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Methods for the Laboratory Evaluation of HAV-Related Comfort in Cyclists †

Stefano Marelli and Marco Tarabini *

Department of Mechanical Engineering, Politecnico di Milano, 20136 Milan, Italy; stefano1.marelli@polimi.it
* Correspondence: marco.tarabini@polimi.it

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Abstract: Cyclists are exposed to hand–arm vibration (HAV) for prolonged periods of time during training sessions and competitions. The vibration can reduce perceived comfort, thus limiting the ability of the cyclist to control the bike in endurance sessions. The study of HAV in cyclists in a controlled environment allows for comparisons between the effects of different postures, materials and technical solutions on perceived discomfort and on the vibration transmitted to specific body segments. This paper describes the experimental setup, the measurement chain and the data processing for the evaluation of bike comfort in the laboratory. The setup is based on single-axis or multiaxial shakers; the time history of the input vibration can be derived from on-field measurements for comparative analyses or can be selected from among classical stimuli for frequency response function evaluation (sine sweep or white noise). Comfort can be quantified via questionnaires; objective measurements can be derived from vibrations measured at different body locations using wearable accelerometers or laser doppler vibrometers. A case study is presented and discussed.

Keywords: hand–arm vibration; HAV; comfort; sport; cycling; measurements

1. Introduction

Cyclists are exposed to hand–arm vibration generated by road (or track) irregularities and transmitted to the handlebars, pedals and saddle through the bike wheels, fork and frame. Vibrations limit comfort, and bike manufacturers are looking for solutions to attenuate the energy transmitted to the hands, in order to improve riding comfort. The possibility of developing diseases seems limited, though the value of A(8) (as defined in the ISO 5349-1) is usually high and the exposure time limit for a 20 km/h trip on a paved street is in the order of tens of minutes [1,2]. A few studies have evidenced possible health risks and discomfort related to cycling. Akuthota and colleagues reported the risk of developing the carpal tunnel syndrome as a result of long-distance cycling [3], while Capitani and Beer [4] indicated that several cyclists experience discomfort or pain after cycling because of inappropriate cycling posture, because of vibration or because of a combination of both factors. The problem of discomfort is particularly relevant for mountain bikers, gravel/cyclocross cyclists or during specific cobbles races [5]. Several studies have focused on laboratory experiments to reproduce cyclists' exposure to HAV. Lépine et al. [6] proposed road-simulating apparatus composed of two hydraulic shakers mounted below the bike wheels. The two shakers were actuated to provide only vertical motion to the wheels. Another study designed a test rig to measure the effects of gloves and handlebars while riding a bike [7]; the authors used the transmitted power and transmitted energy at the cyclist's hands as metrics to evaluate comfort with different grip materials. Tarabini and colleagues compared different grip materials and handlebars for motocross [8]; their experimental setup was based on an electrodynamic shaker reproducing the vertical vibration measured on a motocross bike. Vanwalleghem and colleagues proposed an instrumented seat and handlebar for comfort evaluation while riding a bike [9]. Our work

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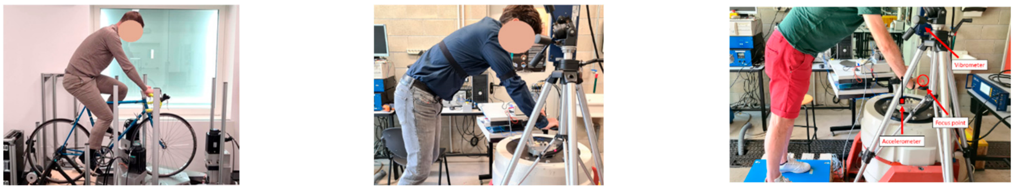
aims to summarize our experience in tests performed for the evaluation of HAV-related riding comfort. This paper will focus on the experimental setup, on the identification of the vibration stimulus and on metrics for the subjective and objective evaluation of comfort.

2. Experimental Setup

We developed two setups for the comparison of different bike components. The first setup (i) allowed us to test the entire bike mounted on smart trainers/rollers, and is the preferred solution for the subjective evaluation of comfort. The plate of a 3D shaker supports the front wheel of the bike and imposes a vibration along the vertical and/or medio-lateral axes (Figure 1a). The rear wheel is mounted on commercial rollers to allow for long-term training in realistic conditions. With this setup, the cyclist's posture is determined using the bike frame dimensions; this implies that different bikes are needed to grant correct bike posture to different cyclists. The second setup (ii) allowed us to test the response of the handlebar itself, mounted on the head of a shaker using an interface that reproduces the fork head (Figure 1b). This is the preferred solution for the estimation of vibration transmissibility in different handlebars and tapes; the setup is simple but requires ad hoc measurements to ensure a realistic contact force distribution between the handlebar and the feet. The test duration is usually limited to a few minutes. In both cases, the shaker control accelerometer is located on the handlebar, in order to generate the desired vibration level at the interface with the hands.



(**a**) (**b**) (**c**)

Figure 1. Pictorial view of the proposed experimental setup. (**a**) The subject is on a bike, holding the handlebar. The front wheel is placed on the shaker, while the rear wheel is fixed on a roller. (**b**) The subjects hold the handlebar mounted on a shaker through a custom interface. (**c**) Example of hand-transmitted vibration measurement chain. A vibrometer points to one knuckle of the hand, while an accelerometer measures the input vibration.

3. Vibration Stimulus

Since there are no reference vibration profiles for cycling, it is possible to adopt two approaches. The first one consists of reproducing the vibration measured on-field during a bike session. The vibration must be measured during the on-field tests at the handlebar, at the same position where the accelerometer of the shaker closed-loop control is fixed. The vibration profile depends on tests parameters such as the speed, the terrain characteristics, the tire pressure and the cyclist's anthropometric characteristics. The PSD of the vibration is then reproduced using of the two facilities described in the previous section. These kinds of experiments are focused on the evaluation of comfort using questionnaires or on the comparison of absolute (RMS) vibration transmitted to different body segments. The selection of participants among recreational or professional cyclists, with different anthropometric characteristics and ages, is strongly recommended. The second option consists of using harmonic or random stimuli; the RMS of the vibration stimulus may vary between 5 and 50 m/s^2; lower values are used to simulate urban or road cycling at low speed, while higher accelerations are meant to simulate off-road and gravel vibration. Harmonic and random stimuli are preferred for the estimation of the transfer function between the handlebar and different body segments, for the objective comparison of different materials.

4. Measurement Chain

The characteristics of the measurement chain should be derived from the ISO 8041; the input vibration on the handlebar can be detected by accelerometers with nominal sensitivity between 10 and 100 $\mathrm{mV/ms^{-2}}$. The vibration transmitted to the hand and to different body segments can be measured using an accelerometer fixed either to the wrist or to the elbow using Velcro® straps or using a Laser Doppler Vibrometer pointed at a reflective tape located on a knuckle (as in Figure 1c) or on the ulnar head. When testing only the handlebar (using the second setup described in Section 2) and not the entire bike, it is important to quantify the push force or the contact pressure. The latter can be measured using capacitive or piezoresistive pressure films; qualitative measurements can be also obtained using low-cost resistive sensors, such as the FSR 408 (Interlink Electronics) or similar sensors. The push force can be measured using a triaxial force plate. The vertical component is measured via subtraction from the static weight, while the horizontal and medio-lateral components are directly measured by the force plate itself. When testing only the handlebar, the cyclist's posture has to be measured to ensure realistic testing conditions. In short-lasting tests, we typically use the Azure Kinect (Microsoft Corporation), which allows us to derive the skeleton of the cyclist after completing the tests; the parameters that we monitor are usually the wrist, elbow and shoulder angles to ensure their steadiness during the tests. The angles are computed from the joint positions and rotations given by the Kinect at a rate of 30 Hz. Alternative solutions are based on wearable sensors (such as XSens Awinda or Notch Wearable) or on optoelectronic systems (in our case, BTS Smart Evo). Wearable solutions were found to be affected by the electromagnetic field generated by the shaker when using the second setup in Section 2, mainly because the handle is close to the shaker magnets. Conversely, the time required for the setup of the markers of the optoelectronic system is high, and the use of this setup is preferred for endurance tests.

5. Metrics

Discomfort can be quantified using subjective evaluations (questionnaires) or vibration transmissibility T, expressed as a function of the vibration frequency f. In each *ID* tested configuration (e.g., a specific grip material or a high/low tire pressure), $T(f)$ is the ratio between the spectrum of the acceleration response $r^{ID}(f)$ and the spectrum of the vibration input $i(f)$.

$$T^{ID}(f) = \frac{r^{ID}(f)}{i(f)} \tag{1}$$

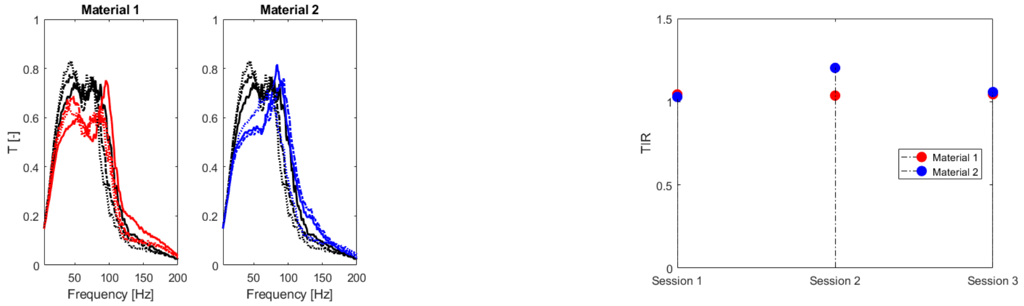
The transmissibility integral ratio (*TIR*) of the configuration *ID* can be computed as the ratio between the integral value of $T^{ID}(f)$ and the integral value of the baseline condition (e.g., the reference grip material or the nominal tire pressure) $T^{BL}(f)$

$$TIR^{ID} = \left(\int_{0}^{f_{Max}} T^{ID}(f)df \right) / \left(\int_{0}^{f_{Max}} T^{BL}(f)df \right) \tag{2}$$

Values of TIR^{ID} lower than 1 indicate better vibration attenuation of the configuration ID with respect to the baseline condition. $T^{ID}(f)$ and $T^{BL}(f)$ can be multiplied by the frequency weighting functions (for instance, $\mathrm{w_h}$ of ISO 5349) to give more relevance to frequencies that are more harmful or annoying for the hand–arm system. The perceived comfort can be evaluated at different time intervals using the CR100 scale proposed by Borg and Borg [10]. For research purposes, we also investigated the correlation between subjective comfort evaluation and TIR^{ID}.

6. Case Study

As an example, we describe an analysis performed to compare the effects of different tapes on comfort while riding a gravel bike. We mounted a gravel handlebar on the head of an electrodynamic shaker (LDS V830) as in Figure 1c. The stimulus was a pseudorandom signal with a PSD measured during a gravel session. The vibration at the hand was measured on the middle finger knuckle using a Polytec OFV 505 vibrometer. The input vibration was measured using a PCB Piezotronic 333B30 accelerometer. The protocol first included a measure of the baseline $T^{BL}(f)$ using no tape, with Material 1—$T^{1}(f)$ and with Material 2—$T^{1}(f)$. The protocol was repeated in three sessions (on different days). $T(f)$ was multiplied by the frequency weighting w_h; the results are summarized in Figure 2a. TIR^1 and TIR^2 are shown in Figure 2b; the results evidence that in this specific case, materials have similar vibration absorption performance. TIR variability depends on several factors, such as posture, and its variability should be carefully considered.



(**a**) (**b**)

Figure 2. (**a**) w_h weighted $T(f)$ for BL (black), material 1 (red) and material 2 (blue). Solid, dashed and dotted lines indicate the different experimental sessions. (**b**) TIR for materials 1 and 2 in the three sessions.

7. Conclusions

In this work, we described a setup and a method that enables comparison of the effectiveness of different bike materials for cycling, with the aim of quantifying their performance and possibly increasing ride comfort. Further studies are necessary to define specific frequency weighting curves to maximizing the correlation between vibration transmissibility and perceived comfort.

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Informed Consent Statement: Subjects involved in the study were informed about the finality of the preliminary study; informed consent was obtained by the participants.

Data Availability Statement: Data are available upon request.

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Conflicts of Interest: The authors declare no conflict of interest.

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