Road Bike Comfort: On the Measurement of Vibrations Induced to Cyclist

ABSTRACT

With ride quality being one of the most sought-after characteristics of a road bicycle by customers as well as by bicycle manufacturers, the vibrational behaviour of the bicycle/cyclist system has grown into an active field in sport engineering research in recent years. When assessing this behaviour, bicycle transmissibility and ride comfort, controlling test conditions to obtain repeatable load and acceleration measurements at the cyclist's contact points with the bicycle cannot be overemphasized. Surprisingly however, this consideration has not yet been specifically addressed in the literature. The aim of this paper is a first effort to investigate the effect of a selected set of test conditions on the measurement of vibration induced to the cyclist by a road bicycle. Our results showed that all the test conditions selected had a significant effect on the level of vibration induced to the cyclist.

Keywords: *Bicycle Dynamic Comfort, Bicycle Testing, Vibrations Transmission, Vibration Measurement, Excitation Techniques*

INTRODUCTION

Vibrational comfort is closely linked to human perception and from an engineering point of view, is related to the level of vibration transmitted from vibrating objects to humans. In this matter, major fields of study include vibration in relation to occupational health and safety, transportation-related vibration and a vibration model of human body. The standard organisation ISO has produced standards that describe human exposure to vibration [1, 2]. These standards mainly serve as guidelines for the measurement and analysis of vibration levels transmitted to humans. More recently, vibration transmitted to humans has been the subject of several studies in sports including ice hockey [3], baseball [4], golf [5] and bicycling [6-25]. In road cycling specifically, ride quality has become one of the most sought-after characteristics of a road bicycle by customers as well as by bicycle manufacturers. The vibration generated by road surface defects and transmitted by the bicycle to the hands and the buttocks can be a significant source of discomfort, fatigue and a disincentive to ride. In this regard, it is essential to have an in-depth understanding of vibrational behaviour of the bicycle/cyclist system as well as an adequate assessment of the vibration induced to the bicyclist (VIB) by the road.

Over the past three decades, the bicycle/cyclist system has been the object of several studies which can be classified according to the following four categories: (1) Transducer development and measurement of loads transmitted at the contact points between the cyclist and the bicycle (Alvarez and Vinyolas [6], Rowe et al. [7], Reiser et al. [8], Drouet et al. [9], Bolourchi and Hull [10], De Lorenzo and Hull [11], Drouet and Champoux [12, 13], Caya et al. [14] Champoux et al. [15], Arpinar-Avsar et al. [16] and Chiementin et al. [17]); (2) Road-induced excitation measurement and replication in the laboratory (Lépine et al. [18]); (3) Vibration transmissibility of the bicycle and its components, and ride comfort (Petrone and Giubilato [19], Olieman et al. [20], Giubilato and Petrone [21], Lépine et al.[22], Thite et al. [23]); (4) Model development (Perrier et al. [24, 25]). From a mechanical engineering standpoint, the aforementioned published literature sheds light on the inherent complexity of the study of the bicycle/cyclist system, and by extension, of the vibrational behaviour of this system. Key aspects of this complexity include difficulty obtaining realistic dynamic load measurements, non-linearity of the human body as a structure, the effect of added mass and damping by the cyclist on the vibrational behaviour of the bicycle, and variability introduced by the cyclist to load and acceleration measurements.

In this context, when assessing the vibrational behaviour of the bicycle/cyclist system, bicycle transmissibility and ride comfort, controlling test conditions to obtain repeatable measurements of load and acceleration at the cyclist's contact points with the bicycle is paramount and cannot be overemphasized. Surprisingly however, this consideration has not yet been specifically addressed in the literature. Among all the parameters that are susceptible to affect these load and acceleration measurements, test conditions like cyclist's posture or the excitation condition under the wheels for example can play significant role. The aim of this paper is therefore to report on our first efforts to investigate the effect of a selected set of test conditions on the measurement of VIB.

To increase the benefits of this study, the effect of test conditions was extended to the ranking of two wheel sets in terms of the VIB. Among the bicycle components that could have been selected for investigation, the choice of this particular component was motivated by recent studies by Olieman et al. [20] and Giubilato and Petrone [21] for which conclusions on wheel set ranking differ. Furthermore, it will be shown that if test conditions are not carefully controlled, wheel set transmissibility ranking can be inconsistent.

METHODS

In order to assess VIB , dedicated test apparatuses enabled us to apply excitation displacement at the wheels as well as transducers to measure force at the stem and seat post were developed and are presented in part (a) of this paper. The test conditions investigated in this study are detailed in part (b). A description of the statistical data analysis used to evaluate the effect of the test conditions on the VIB is provided in part (c).

a) Test apparatuses

On-road testing is unlikely to provide an adequate environment when seeking repeatable results [18]. For the purposes of this paper, all measurements were carried out indoors in a laboratory to establish a more controlled and therefore adequate testing environment. All the tests were carried out using the same bicycle. Wheel tyres were inflated to 8 bars. Two laboratory road-simulating apparatuses were used: (1) a road simulator equipped with two hydraulic shakers which enabled us to control the vertical displacement under both wheels (Fig. 1a); (2) a homemade bicycle treadmill with a wooden dowel attached to the belt to generate impact on the wheels [18](Fig. 1b). In both cases, the bicycle is vertically maintained by bungee cables. These bungees are soft enough compare to the bicycle to not affect its dynamic but they are stiff enough to support the cyclist while he is sitting on the bicycle.

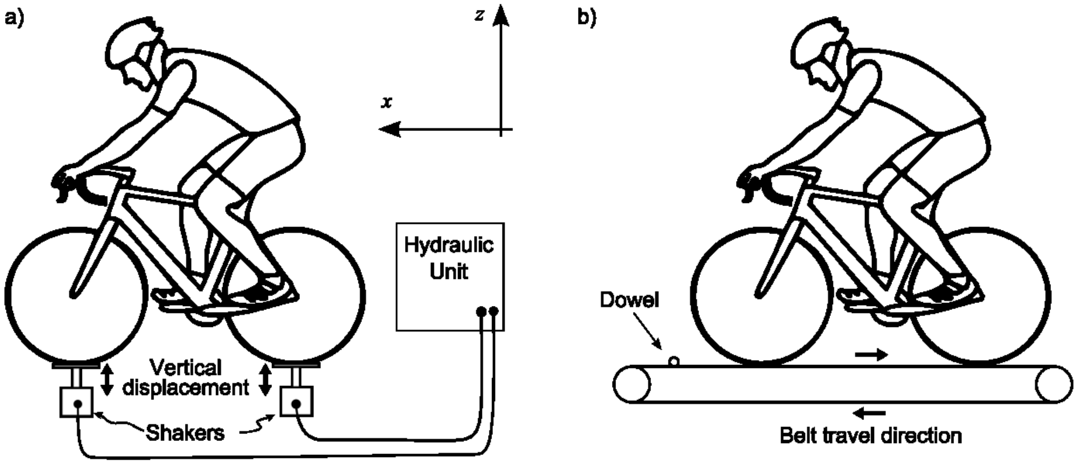

Fig. 1 Road-simulating apparatuses: (a) Road simulator equipped with two hydraulic shakers; (b) Bicycle treadmill with a wooden dowel attached to the belt

During each test, the cyclist's posture was controlled as follows:

- The cyclist took a “natural position” on the bike~~,~~ with their hands resting on (not grasping) the brake levers or the handlebar
- The cyclist applied and maintained a constant static vertical force at the hands. This force was monitored using an instrumented stem
- The bike cranks were fixed in a horizontal position with the left crank at the front
- The cyclist did not pedal and remained seated at all times

The complete testing bicycle specifications are given in Table 1. Wheel sets were selected according to the results of a previous study [22] where wheel set A was found to be the most force transmitting and wheel B, the least force transmitting wheel set. The selection of a large difference of force transmissibility between wheel sets ensured better ranking capability during the different tests conducted for this paper.

Table 1 Test bicycle configuration

Component	Description
Frame	Cervélo R3
Size	56 cm
Fork	Cervélo FK25
Headset	FSA IS3 Tapered – 6 mm TC
Seatpost	Instrumented by the authors
Rear Derailleur	None
Front Derailleur	None
Brake hood	Shimano 105
Brake Calipers	None
Bottom Bracket	FSA BBright
Crankset	Rotor 3DF BBright
Handlebar	3T Ergonova PRO
Stem	Instrumented by the authors
Saddle	Selle Italia Nitrox
Chain	None
Pedals	Avenir standard 9/16" x 20
Wheel set A	Fulcrum 7, Vittoria Rubino Pro 700x23C clincher tyres
Wheel set B	Zipp 202, Vittoria Corsa CX 21-28" tubular tyres

To assess the VIB, four measurands were considered: vertical acceleration (a_{VIB}) and vertical force (F_{VIB}) at the stem and at the seat post. At the stem (Fig. 2), both the acceleration and the force were measured at the stem-handlebar connection using a PCB 352C68 accelerometer and a strain gauge instrumented stem (Drouet and Champoux [13]). Stem a_{VIB} and F_{VIB} are the RMS value of the acceleration and the force signal was filtered with the 5349 ISO standard frequency-weighting curves for hands transmitted vibration [1]. Similarly, at the seat post, both the acceleration and the force were measured at the seat post-saddle connection using a PCB 352C65 accelerometer and a strain gauge instrumented seat post. Seat post a_{VIB} and F_{VIB} are the RMS value of the acceleration and the force signal were filtered with the 2631 ISO standard vertical frequency-weighting curves for whole body transmitted vibration [2]. Because ISO standard 2631 [2] indicates that the human perception of vibration at the feet is four times less than the perception of vibration at the buttocks and also because the authors' personal experience suggests that the VIB at the feet can, from a perception point of view, be neglected in contrast to vibration felt at the hands, no vibration measurement was made at the pedals in order to simplify the analysis.

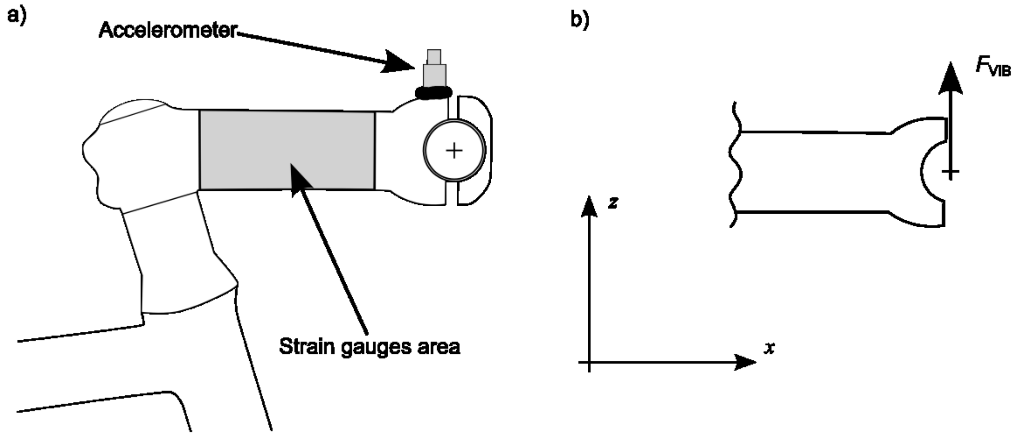

Fig. 2 Instrumented stem: (a) transducers position; (b) application position of the measured force

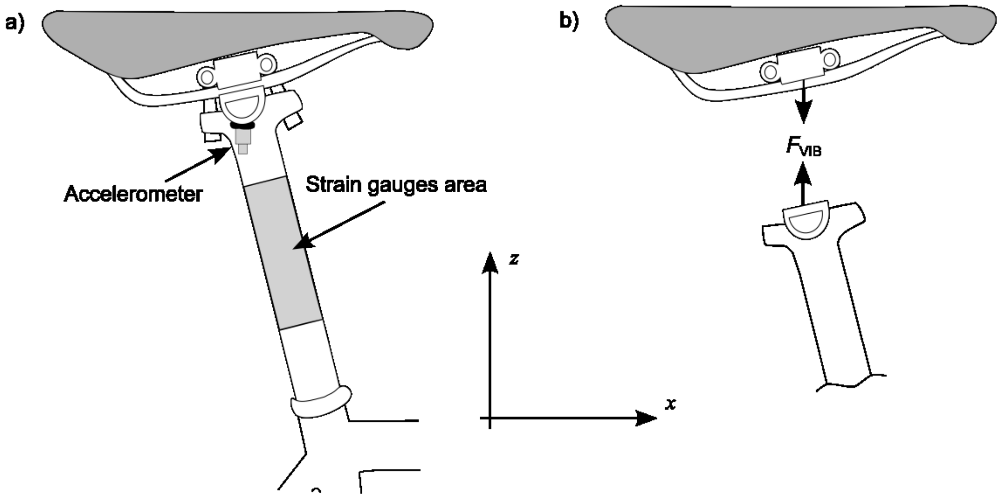

Fig. 3 Instrumented seat post: (a) transducers position; (b) application position of the measured force

b) Test conditions

A multitude of test conditions can affect VIB measurement. Based on past research [26], these conditions can be classified according to two main categories: (1) cyclist-related and (2) excitation-related conditions. In this study, four cyclist-related conditions (hand position, wrist angle, static stem force level, and the cyclist's mass) and one excitation-related condition (loading condition at the tyres) was been investigated and are described below.

Hand position

The three following common hand positions on the handlebar were considered (Fig. 5): (a) on the brake hoods with no contact between hands and handlebar; (b) in the drop on the lowest part of the handlebar; (c) on top. For these three positions, the cyclist's hand was resting on the handlebar without grasping it.

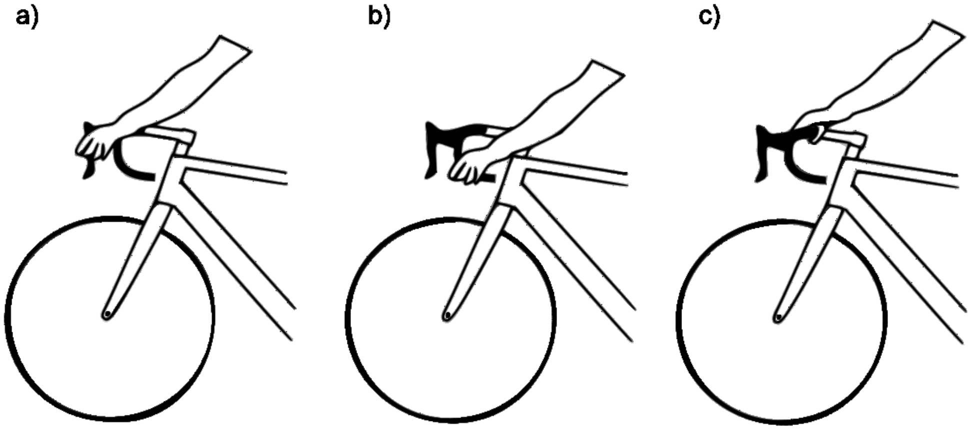

Fig. 5 Tested hand positions: (a) on the brake hood; (b) in the drop; (c) on top

Wrist angle

The two following common wrist angles were considered:

- Wrist angle 0°: position used by the majority of cyclists where the forearm is in line with the hand (Fig. 1a).

Wrist angle 60°: position used by cyclists with hypermobile wrists positioned at ≈ 60° in extension and ≈ 60° in ulnar deviation (Fig. 4).

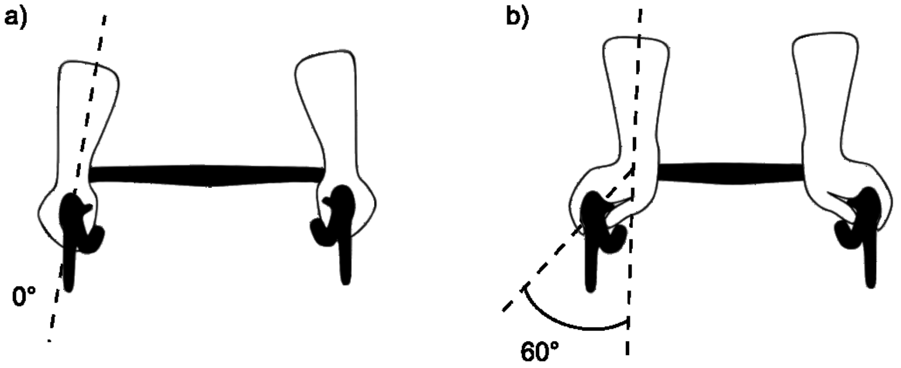

Fig. 4 Tested wrist angles: (a) 0°; (b) 60°

Static stem force level

With their hands resting on the handlebar, the cyclist applies a downward static force at the stem-handlebar connection. To evaluate the effect of this force on the VIB, three force levels were considered: (1) the nominal force level when the cyclist is adopting their natural position on the bicycle; (2) the nominal level minus 30 N; (3) the nominal level plus 30 N. During the tests, the cyclist was asked to maintain a given force level within a ±3 N range.

Cyclist's mass

To evaluate the effect of the cyclist's mass on the VIB, two cyclists of similar height but different masses were used as testers: cyclist #1: height = 1.82 m, mass = 70 kg; cyclist #2: height = 1.80 m, mass = 92 kg.

Loading condition at the tyres

A set of five load cases at the tyre were considered. These conditions were selected based on the authors' experience in the field [27] and are described in table 2. They mainly reflect (1) the typical road-induced excitation for road bicycle as encountered in the field and (2) the capabilities and characteristics of apparatuses usually used for assessing a bicycle's vibrational behaviour (vertically moving shakers and treadmill [18]).

The load cases are made of three excitation types (granular asphalt road [18], impact and random white noise) and two typical tyre deformation conditions (flat patch and local deformation). A random white noise excitation (0 to 100 Hz, RMS amplitude of 0.3 mm) was included in the load cases. This is an easily and widely available signal and therefore it presents an advantage for comparison studies by relieving the experimenter of the burden of measuring and replicating actual road excitation.

Table 2 Loading condition cases parameters

Load case	Excitation apparatus	Excitation type	Tyre contact condition
A	Hydraulic shakers	Granular asphalt road	Local deformation with 54 mm-diameter half dowel (Fig. 6a)[1]
B	Hydraulic shakers	Granular asphalt road	Flat patch (Fig. 6b)
C	Hydraulic shakers	Vertical impacts (z-axis) of 25 ms duration and 45 mm amplitude	Local deformation with 54 mm-diameter half dowel (Fig. 6a)[1]
D	Hydraulic shakers	Random white noise, 0 to 100 Hz, 0.3 mm of RMS amplitude	Flat patch (Fig. 6b)
E	Treadmill	Impacts created by a 16 mm diameter wooden dowel attached to the treadmill belt moving at 26 km/h. These impacts have both a vertical (*z*-axis) and horizontal (*x*-axis) components and are repeated every 0.7 s.	Local deformation/Flat patch[2]

Note 1: At all time, the tyres are solely in contact with the half dowel.

Note 2: At one point during the impact, the tyre loses contact entirely with the belt and is only touching with the dowel. This load case is performed in two phases: (1) only the front wheel is touching the belt during F_{VIB} and a_{VIB} measurement at the stem; (2) only the rear wheel is touching the belt during F_{VIB} and a_{VIB} measurement at the seat post.

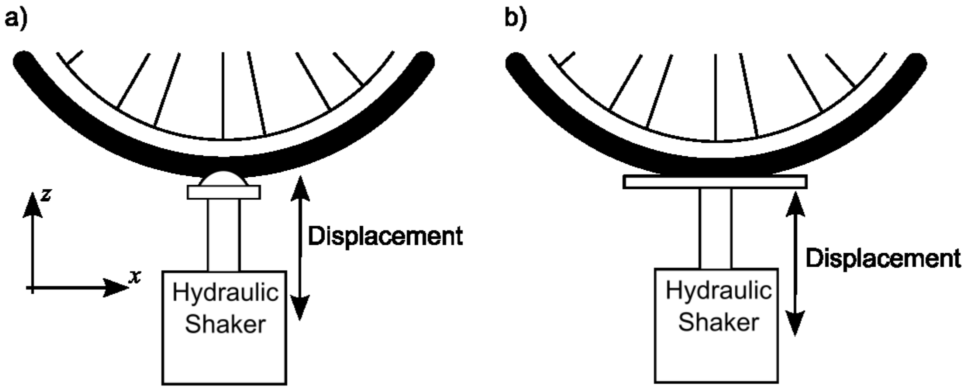

Fig. 6 Shaker contact surfaces: (a) Local deformation with 54 mm-diameter half dowel; (b) Flat patch

c) Statistical data analysis

In this study, the bicycle/cyclist system was considered as a stochastic system because of the random variation of the cyclist's dynamic behaviour. A statistical approach was therefore used to analyse the effect of test conditions on the VIB, as well as a on the wheel set ranking for VIB. For each of the 15 study cases presented in Table 3, force and acceleration measurements were repeated three times in a random order to increase the power of the statistic tests.

The effect of the test conditions on wheel set ranking are independently analysed using SPSW 17.0 (IBM) with an analysis of variance (ANOVA). The normality of the RMS value residues distribution was checked using a normal probability plot in order to ensure the validity of the ANOVA [26]. When the ANOVA revealed a significant effect of a set of test conditions, pairwise comparisons between the test conditions in this set were performed using the Bonferroni test [26]. We noted that even considering that the static stem force the cyclist applied at the stem during every test (the force signal average) was controlled within ± 3 N, variation nevertheless had an effect on the measurement. To dissociate the effect of this degree of variation from the effect of the test parameters, the static stem force was used as a covariate in the ANOVA [26].

Table 3 Study cases parameters combinations

Study case	**Hand position**	**Wrist angle (°)**	**Static stem force (nominal, N)**	**Cyclist**	**Load case (Table 2)**
1	Hood	0	190	2	A
2	Hood	60	190	2	A
3	Hood	0	160	2	B
4	Hood	0	220	2	B
5	Top	0	190	2	A
6	Drop	0	190	2	A
7	Hood	0	140	1	A
8	Hood	0	140	1	B
9	Hood	0	140	1	C
10	Hood	0	140	1	D
11	Hood	0	140	1	E
12	Hood	0	190	2	B
13	Hood	0	190	2	C
14	Hood	0	190	2	D
15	Hood	0	190	2	E

RESULTS

The results are displayed using four graphs in a 2x2 configuration representing the tests mean values of (a) a_{VIB} at the seat post (upper left graph); (b) a_{VIB} at the stem (upper right graph); (c) F_{VIB} at the seat post (lower left graph); (d) F_{VIB} at the stem (lower right graph). Test results are presented with a confidence interval of 95%. Test results for the hand position, wrist angle, static stem force and load case are presented in Fig. 7 and 8 respectively. The mean values of a_{VIB} and F_{VIB} of the study case replications are presented for wheel sets A (○) and B (*).

The ANOVA *p*-values (level of significance) related to the hand position, wrist angle and static stem force are presented in Table 4. Pairwise comparisons between hand positions effect on VIB are presented in Table 5. The ANOVA *p*-values related on wheel sets VIB comparison for each type of excitation are presented in Table 6. The general ANOVA *p*-value of wheel sets VIB comparison regardless of the excitation type (those parameters are taken as covariates) are presented for both cyclist in Table 7.

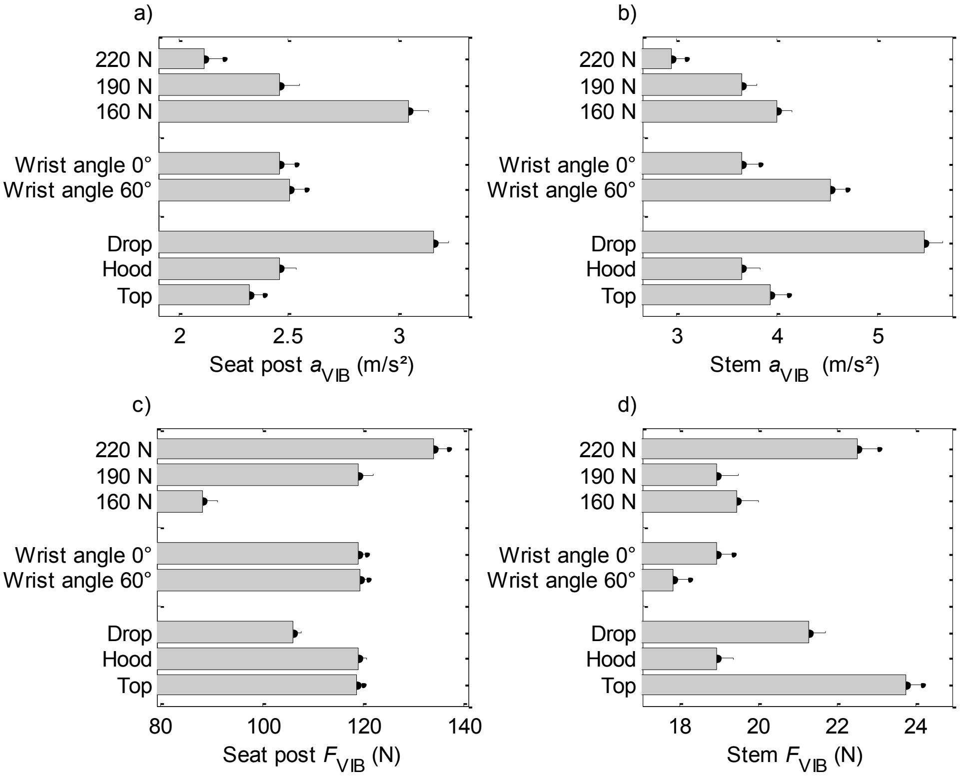

Fig. 7 Effect of the hand position, wrist angle and static stem force of cyclist #2 for VIB. Uncertainty bars correspond to high and low end values of 95 % confidence interval

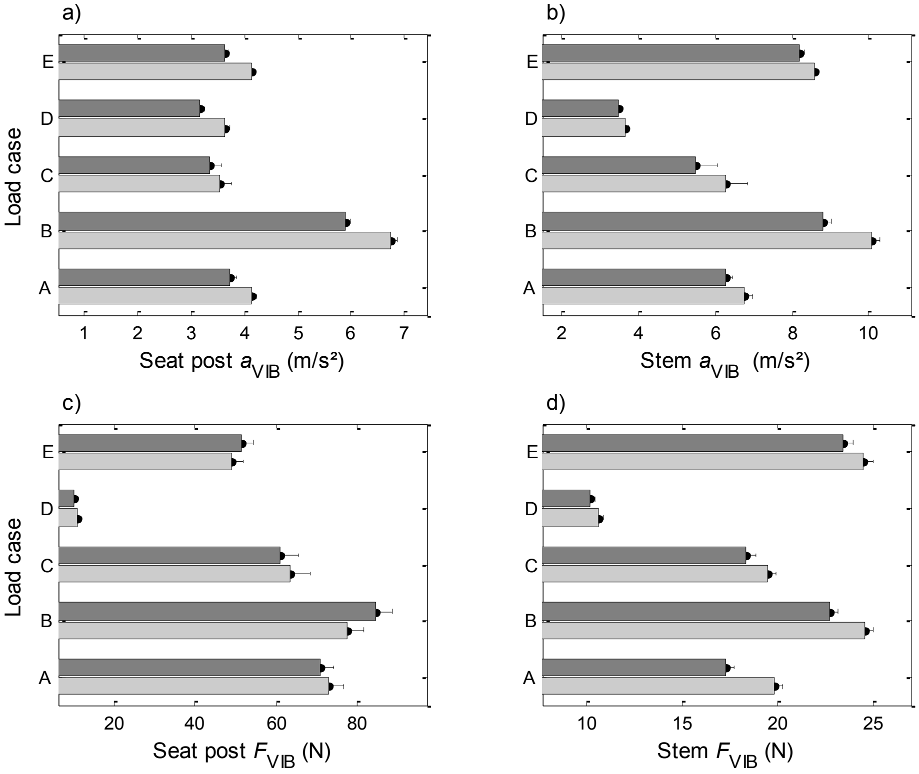

Fig. 8 Effect of the load case on discrimination between wheel set A (darker bars) and wheel set B (lighter bars) with cyclist #1. Uncertainty bars correspond to high and low end values of 95 % confidence interval

Table 4 ANOVA *p*-values related on cyclist #2 hand postion, wrist angle and static stem force effect on VIB

Measurand	Hand position	Wrist angle	Static stem force
a_{VIB} at the seat post	0.000	0.480	0.011
a_{VIB} at the stem	0.000	0.001	0.005
F_{VIB} at the seat post	0.000	0.820	0.002
F_{VIB} at the stem	0.000	0.013	0.030

Table 5 Hand positions of cyclist #2 *p*-value pairwise comparison adjusted with Bonferroni correction

Measurand		Hood	Drop
a_{VIB} at the seat post	**Top**	0.228	0.000
	Hood	-	0.000
a_{VIB} at the stem	**Top**	0.691	0.001
	Hood	-	0.000
F_{VIB} at the seat post	**Top**	1.000	0.000
	Hood	-	0.000
F_{VIB} at the stem	**Top**	0.000	0.011
	Hood	-	0.014

Table 6 ANOVA *p*-values related on wheel sets VIB comparison for each type of excitation with cyclist #1

Measurand	Load case A	Load case B	Load case C	Load case D	Load case E
a_{VIB} at the seat post	0.021	0.000	0.015	0.167	0.017[1]
a_{VIB} at the stem	0.084	0.001	0.191	0.056	0.093[2]
F_{VIB} at the seat post	0.318	0.248	0.288	0.762	0.414[1]
F_{VIB} at the stem	0.000	0.018	0.212	0.092	0.013[2]

Note 1: Impacts at the rear wheel only

Note 2: Impacts at the front wheel only

Table7 ANOVA *p*-values related on wheel sets VIB comparison on every test made with cyclist #1 and cyclist #2 considering the excitation types as covariates

Measurand	Cyclist #1	Cyclist #2
a_{VIB} at the seat post	0.000	0.243
a_{VIB} at the stem	0.002	0.022
F_{VIB} at the seat post	0.716	0.262
F_{VIB} at the stem	0.000	0.000

Hand position, wrist angle and static stem force test conditions analysis

The results show that the hand position, wrist angle and static stem force test conditions have a significant effect on the VIB. This is confirmed by the ANOVA (Table 4) where the *p*-values related to conditions are below the level of significance (0.05).

Fig. 7 suggests that the drop position has a significant effect on all four measurands and the top and hood positions effect is only significant on F_{VIB} at the stem. These conclusions are also seen on the pairwise comparison (Table 5) where the drop position has *p*-value below the 0.05 level of significance on both comparison and the hood position is only significant when it is compared with top position in F_{VIB} at the stem.

Fig. 7 suggests that the wrist angle has a significant effect on stem measurands (a_{VIB} and F_{VIB}) and not on the seat post measurands. This is clearly demonstrated by the ANOVA *p*-values (Table 4) that are only significant for the stem measurands.

As seen with the ANOVA *p*-value (Table 4) the static stem force has a significant effect on all four measurands. An noteworthy trend can be found on Fig. 7; when the static force at the stem increases, the a_{VIB} decrease and the F_{VIB} increase at the saddle and the stem.

Wheel sets transmissibility ranking analysis

Although Fig. 8a, b and d suggest that it is possible to establish a transmissibility ranking of wheel sets and that the value of the three measurands are higher for wheel set A than for wheel set B for every load case, it is not significantly so for all of them based on the *p*-values in Table 6. For a significance level of 5 % the following conclusions can be drawn:

- Load case B significantly distinguishes wheel set A and B based on a_{VIB} at the seat post and the stem, and based on F_{VIB} at the stem.
- Load cases A and E significantly distinguish wheel sets A and B based on a_{VIB} at the seat post and, based on F_{VIB} at the stem.
- Load cases C and D only significantly distinguish wheel sets A and B based on a_{VIB} at the seat post.

Fig. 8c shows that no significant difference between wheel sets A and B can be established using F_{VIB} at the seat post.

Even though the results presented in Fig. 8 and Table 6 were obtained for cyclist #1, wheel set comparisons for cyclist #2 were also carried out. For both cyclists, wheel set A had a higher level of VIB than wheel set B. ANOVA performed for each cyclist including every type of excitation as covariate showed almost the same p-value for both cyclists (Table 7) with the exception that cyclist #1 had a lower a_{VIB} significance level at the seat post.

DISCUSSION

Results show that all the test conditions considered in this paper had a significant effect on at least one of the four measurands. They showed that the loading condition at the tyres did not affect the transmissibility ranking of the two wheel sets used in terms of force and acceleration at the stem and at the seatpost.

Results also suggest that to properly assess the VIB by a road bicycle and to achieve valid and repeatable wheel set transmissibility ranking, precautions should to be taken during force and acceleration measurements as test conditions remain either unchanged (load condition, cyclist's mass, hand position) or tightly controlled (wrist angle and static stem force).

If, for example, these precautions are not respected and test conditions are changed during wheel set ranking assessment tests, the ranking can be biased. To illustrate this, we established a test where cyclist #2 was asked to use (1) hood hand position, 0° of wrist angle and a static stem force of 160 N for wheel sets A measurements and (2) hood hand position, 60° of wrist angle and a static stem force of 220 N for wheel sets B measurements. All measurements were performed using load case B. The results (Fig. 9) showed that, by intentionally changing the wrist angle and static stem force during the tests, wheel set transmissibility ranking in terms of acceleration at the stem and seat post was inverted. Wheel set A now transmits less acceleration at the stem and seat post than wheel set B with respectively 0.079 and 0.022 of significance (p-value) which is opposed to the ranking established with constant test conditions.

Fig. 9 Biased wheel sets comparison where cyclist #2 has 0° of wrist angle and a static stem force of 160 N for wheel sets A (○) and 60° of wrist angle and a static stem force of 220 N for wheel sets B (*)

When considering the stochastic nature of the bicycle/cyclist system, the authors stress the fact that it is imperative to assess VIB using a statistical approach. No conclusions should be drawn based on single force or acceleration measurements due to measurement uncertainties. Repeated force and acceleration measurements and the use of ANOVA are therefore strongly recommended.

CONCLUSION

The aim of this study was to investigate the effect of cyclist-related and excitation-related test conditions on the measurement of VIB by a road bicycle as well as on the ranking of two wheel sets in terms of VIB.

A total of five test conditions were selected and their effects investigated in terms of transmitted force and acceleration at the seat post and stem. Our results showed that all of the test conditions had a significant effect on at least one measurand. Though the test conditions had a significant effect on the VIB, they did not affect the transmissibility ranking for the two wheel sets used in the study.

In consideration of our findings comparing the vibrational behaviour of the bicycle/cyclist system, bicycle transmissibility and ride comfort, in order to get repeatable measurements of load and acceleration at the cyclist's contact points with the bicycle, it is vital to be well aware of the importance of the test conditions and acting accordingly to control them as best possible. Without this knowledge in hand, experimenters could easily come to an incorrect conclusion.

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