other was placed on the foot at the metatarsus to acquire the output acceleration. This position was chosen because it permitted firmly attaching the IMU to the foot, still guaranteeing acceptable comfort for the subjects while wearing their shoes, and not affecting their natural movement while riding. The sensors were placed on the same side for road bike and mountain bike rides to ensure consistency in the data.

Each trial comprised a 30 s reference signal acquisition and a bike ride. The first acquisition was used as a reference for the extraction of the acceleration data in the direction of the general coordinate system, common to the foot and the pedal. During this acquisition the subject was asked to remain standing still with the feet on a flat surface and the bike positioned on a flat surface, maintained as vertically as possible, with the pedal in vertical position. Each subject performed a road bike and a mountain bike ride. The road bike rides were performed on paved roads, while the mountain bike rides took place on off-road trails. No particular requirements were set, to make the experimental trials as ecologically valid as possible. The duration of the trials wasn’t previously set, but it was determined case-by-case, in order to have enough data for the analysis.

2.3. Data processing

The acquired data were pre-processed using the Capture.U desktop application (Vicon, UK); obtaining two sets of data for each subject, one from the pedal and one from the foot, with a sampling frequency of 1600 Hz. The data were then imported into MATLAB R2024b (The MathWorks Inc., 2023, Natick, Massachusetts), where all the data processing was conducted. Firstly, the accelerations in the direction of the axes of the general coordinate system were retrieved. The general coordinate system was defined as a right-handed coordinate system integral with the pedal, with the x-axis aligned longitudinally to the pedal, directed towards the front wheel, the y-axis transversally, and the z-axis vertically, directed upwards perpendicular to the pedal. The constant component of the acceleration signals was removed by means of a high-pass Butterworth third-order filter with a cut-off frequency of 0.1 Hz. The parts of the signals when the subjects were moving were selected to get rid of the moments when the subjects were forced to stop. To select the phases of the pedalling cycle, the low-frequency component of the acceleration signals, related to the pedalling movement, were extracted by applying a low-pass third-order Butterworth filter with a cut-off frequency of 2 Hz. Based on the chosen coordinate system the low-frequency component of the acceleration in z direction reached a local maximum when the crank arm was at 0°, also called top dead centre (TDC), and a local minimum at 180°, also called bottom dead centre (BDC); while the low-frequency component of the acceleration in x direction had a local maximum at 90°, and a local minimum at 270°. The crank arm was considered at 0° when vertical directed upwards, at 90° when horizontal directed towards the front wheel, at 180° when vertical directed downwards, and at 270° when horizontal directed towards the rear wheel. The angle time history was obtained by interpolation in the different quadrants, assuming a constant angular velocity. The pedal stroke was divided as follows: downstroke (30°-150°), backstroke (150°-210°), upstroke (210°-330°), overstroke (330°-30°) [6], [7]; the subdivision of the pedal stroke is shown in Figure 1. Due to a limitation in the coding, the overstroke phase was analysed separately between 330° and 0°, and between 0° and 30°. The high-frequency acceleration components, related to the vibrations, were obtained by applying a high-pass third-order Butterworth filter with a cut-off frequency of 2 Hz. The analysis of the acceleration signals was divided into two parts, the analysis of the overall signals not divided into the pedalling phases and the analysis of the different phases. For the analysis of the overall signal, a Hanning window was applied to reduce the leakage, with an overlap of 50% to reduce data loss at the edges. To compensate for energy loss due to the windowing, the energy compensation factor equal to 1.63 was applied. The averaged spectra of the acceleration signals were calculated by RMS averaging the spectra of 5 s long subsets. The main quantities used in the analysis are Power Spectral Density (PSD), RMS, and H_1 estimator with coherence. All the spectral functions were evaluated in a frequency range from 0 Hz to 800 Hz to avoid aliasing. To evaluate the exposure to vibration, the signals were also processed following ISO 2631-1 guidelines. Weighting curves were applied, A(8) values and Vibration Dose Values (VDV) were calculated and compared to the limits imposed in the European Directive 2002/44/EC.

The part of the signal in which an actual movement was present was further divided into shorter segments in which the pedal strokes were well distinguishable. The phase detection process and the frequency analysis were performed separately for each pedal stroke. The spectrum of the acceleration of each phase was calculated separately for each pedal stroke, and power spectrum (PS), RMS, and H_1 estimator were derived; the results obtained for each pedal stroke were then averaged. Due to the short duration of each phase no windowing function was applied.

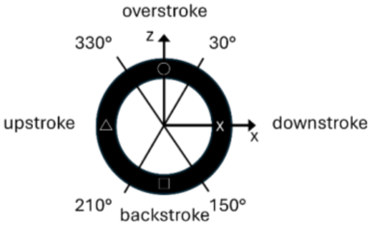

Figure 1: Subdivision of the pedalling cycle.

3. Results and discussion

3.1. Vibration exposure

When examining the vibration exposure following ISO 2631 guidelines, it has been highlighted that the use of VDV as an additional parameter together with A(8) values is essential to correctly evaluate vibration exposure when shocks are present; in fact VDV better relates to the energetic content of vibration, while A(8) values are influenced by direction-related multiplying factors. In addition, the vibration exposure was observed to be higher at the foot with respect to the pedal, and the most excited direction is along the z-axis, perpendicular to the foot and the pedal. The VDV evaluated at the foot in z direction is 13% and 20% higher than the one at the pedal, respectively for road bike and mountain bike. The limits to the exposure are indicated in the European Directive 2002/44/EC; the Exposure Action Value (EAV) was overcome by all the subjects in all the conditions and directions; while the Exposure Limit Value (ELV) was reached by all the subjects in at least one direction. If A(8) values in z direction are considered, at the foot EAV was reached after a maximum of 41 minutes for road bike rides and after a maximum of 6 minutes during mountain bike rides. The ELV was reached after a maximum of 3 hours 37 minutes during bike rides and after a maximum of 35 minutes during mountain bike rides. These times confirm that vibration experienced during MTB rides is higher than the one observed during road bike rides; moreover they show that the limits are reached after a short time, not comparable to the duration of competitions.

3.2. Overall crank cycle

3.2.1. RMS

One of the crucial steps during the evaluation of vibration exposure following ISO 2631 is the frequency weighting of the acceleration signals, this procedure causes a reduction in the energetic content of the signals. The reduction in average acceleration RMS after the application of the weighting curves is shown in Table 1; it is possible to see that the energetic content of the signals recorded during road bike trials is more affected by the weighting process, with respect to MTB rides.

Table 1: Percentage reduction of acceleration RMS after the application of the weighting curves.

	Pedal		**Foot**	
	Δ% RB	**Δ% MTB**	**Δ% RB**	**Δ% MTB**
x	-46%	-30%	-28%	-23%
y	-49%	-32%	-43%	-40%
z	-47%	-24%	-46%	-27%

3.2.2. PSD

Examining the average PSD functions of the acceleration signals recorded in x direction at the pedal, the main peak in the energy content at around 20 Hz is strongly reduced by the weighting process. At the foot the main peak is at around 13 Hz, and also in this case it is reduced by the weighting process. In z direction the peak in the average PSD function is at around 13 Hz for both the pedal and the foot, and also in this case it is reduced by the weighting process. The amplitude of the PSD function of the acceleration in z direction is greater than the one in x direction, confirming that the most excited direction is the one perpendicular to the pedal and foot. In both the directions, the amplitude of the PSD function of the acceleration recorded at the foot is higher than the one recorded at the pedal, meaning that the vibration is amplified from the pedal to the foot. In general, the weighting process causes the total suppression of the energetic content above 30 Hz. In both the directions the energetic content of the acceleration recorded during road bike rides doesn't exhibit a clear peak, but it is spread up to 30 Hz – 40 Hz; this characteristic justifies the higher reduction in acceleration RMS for the road bike signals with respect to MTB signals because the suppressed components above 30 Hz in road bike rides account for a larger fraction of the total energy

3.2.3. Transmissibility

The analysis of vibration transmissibility in x and z direction, shows different results. In x direction (Figure 2) the peaks in transmissibility are at lower frequencies with respect to z direction. The main peak observed in the mean transmissibility obtained from road bike trials is at 4 Hz, with an additional peak at 10 Hz; in the mean transmissibility obtained from MTB trials the main peak is at 10 Hz and the peak at 4 Hz is not present. In road bike trials vibration is amplified from the pedal to the foot up to 100 Hz, with a mean amplitude at the main peak at 4 Hz of 3.2, meaning that at this frequency the vibration experienced at the foot is, in average, more than 3 times higher than the one at the pedal. In MTB trials vibration is amplified up to 200 Hz, with a mean amplitude at the peak at 10 Hz of 2.8.

In z direction (Figure 3) the mean transmissibility obtained from road bike trials and MTB trials have a common peak at around 18 Hz; at higher frequencies in MTB trials there is the main peak at around 60 Hz, while in road bike trials the mean peak is at 67 Hz. The overall average main peak, considering all the trials together, is at around 65 Hz, with an amplitude of 2.8. Vibration is amplified up to 150 Hz and 205 Hz, respectively for road bike and MTB trials, and up to 180 Hz for the mean transmissibility.

The resonant frequencies of the corresponding anatomical locations present in the literature are 76 Hz and 75 Hz [8], higher than the one found in the current study. In previous studies it was observed that grip force and muscle tension influenced vibration transmissibility in HAV and WBV [9], [10], [11]; in cycling different muscles are involved in the movement during the different phases of the crank cycle, so the change in muscle tension along the pedalling cycle may influence the transmission of vibration.

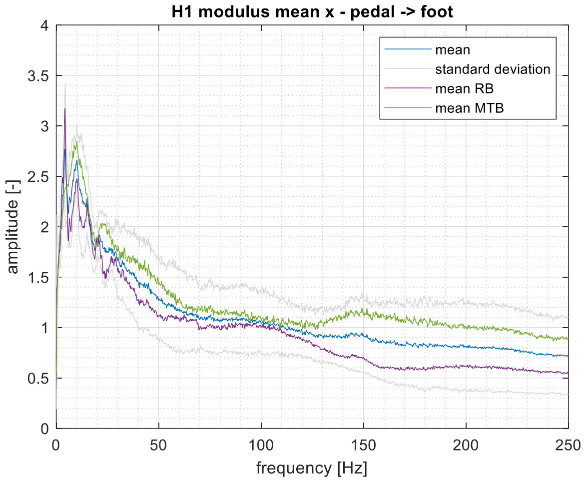

Figure 2: Mean ± standard deviation transmissibility modulus in x direction.

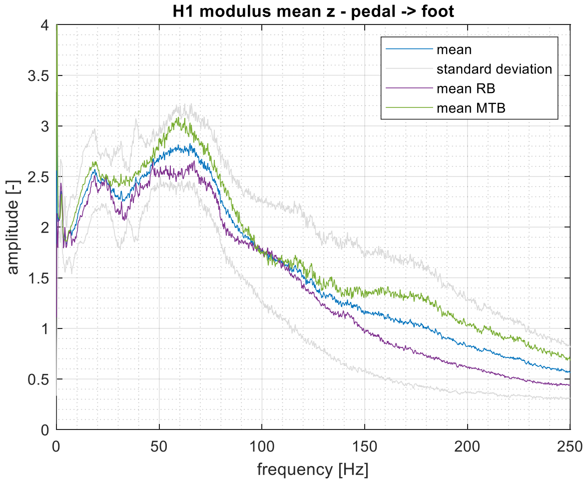

Figure 3: Mean ± standard deviation transmissibility modulus in z direction.

3.3. Crank cycle phases

To better understand how the transmissibility varies during the pedal stroke and if it is influenced by the activity of the muscles involved in the movement, the mean vibration transmissibility in the different phases of the pedal stroke is evaluated and compared with the muscle activation in the corresponding phases [6], [7], [12]. The results obtained are shown in Figure 4; in the first half of the overstroke (330°-0°) the peak in transmissibility is at around 50 Hz, lower than the value found for the entire pedal stroke (65 Hz) and also lower than the value found in standing position (76 Hz). In the second half of the overstroke (0°-30°), the peak is located at 64 Hz, similar to the result of the overall cycle. During downstroke (30°-150°), and backstroke (150°-210°) the peaks are at 72 Hz, and 76 Hz, respectively, similar to the values in standing position. Lastly, the peak during the upstroke (210°-330°) is at 50 Hz, the same as the overstroke.

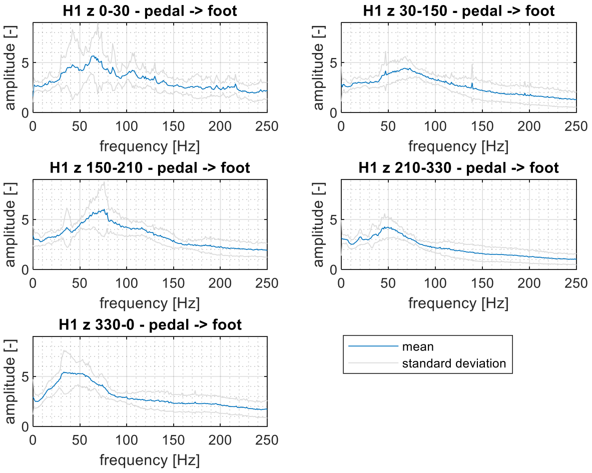

Figure 4: Mean ± standard deviation transmissibility modulus in z direction in the different phases of the pedalling cycle.

During downstroke, the high peak frequency can be related to the high muscle tension required for the production of the power output. Although during the backstroke power output is limited, a transition between the pushing phase and the pulling phase happens; this phase is characterized by the activation of the *soleus*, *gastrocnemius lateralis*, *gastrocnemius medialis* in the first part, and to a lesser extent also of the *tibialis anterior*. The stiffening of the ankle joint caused by the activity of the muscles close to the foot, may contribute to the increase in peak frequency. During the upstroke and the first part of the overstroke (until top dead centre), where the peak in transmissibility is at lower frequencies, the leg shows a compliant behaviour, mainly following the movement of the pedal; in fact the only active muscles are the *soleus* and the *gastrocnemius lateralis*, but to a lesser extent with respect to the downstroke and the backstroke. The lower peak frequencies may be related to the low tension of the muscles. After the top dead centre, the muscles start their activity again in preparation for the downstroke. Even though overstroke is associated with a low power output, the increase in muscular activity may be associated with the increase in peak frequency.

These considerations suggest a relation between the frequency at which the peak in transmissibility is observed, the power output and the level of muscular activation during the different phases of the pedalling cycle; however, only a preliminary hypothesis, based mainly on qualitative data rather than on quantitative data, can be obtained. The main limitations of this analysis lie in the limited sample size and in the low amount of data available. To better understand this aspect, further studies, specifically designed are necessary.

4. Conclusions

Although some limitations related to the sample size and to the presence of some confounding factors are present, some conclusions can be drawn. The results showed that vibrations measured at the foot were consistently higher than those measured at the pedal, suggesting that the foot is a critical point for vibration exposure in cycling. In the evaluation of vibration exposure, the importance of the selection of the parameters used in the analysis was highlighted. In the current study VDV was found to better represent the energetic content of vibration, with respect to A(8) values. It was also observed that the application of the weighting curves strongly affects the energetic content of the acceleration signals. In particular, at 65 Hz, where the peak in transmissibility is located, the signals are attenuated by one order of magnitude. This means that an important part of the vibration components is not considered in the evaluation of vibration exposure. This evidence highlights the need for the development of additional weighting curves for the evaluation of foot-transmitted vibration. The change observed in transmissibility peak frequency in the different phases of the pedalling cycle, suggests that the transmission of vibration is influenced by the level of contraction of the muscles close to the foot.

However, the strength of this result is limited by the limited number of participants, and by the limited amount of information available related to the contraction of the muscles in the lower part of the lower limbs during cycling.
Overall, this study provides an initial insight into the mechanism of foot-transmitted vibration during cycling and can represent a starting point for future studies focusing on specific biomechanical, physiological, and design aspects of vibration transmission.

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