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Hand-arm vibration in motocross: measurement and mitigation actions

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SUMMARY

Objective. This study focused on the quantification of vibration which reaches the hands of motocross riders and on the reduction of such vibration thanks to the handlebar and handlebar mounts.
Background. Vibration transmitted through the hand and arm can lead to vascular and musculoskeletal problems that are well documented in the scientific literature. Controlled studies identifying plate-handlebar characteristics effects on the vibration attenuation in motocross are lacking.
Methods. We measured the vibration exposure of professional and recreational motocross riders on a motocross track and replicated the vibration patterns on a LDS V930 shaker in the laboratory, to analyze the effectiveness of various components in reducing the rider vibration exposure. Laboratory tests were performed with ten subjects randomly gripping different combinations of handlebars and steering plates, and questionnaires were used to evaluate the comfort. Objective measurements of vibration reduction were then compared to the subjective values of perceived comfort.
Results. According to the current EU legislation, the measured vibration levels reach the exposure limit in less than 1h. The mechanical characteristics of the handlebars and steering plates have a limited effect on the vibration transmitted to the rider's hands. The rubber elements that many manufacturers use to reduce the vibration have limited effects at frequencies that are harmful for the musculoskeletal system. Questionnaires results have no correlation with the measured plate and handlebar performances.
Conclusions. Most of the techniques used to reduce the hand-arm vibration exposure of motocross drivers are ineffective.

KEY WORDS

Hand-Arm vibrations; transmissibility, riding comfort, steering plate, handlebar, steering system, handlebar's grip, motocross

INTRODUCTION

Ground vehicles' manufacturers put a lot of effort into increasing driving comfort, mainly reducing the vibration energy introduced by road irregularity and transferred to the human body. High levels of vibration do not only generate discomfort, but as documented in the scientific literature, they are also strongly correlated to musculoskeletal disorders. A prolonged exposure to hand-arm vibration (HAV) can lead to several disorders, known as hand-arm vibration syndrome (HAVS) (Poole et al. 2016). HAVS includes neurological, vascular and musculoskeletal injuries. Neurological damage due to vibration exposure is irreversible and can result in finger numbness and tingling, as well as a reduction in tactile perception and of the temperature sensitivity. The vascular damage caused by impaired blood circulation in the fingers (M. Bovenzi 1998) often results in temporary blanching (vibration white finger, VWF), during which fingers feel numb. The blanching is temporary, but the reestablishment of blood circulation is painful. In the most severe cases, the blood circulation impairment is permanent and requires finger amputation. Vibration may also lead to musculoskeletal injuries (arthritis, tendinitis and muscle fibers modification) which decrease grip force, reduce hand mobility and cause diffused pain in the entire hand and arm system. The possibility of developing HAV related injuries depends on the vibration magnitude and on the exposure time. Type of injury (neurological, vascular and musculoskeletal) however, depends on the frequency of the vibration (M. Bovenzi 1998, Hangberg 2002). Low-frequency vibration exposure mainly leads to osteoarthrosis in the elbow, wrist and acromioclavicular joint. Impacts with high-energy transfer to the hands often result in musculoskeletal disorders. These disorders are usually more severe in the presence of static joint loading. Finally, high frequency vibration increases the risk of vascular diseases (Farkkila et al. 1979, M. Bovenzi 1998). Epidemiological studies pointed out a discrepancy between the risk for VWF and that predicted by the ISO 5349 standard. This suggested that the w_h ISO weighting curve may be inappropriate for assessing the vibration-induced vascular effects (Bovenzi 1998).

Effects of vibration on the hand-arm system

There is clinical and epidemiologic evidence that symptoms and signs of VWF may be reversible after the reduction or cessation of vibration exposure, but the reversibility of VWF is inversely related to age, the duration of exposure, and the severity of the disorder at the time the vibration exposure ceases (Bovenzi, 1998). Regarding the neurologic component of HAV syndrome, there is epidemiological evidence for occurrence of loss of manual dexterity, deterioration of finger tactile perception, digital numbness and paranesthesia in occupational groups exposed to hand-transmitted vibration (Violante et al. 2000). It has been reported that unmyelinated C-fibers and thin myelinated A-δ nerve fibers, which mediate the perception of temperature can be damaged by occupational exposure to hand-transmitted vibration (Hirosawa et al. 1992).

Clinical and epidemiological data have revealed an increase in thermal and vibrotactile perception thresholds of fingertips with increasing daily vibration exposure, duration of exposure, or lifetime cumulative vibration dose (Lundström et al. 1999, Bovenzi et al. 2011, Lindsell & Griffin 1998, Ye & Griffin 2018). According to Bovenzi (1998) the osteoarticular component is a controversial matter, because early radiology investigations revealed a high prevalence of bone vacuoles and cysts in the hands and wrists of vibration-exposed workers, but later studies showed no significant increase with respect to control groups made up of manual worker.

The European Union adopted a Directive in 2002 (Directive 2002/44/EC) on the minimum requirements for the health and safety of workers exposed to vibration. The Directive introduces exposure action and limit values for both hand-arm and whole-body vibration: the Exposure Action Value (EAV) is the daily amount of vibration above which employers are required to take action to limit the exposure itself, and for HAV is 2.5 m/s^2 (daily exposure, weighted RMS acceleration level). The Exposure Limit Value (ELV) is the maximum amount of vibration an employee may be exposed to on any single day; the value should never be exceeded, as exposure to vibration levels larger than ELV is associated with high risk of developing HAVS.

HAV and WBV Exposure in road Vehicles

The literature about HAV exposure of motorcycle riders is limited Industrial Industries Advisory Council (April 2017). The first studies on the side effects of hand-arm vibration applied to motorcycles date back to 1997. Mirbod et al. (1997) performed a study that aimed to evaluate subjective symptoms in the hand-arm system of all traffic police motorcyclists of a Japanese city. The secondary output of their study was to assess the hand-arm vibration exposure associated with their daily tasks. The first objective has been fulfilled by means of a questionnaire submitted to 150 persons, in which information about the occupational history and the presence of subjective symptoms in the hand-arm system was collected. This survey revealed that the most significant riding side effect is shoulder stiffness, as almost one officer out of two suffered from this symptom. Authors concluded that finger numbness, finger stiffness, shoulder pain were common among the police drivers. The measured handlebar vibration (measured according to the ISO 5349 standard) was 2.8 – 4.5 m/s^2 (8 hours equivalent). The subjects with larger vibration dose showed significantly higher prevalence of symptoms in the fingers and shoulders in comparison with the control group. A similar analysis was carried out by Shivakumara and Sridhar in 2010. The work focused on the study of the vibration effect on the driver and the measurement of the magnitudes of vibration in motorcycles. The authors considered both HAV and whole-body vibrations (WBV). The experimental activity showed that the HAV level exceeded ELV, as 8 hours of work lead to a HAV exposure level of 4.8-7.6 m/s^2.

Astöm et al. (2006) studied the HAVS and musculoskeletal symptoms in the neck and the upper limbs in professional drivers of terrain vehicles. They asked a group of almost 800 professional drivers of forest machines, snowmobiles, snow-groomers and reindeer herder, and a group of almost 300 randomly selected males to complete a questionnaire about HAVS' symptoms and musculoskeletal symptoms in the neck and the upper limbs. The analysis of the questionnaire showed that there is a relation between exposure to driving terrain vehicles and some of the HAVS' symptoms. Moreover, increased odds of musculoskeletal symptoms in the neck, shoulders and wrists were also found, and it seemed to be related to the cumulative exposure time.

The number of studies related to the motocross is more limited. Grange (2009) and Humpherys (2018) evidenced that there is a large prevalence of chronic exertional compartment syndrome in motocross drivers; riders often refer to the forearm pain as "arm pump" that results in a decrease in riders' performance and may force the riders to stop driving. The orthopedic literature offers little information regarding evaluation and treatment of this pathology. Symptoms are similar to those of HAVS and can be due to variations of the blood flow to the muscles in the forearm combined with relatively decreased venous outflow and to the vasoconstrictor effect of the vibration (Simões et al. 2016, Ascensao et al. 2007).

Scope of the work

The literature review evidences that there is a lack of knowledge on the vibration exposure of motocross drivers and on the effect that different materials have on the vibration transmitted to riders. The present study aims to quantify the vibration exposure of professional and recreational motocross drivers, and to identify the best combination between handlebar and steering plate to reduce the vibration transmitted to the rider'shands.

MATERIALS AND METHODS

Preliminary motocross track tests focused on the quantification of the vibration exposure of professional and recreational motocross drivers. Subsequently, in order to identify the best combination between handlebar and steering plate to reduce the vibration transmitted to the rider's hands, the vibrations measured in track tests were experimentally reproduced in the laboratory. The effectiveness of the different solutions was assessed both by objective evaluations (vibration measured on the subject hand) and on subjective comfort evaluation (based on questionnaires results).

Motocross track tests

Different tests were performed on a single track. Two types of 4-stroke motorcycles were driven by two drivers: 1) KTM EXC 350 F driven by an amateur driver; the second is a Honda 450 CRF cross driven by a professional driver. Motorcycle 2 was tested in two different sessions characterized by different track and traffic conditions. The measurement method was similar to the one used in other sports applications by Tarabini et al. (2015). Both motorcycles were instrumented with a triaxial accelerometer (PCB 356 A21) on the steering plate, measuring the accelerations along three directions x (fore and aft), y (medio-lateral) and z (almost vertical, aligned with the fork direction) while a single-axis accelerometer Endevco 27 F11 was located close to the throttle, measuring the vibration along the z axis. This configuration neglected the high frequency attenuation provided by the grips and the gloves, that were characterized in dedicated laboratory tests. Data were sampled by a NI 9234 acquisition board that was stored in a specifically designed case fixed on the lower and upper plates, in place of the number board (**figure 1**). A miniaturized personal computer, located in a backpack, sampled the data that were analyzed offline.

The parameters used to quantify the vibration exposure are the weighted levels of vibration along three mutually perpendicular axes, according to the ISO 5349 standard. The accelerations measured by the two vibration pickups shown in **figure 1** (x_1, y_1, z_1, z_2) were frequency-weighted using the w_h curve ($x_{1,w}$, $y_{1,w}$, $z_{1,w}$, $z_{2,w}$) and then used for the computation of the weighted level of vibration (RMS of the weighted vibration along each axis, $a_{x1,w}$, $a_{y1,w}$, $a_{z1,w}$, $a_{z2,w}$). The parameter used for the quantification of the driver risk is the vector sum of the magnitude of vibration (a_v), computed in accordance with the ISO 5349. In addition, the daily vibration exposure A(8), computed according to

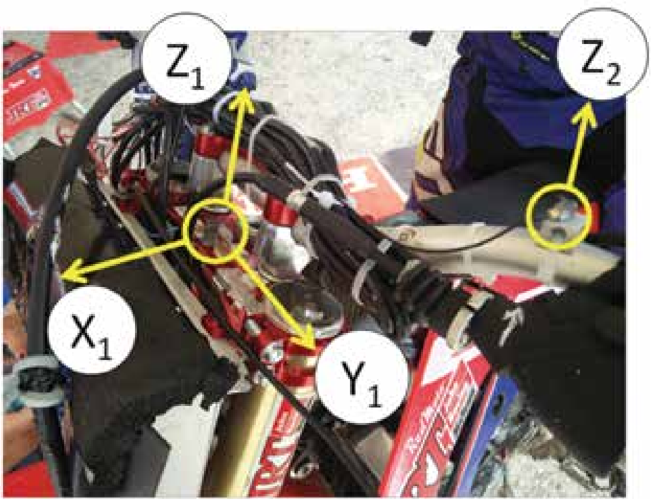


Figure 1. Position of the accelerometers in track tests and orientation of the measurement axes.

the ISO 5349 standard, has been evaluated considering one hour of activity each day (typical of professional drivers) as well as the time to reach the exposure action and limit values (EAV and ELV, 2.5 and 5 m/s^2 respectively as defined in the Directive 2002/44/EC of the European Parliament and of the Council). With the aim of assessing the danger of vibration to the vascular, musculoskeletal and neurological systems, the vibration spectra have been analyzed similarly to what was done in existing literature studies (Alberti, et al. 2006) and as suggested by the ISO 5349 standard in presence of repeated shocks.

Laboratory tests

To select which handlebar components would be tested, the two motocross riders were asked to suggest readily available commercial components which, to their knowledge, incorporate some form or anti-vibration features/materials. The riders identified 3 handlebars and 4 steering plates, and the parts were chosen accordingly. Handlebars 1 and 3 incorporated rubber elements, while handlebar 2 was rigid. All the steering plates incorporated rubber or anti-vibration elements; the steering plate C and the handlebar 1 were provided by the manufacturer with rubber elements of varying stiffness; in these cases, a subscript was used to indicate which rubber element was chosen and to characterize the stiffness. Handlebars and steering plates are shown in **figure 2** and **figure 3** respectively. Handlebars were labeled 1r, 1y, 1b (handlebar 1 with red, yellow or blue rubber), 2 and 3; in the formulas, the subscript *h* was used to identify the quantity referring to a specific handlebar (being h an integer number between 1 and 5). Steering plates were labeled A, B, Cw, Cg (handlebar 1 with white or green) and D; in the formulas, the subscript *p* was used to identify the quantity referring to a specific steering plate (being *p* an integer number between 1 and 4). All the combinations of plates and handlebars were mounted on a vibration generator (LDS V830, maximum stroke ±25 mm) which reproduced the vibration measured on the track test in the most severe configuration. Volunteers gripped the handlebar trying to reproduce the typical motocross driver posture. Steering plate vibrations along the x and z direction were measured using two piezoelectric accelerometers (Endevco 27A11); the handlebar vibration in correspondence of the hand was measured using a piezoelectric tri-axial accelerometer (PCB 356B21). The experimental setup is shown in in the upper part of **figure 4.**

SUBJECTS AND METHODS

Ten volunteers tested all the 20 plate-handlebar combinations; *i* is used to indicate tests performed by each volunteer, each volunteer completed the tests in less than 2 hours, including the time required for changing the experimental setup (duration of data acquisition for each configuration

Figure 2. Tested handlebars.

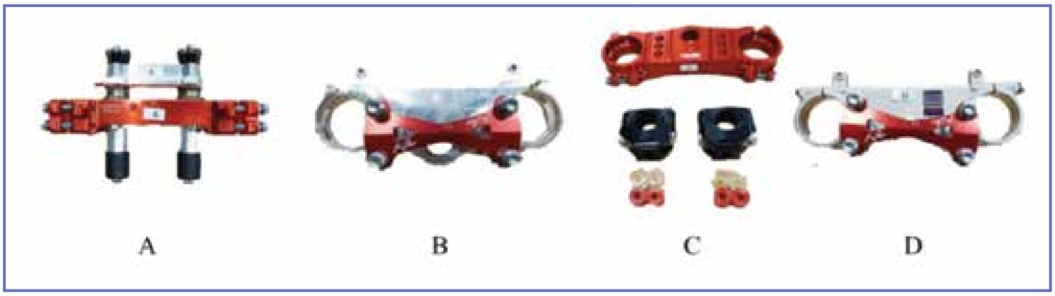


Figure 3.Tested steering plates.

120 s). The vibration exposure in our tests was lower than the EAV and consequently the risk for the participants was negligible. All the volunteers gave their written consent to the study, which met the current ethical guidelines in sports. Exclusion criteria were moderate or severe upper limb injuries in the 6 months preceding the assessment and diabetes. The effectiveness of the different combinations was quantified by the vibration measured at the handlebar ($a_{p,h,i}$) which was obtained (under the hypothesis of system linearity) by multiplying the track w_h weighted acceleration spectrum times the transmissibility.

After each test, participants were asked to report their level of discomfort $D_{p,h,i}$ for the plate p and the handlebar h on a 0-9 scale. Marks were normalized ($d_{p,h,i}$) by subtracting the average discomfort μ_i reported by the participant for all the handlebars and plates and dividing the difference by the standard deviation σ_i of data reported by the same participant, similarly to what was done in similar literature studies (Tarabini 2018, Dickey 2007).

$$\mu_i = \frac{1}{20}\sum_{p=1}^{4}\sum_{h=1}^{5} D_{p,h,i}$$

$$\sigma_i = \sqrt{\frac{1}{20}\sum_{p=1}^{4}\sum_{h=1}^{5}\left(D_{p,h,i} - \mu_i\right)^2}$$

$$d_{p,h,i} = \frac{D_{p,h,i} - \mu_i}{\sigma_i}$$

The average discomfort for each plate-handlebar combination was computed starting from the normalized discomforts reported by each of the i-th subjects as follows:

$$\overline{d_{p,h}} = \frac{1}{10}\sum_{i=1}^{10} d_{p,h,i}$$

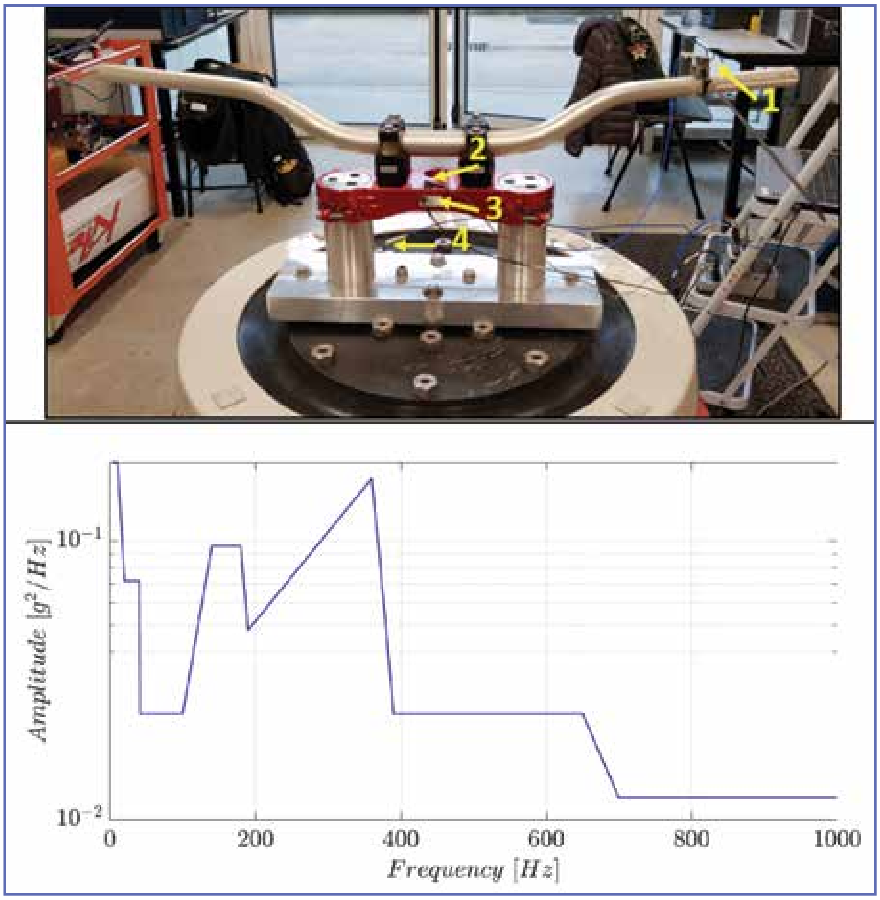


Figure 4. On the top the experimental setup with accelerometers located on the handle (1), on the steering plate along vertical and horizontal vibration (2 and 3) and on the shaker head (4). On the bottom, shaker input power spectral density.

RESULTS

Track tests

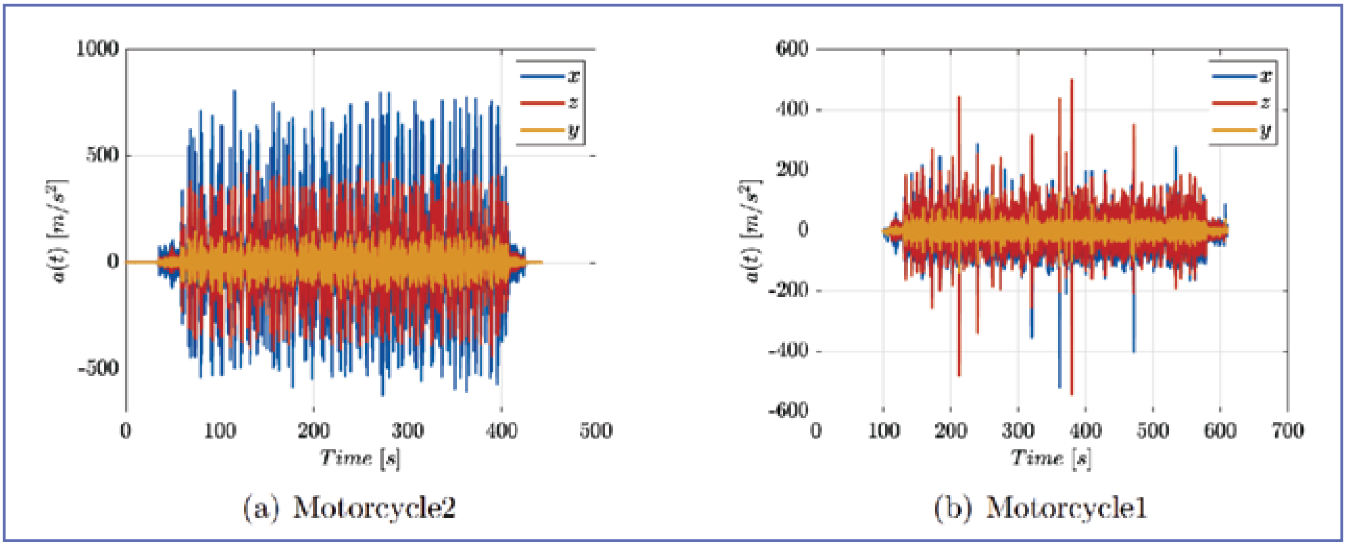
The time histories of the vibration measured during the track tests are shown in **figure 5**.

The vibration levels (weighted and unweighted) measured in the different experimental sessions along the three axes are summarized in **table I**. Results show that after 1 hour of activity, the exposure is systematically larger than the EAV (2.5 m/s^2). In the most critical situation (Motorcycle 2, session S3), the limit value is reached after 0.9 h (54 minutes), thus indicating that the continuous exposure to hand-arm vibration might lead to the set of disorders indicated as HAVS.

Given that the vibration frequency content heavily influences the disorder that the riders might develop, the short-time Fourier transform (STFT) of the vibration (i.e. the evolution of vibration frequency with respect to time) has been analyzed. **Figure 6** shows the STFT of the vibration along the z axis shown in **figure 5 (a)**. The spectrogram shows the clear presence of three different vibration components. The vibration between 0 and 20 Hz are the ones generated by the road irregularities and jumps. The components between 100 and 400 Hz are the vibrations generated by the 4-stroke engine, while the components above 400 Hz (with the smaller amplitude) are reasonably due to structural vibration.

The vibration level along the z axis obtained in laboratory test with the different plate-handlebar combinations are summarized in **figure 7**. The plot shows that the effect of the materials is minor, as the vibration levels are close to 12 m/s^2 (i.e. the value imposed on the shaker head) for all the considered configurations.

The substantial equivalence between all the tested solutions is confirmed by the questionnaires' result, as the differences between the average discomfort ($\overline{d_{p,h}}$) for each combination of plate p and handlebar h (shown in **figure 8**) are small in comparison with the data dispersion. The plot shows that the Plate A and handlebar 2 was the combination which had the lowest mean discomfort. In this configuration, the



(a) Motorcycle2 (b) Motorcycle1

Figure 5. Time histories of the vibration measured at the steering plate for the motorcycle 1 (a) and 2 (b).

Table I. Unweighted vibration levels (x, y and z) and weighted vibration levels (awx, awy and awz) and exposure level after 1 hour of activity measured in the different experimental sessions at the steering plate. The last two columns indicate the time after which the exposure limit value and action values are reached.

Motorcycle	Session	x	y	z	a wx	a wy	a wz	a(8), T=1h	T (ELV)	T(EAV)
		(m/s² RMS)	(m/s² RMS)	(m/s² RMS)	(m/s² RMS)	(m/s² RMS)	(m/s² RMS)	(m/s² RMS)	h	min
1	S1	24.4	7.5	25.7	5.0	2.3	8.1	3.5	2.1	31
2	S2	60.9	14.7	52.2	5.8	3.4	9.4	4.1	1.5	22
2	S3	83.9	17.8	66.7	8.0	4.1	12.0	5.3	0.9	13

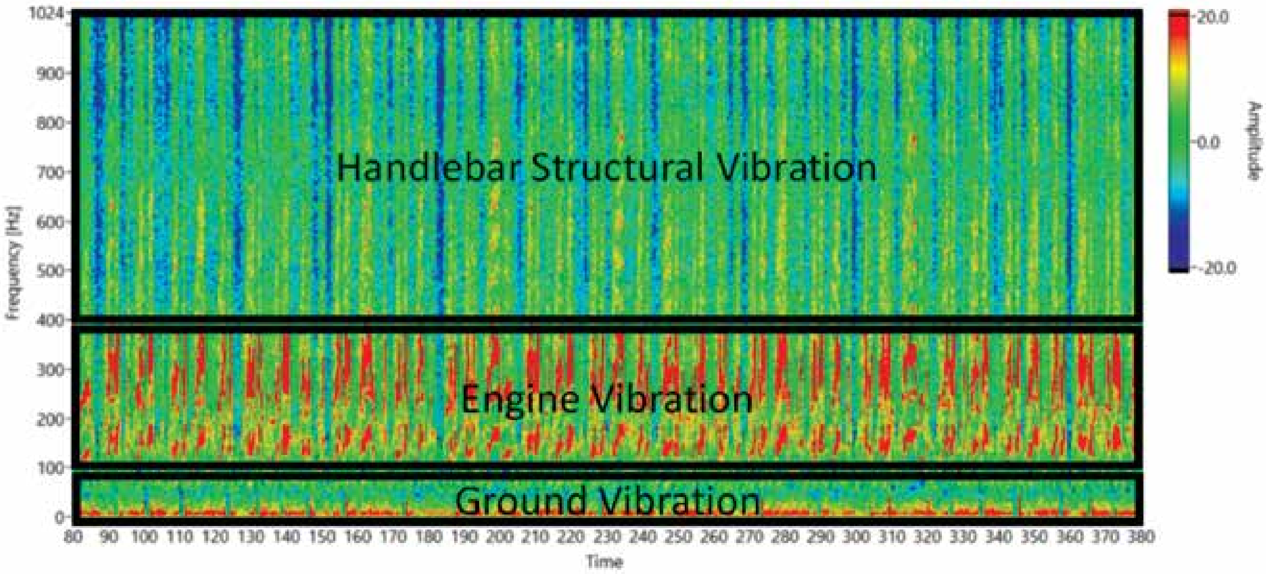
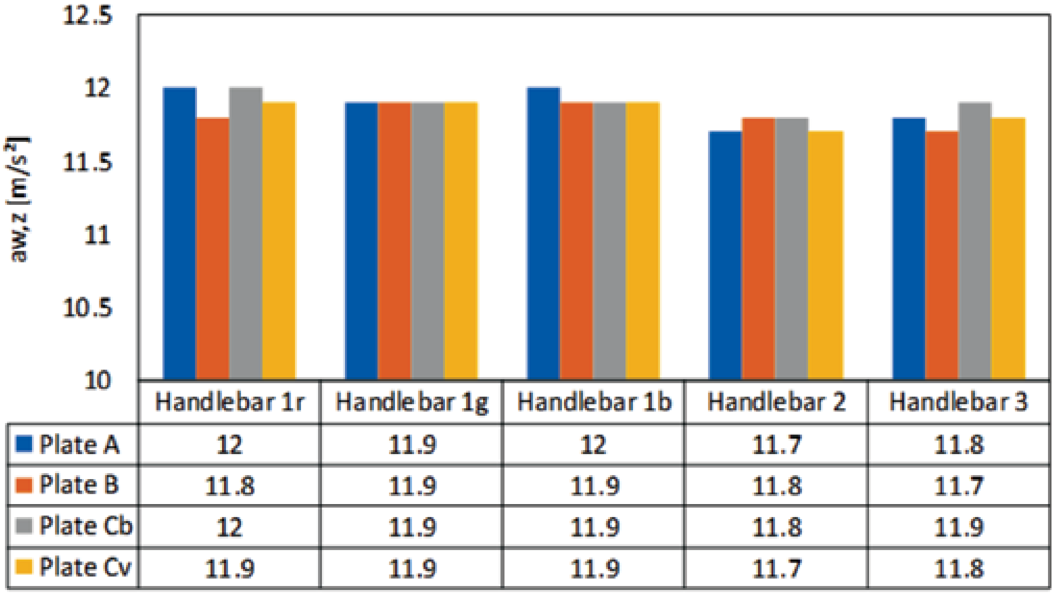


Figure 6. Short-time Fourier Transform of the vibration measured at the steering plate Plate-handlebar test.



	Handlebar 1r	Handlebar 1g	Handlebar 1b	Handlebar 2	Handlebar 3
🟦 Plate A	12	11.9	12	11.7	11.8
🟧 Plate B	11.8	11.9	11.9	11.8	11.7
⬜ Plate Cb	12	11.9	11.9	11.8	11.9
🟨 Plate Cv	11.9	11.9	11.9	11.7	11.8

Figure 7. Hand weighting function on the left, acquired hand weighted acceleration on the right.

measured vibration is 11.7 m/s². The configurations that lead to the highest discomfort are the combinations of plate Cv with handlebars 1r and 3; in these configurations the vibration levels were 11.9 and 11.8 m/s² respectively.

The small differences between the tested configurations was confirmed by the boxplots of the normalized discomfort categorized in different groups on the basis of the plate and handlebar, shown in **figure 9**. The graph shows that the variability of

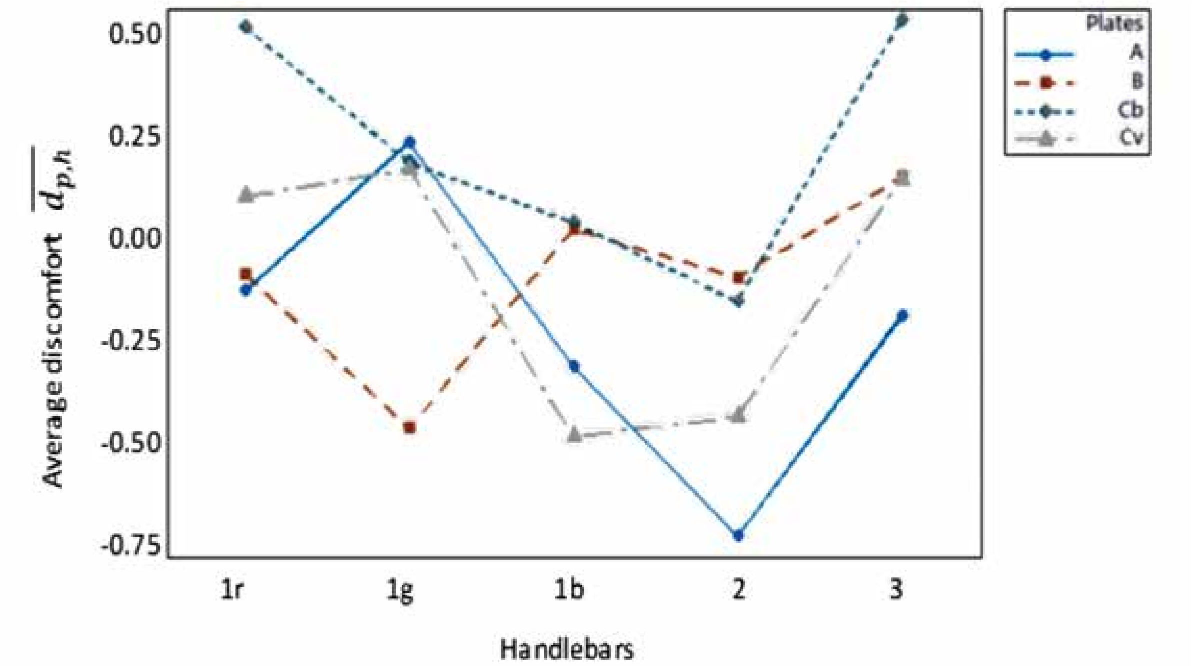


Figure 8. Average discomfort as a function of the handlebar h and plate p.

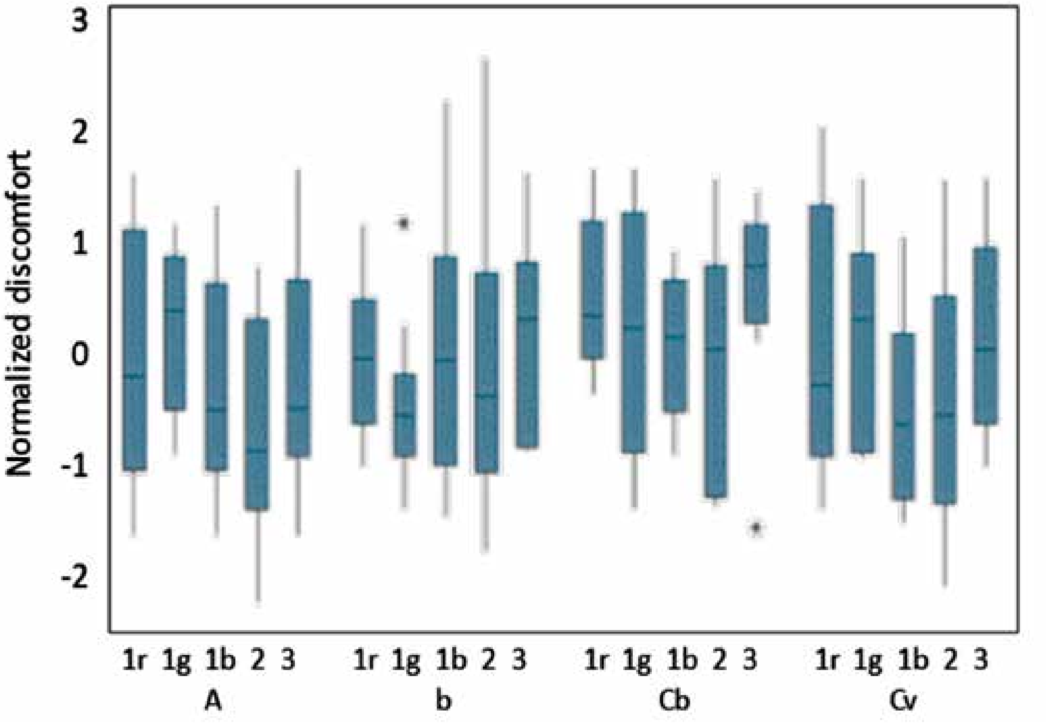


Figure 9. Boxplot of the reported discomfort for the different plates/handlebar configuration.

the discomfort reported by subjects is much larger than the difference between the average discomfort, thus evidencing that a plate-handlebar combination can be comfortable for some participants, but uncomfortable for others.

DISCUSSION

According to the current EU legislation, the vibration to which motocross riders are exposed, might lead to different disorders of the hand arm system. Results showed that the EAV can be reached in approximately 30 minutes by a recreational driver (session S1) and less than 15 minutes by a professional driver (session S3). This is consistent with the phenomenon of the arm pump (IIAV, 2017), resulting in intermittent forearm pain during and after the training period. The high vibration exposure suggests that professional motocross drivers might develop the HAVS, consistently with the existing literature studies that reported finger numbness for mailman driving motorcycles (Mirbod et al. 1997).

As reported in an information note of the Industrial Injuries Advisory Council of the United Kingdom (IIAV, 2017), the scientific literature is rather patchy, but shows that the vibration on the motorcycle's handlebar can be of sufficient magnitude to lead to HAVS. The potential for vibration on the handlebars of motocross to cause relevant HAV pathologies is even more relevant, given the magnitude of the vibration evidenced in our tests and the presence of shocks and transient events, whose adverse effect has been largely documented in the literature (Burstrom et al. 1999, Moschioni et al. 2011, Bovenzi 1998).

The spectral analyses evidenced the presence of different vibration components: the effect of the interaction between the motorcycle and the track is evident at frequencies below 20 Hz. These frequencies, according to the current scientific literature (Bovenzi 1998, Hangberg 2002), may lead to musculoskeletal disorders. The vibration coming from the engine (with frequencies between 100 and 400 Hz) might lead to the finger numbness and vascular diseases (Farkkila 1979, Bovenzi 1998).

The dominant vibration direction at low frequencies, is the vertical one; the vibration is mainly due to the track irregularities not absorbed by the suspensions. At higher frequencies, the vibration along the three axes is comparable, being generated by the engine and by the frame structural resonances.

Unfortunately, the effectiveness of the anti-vibration handlebars on the reduction of vibration is minor. Results of the laboratory tests showed that the plates and the handlebar mount transmit the entire vibration at frequencies below 200 Hz. The average attenuation between 200 and 400 Hz is usually limited, while above 400 Hz all the combinations exhibit resonances that increase the vibration transmitted to the rider. In general, the handlebars and the plates seem designed without accounting for the basic principles of anti-vibration devices and do not account for the direction of the vibration.

The structural handlebar and plate characteristics can be optimized following the approach described by Saggin et al. (2012). Preliminary results evidenced that in the case of motocross, where the vibration coming both from the ground and the engine is relevant, the anti-vibration solutions proposed by different manufacturers are equivalent. The situation might be different for enduro riders, where the dominant vibration is the one coming from the engine. In this case, the presence of compliant elements in the handlebar paired with the dominant tonal component in the vibration spectrum (constant engine regime) could improve the performances of handlebars and steering plates that incorporate soft elements with respect to the rigid ones. This consideration, although reasonable, has to be experimentally validated and could be the topic of forthcoming studies.

In general, results evidenced that the discomfort reported by the different subjects has a very poor correlation with the measured vibration exposure, thus indicating that the design of the anti-vibration solutions should be based on the vibration characteristics and on the optimization of the transfer function, and not (as currently performed) by subjective comfort evaluations.

CONCLUSIONS

Our investigations evidenced that the vibration exposure of professional motocross driversreaches EAV indicated by the Directive 2002/44/EC in approximately 20 minutes and the ELV min 1 hour. Recreational riders reached EAV and ELV in 30 minutes and 2 hours, respectively. The different handlebars mounts are not effective in the reduction of vibration. The proposed methods for reducing the vibration increase the exposure at high frequencies, thus increasing the risk of HAVS. Results presented in this work suggest that the vibration exposure of motocross drivers should be monitored and that almost all the combinations of handlebars and steering plates are equivalent from a comfort point of view.

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CONFLICT OF INTERESTS

Kite Performances provided the steering plates and the handlebars to Politecnico di Milano. There was no influence on experiments or data analyses that were performed by Politecnico di Milano.

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