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ORIGINAL PAPER

The relative contribution of road bicycle components on vibration induced to the cyclist

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Abstract Improving comfort in road bicycle design is a paramount concern for cyclists, who are affected by the vibrations caused by constant contact with the road surface. The cycling community has deployed many efforts in the attempt to understand and improve bicycle comfort. However, these attempts have been focused on specific components such as the fork, frame and wheels without knowing their relative influence on vibration induced to the bicyclist (VIB). The objective of this paper is to assess the relative contribution of bicycle components on the VIB at the cyclist's hands and buttocks. A factorial design test comparing the VIB in acceleration, force and power of different bicycle components has already shown that the handlebar and fork are the preponderant components for the VIB measured at the cyclist's hands. At the buttocks, the preponderant components are the wheels and frame.

Keywords Bicycle dynamic comfort · Bicycle testing · Factorial design · Vibration measurement

1 Introduction

Road cycling is a sport in which equipment design has a major impact on the cyclist's overall performance and experience. As this sport has progressed over the years, most of improvements in bicycle design have been focused on reducing the bicycle's mass and aerodynamic drag, and on increasing stiffness. More recently however, the ride quality of road bicycles has become a more desirable characteristic for users as well as an important design issue for bicycle manufacturers. Once the cyclist is properly positioned (fitted) on the bicycle, one of the important elements contributing to the ride quality is related to the level of vibration transmitted from the road to the cyclist via the various components of the bike.

In the process of increasing the quality of the ride and improving cyclist comfort, the assessment of the vibrations induced to the bicyclist (VIB) is an essential step and an active research topic in sports engineering. However, we should keep in mind that the study of VIB does not include any human perception. The comfort assessment based on VIB assumes that less VIB cannot increase discomfort. Therefore, the VIB measurement is only a convenient method to objectively quantify comfort in an engineering point of view since comfort itself is subjective. Many researchers accept this shortcoming of VIB and use them in their studies. These studies are divided into three parts: (1) developing force transducers, (2) developing excitation techniques, and (3) investigating the characteristics of a bicycle that reduces the VIB.

An important part of research on VIB is the development of bicycle force transducers such as instrumented pedals, stems and seat posts. These transducers measure loads at the contact interface between the cyclist and the bicycle [1–6]. They also enable us to assess a metric to quantify VIB with the ultimate goal of reducing it. Richard et al. [7] used force and energy transmitted to the cyclist measured by an instrumented stem to investigate comfort. Vanwallenghem et al. [8] also used an instrumented handlebar and seat post to measure the absorbed power as a metric for cyclist comfort.

Embedded force transducers and accelerometers have been incorporated on instrumented bicycles to measure

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VIB with different excitation techniques. The most common excitation technique for a bicycle is to ride on a road [8–13]. The VIB has also been measured using different excitation techniques in the controlled environment of the laboratory. Hastings et al. [14] compared the VIB among three bicycle frames mounted by a cyclist on a treadmill. Thite et al. [15] compared the VIB between two different mountain bike frames and a dummy cyclist excited by a shaker. Lépine et al. [16] developed a test rig that mimics the road excitation in a laboratory to compare the VIB between different bicycles. Bicycle component vibration transmissibilities were also compared using an incomplete bicycle assembly. For example, wheel transmissibility was studied via different test rigs; one developed by Petrone et al. [17] and the other developed by Lépine et al. [18].

Force transducers and excitation techniques allowed some research on the bicycle's characteristics that could reduce VIB. The fork and frame structural damping effect on bicycle vibrational behavior and VIB were studied [15, 19, 20]. The modal proprieties and mode shapes of bicycles were also studied to provide a better understanding of bicycle dynamic response to improve comfort [21, 22]. The relationship between VIB and wheel set characteristics such as tire pressure, number of spokes, rim material, radial stiffness, etc. has also been studied and discussed in the literature [10, 11, 17, 18, 23].

Several attempts have thus been made to understand the effect of a bicycle's characteristics on vibrational behavior and to ultimately increase cyclist comfort. However, these studies have been focused on specific components such as the fork, frame and wheels without knowing their relative influence on VIB on a fully assembled bicycle. The objective of this paper is to assess the relative contribution of bicycle components on the VIB at the cyclist's hands and buttocks. This will draw the cycling community's attention to the VIB preponderant components during the selection and assembly of components to design more comfortable bicycles.

2 Methodology

The relative contribution of road bicycle components on VIB was determined via a factorial design experiment. This factorial design investigated the effect of all possible combinations of the factor levels on the VIB. In this case, the factors represented the bicycle component categories and were separated into two levels: the lowest (−) and the highest (+) vibration transmitting component. In other words, the bicycle assembly was divided into 5 factors (bicycle component categories): wheels, fork, frame, stem and handlebar. As well, each factor had two different levels (component selection): the components with the lowest (−) and the highest (+) VIB level. The seat post and the brake hood were used as transducers; consequently they were not included in these factors. The method used to measure and compare VIBs between component categories is presented in part (a) of this paper. Part (b) presents how the factor levels were selected to finally perform the factorial design experiments used to quantify the relative contribution of road bicycle component categories on the VIB detailed in part (c).

2.1 VIB measurement method

In this paper, VIBs were measured on a bicycle in the controlled environment of the laboratory. The bicycle was vertically excited by a road simulator composed of two hydraulic shakers positioned under the wheels (Fig. 1). The wheels were not attached: they simply rested on the shakers' heads. These shakers reproduced a 30 s excitation simulation of a bicycle at 26 km/h on a granular road as described by Lépine et al. [16]. This time replication accurately reproduced the specific spectrum and stochastic nature of road vibration including its non-stationary and transient events. The RMS acceleration at each shaker head was 13 m/s^2. The downward acceleration of the shakers was not enough to cause a loss of contact between the wheels and the shakers.

A cyclist was seated on the bicycle during measurements. The bicycle and the cyclist were kept vertically stable with bungee cables wrapped around the seat tube and attached to a fixed structure on each side of the bicycle. These bungee cables were horizontally positioned to be compliant enough in the vertical direction to make sure they did not affect the bicycle's dynamics in that direction, and were able to hold the cyclist and the bike in a vertical position. Therefore, the bicycle was not constrained in any direction (relative to small movements).

The cyclist's position was controlled by the static force applied by the hands on the handlebar. The hands were resting (not grasping) on the brake hoods and the pedals

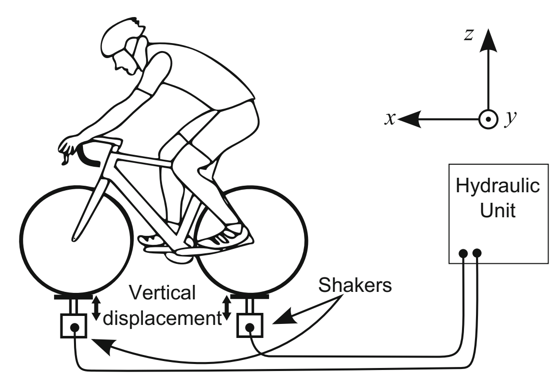

Fig. 1 Bicycle excitation setup: the road simulator

were set at a fixed horizontal position (no pedaling movement). The same cyclist was used for all tests. The cyclist weighed 70 kg and was 1.82 m tall. Previous studies show that the results from this cyclist can be applicable to cyclists of different weights and heights [24]. The method used to measure VIB has been approved by the ethics committee of Université de Sherbrooke.

The VIBs were measured at three different cyclist contact points on the bicycle depending on the test performed: (1) the vertical force and acceleration transmitted via the saddle and to the cyclist's buttocks were measured with a strain gage instrumented seat post and a PCB 352C65 accelerometer (Fig. 2); (2) the force and the acceleration transmitted via the handlebars to the cyclist's hands were measured with a strain gage instrumented stem and a PCB 352C68 accelerometer (Fig. 3); (3) the force and the acceleration transmitted to the cyclist's hands were measured with a strain gage instrumented brake hood and a PCB 352C68 accelerometer under the hands (Fig. 4).

Using instrumented bicycle components, three measurands were used to quantify the level of VIB: (1) the acceleration a_{VIB}, (2) the force F_{VIB} and (3) the absorbed power P_{VIB}. Seat post a_{VIB} and F_{VIB} were calculated using the RMS value of the transducer signal filtered with the 2631 ISO standard vertical frequency-weighting curves for whole body transmitted vibrations [25]. The stem and brake hoods a_{VIB} and F_{VIB} were calculated using the RMS value of the transducer signal filtered with the 5349 ISO standard frequency-weighting curves for hand transmitted vibrations [26]. The average power absorbed by the cyclist P_{VIB} was calculated at all contact points with the combination of the force $F(t)$ and velocity $v(t)$ for the test duration T, as

$$P_{\text{VIB}} = \frac{1}{T}\int_{0}^{T} F(t)v(t)dt \tag{1}$$

The velocity was calculated from the integration of the accelerometer time signal. Any trend in the acceleration was removed to avoid integration error. The phase between the force and the acceleration signals was also calibrated to avoid any phase mismatch error.

2.2 Factor levels selection

To define the levels of each factor (bicycle component category) used in the factorial design, the VIB level of several components available on the market were compared and ranked. The ranking was done by swapping the component on the same bicycle and measuring the VIB variation in acceleration, force and power. The component with the highest VIB level will be the (+) in its respective category (factor) and vice versa. The list of components and the characteristics of each factor are presented in Tables 1, 2, 3, 4, 5. The dimensions of the components were selected to keep the cyclist's position as constant as possible.

The wheel set transmission ranking was done by comparing the VIB variation between different front wheels (Table 1). Identical clincher or tubular tires were installed on the rim, i.e. Vittoria Rubino Pro Slick 700 × 23c with Vittoria inner tube for the clincher tire and Vittoria Corsa CX 21–28′ for the tubular tire. The type of tires on the wheel sets (clincher or tubular) in the factor level selection was not important because the goal was to select the lowest and highest transmitting wheel sets regardless of the tire type. Therefore, the difference in transmissibility between tire types assumed by many was included in this factorial design, but it was not studied directly. The width was the axial length of the rim and the depth was the radial length of the rim. The total mass included the wheel and the tire but not the skewer.

The Fulcrum 7 rear wheel was installed on the bicycle frame during every comparison. Each wheel was tested 5 times in a random order. The VIBs were measured in force, acceleration and power at the brake hoods for wheel rankings. The same cyclist, frame, fork, stem and

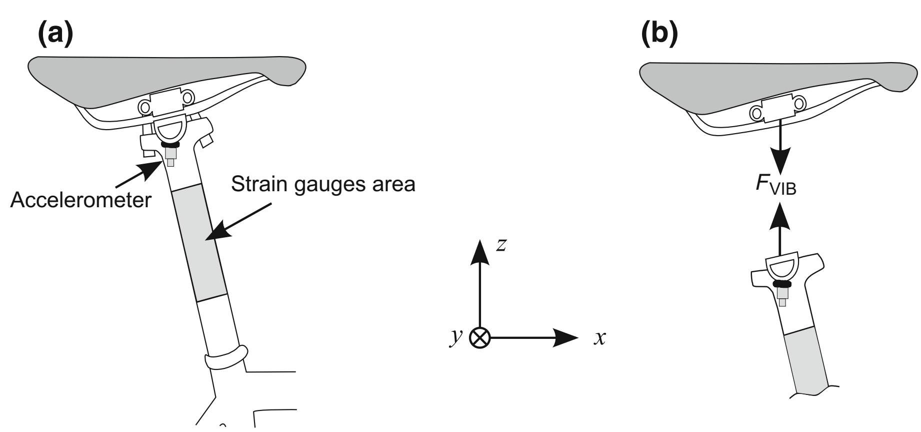

Fig. 2 Instrumented seat post **a** transducer position; **b** applied position of the measured force

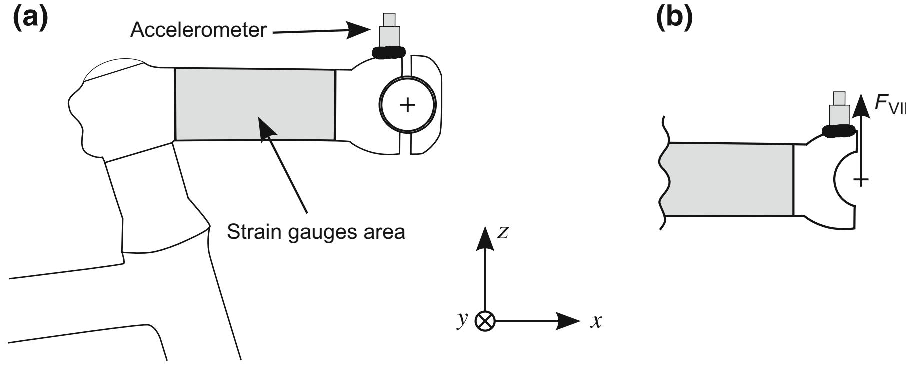

Fig. 3 Instrumented stem **a** transducer position; **b** applied position of the measured force

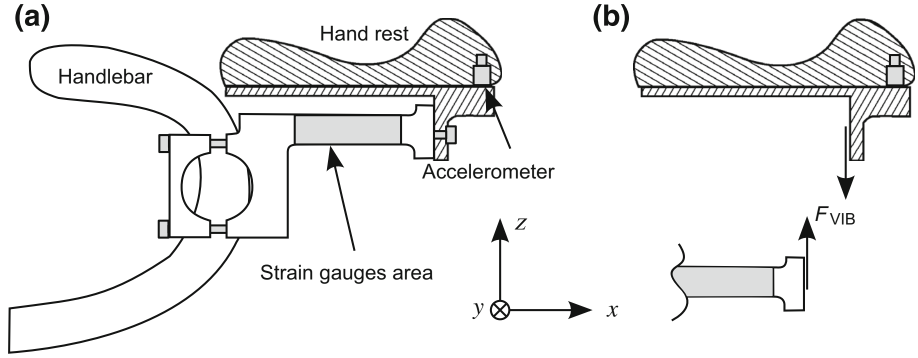

Fig. 4 Instrumented brake hood **a** transducer position; **b** applied position of the measured force

Table 1 Components tested for the wheel factor

Name	Tire type	Number of spokes	Spoke pattern	Spoke material	Rim material	Rim width (mm)	Rim depth (mm)	Total mass (g)
Fulcrum 7	Clincher	20	Radial	Steel	Aluminum	21.0	25.5	1,160
Kinlin XR-200	Clincher	20	Radial	Steel	Aluminum	18.5	23.0	900
Campagnolo NeutronUltra	Clincher	22	Radial	Steel	Aluminum	20.9	19.0	990
Lightweight	Tubular	16	Radial	Carbon	Carbon	20.2	53.0	780
Campagnolo Victory Strada	Tubular	32	Cross	Steel	Aluminum	19.9	11.0	910
Zipp 404 Firecrest	Tubular	16	Radial	Steel	Carbon	24.0	58.0	850
Zipp 202	Tubular	20	Cross	Steel	Carbon	21.5	25.0	810

handlebar were used for all tests. The tire pressure was set at 8 bars.

Only the front wheels were compared due to wheel set availability i.e. more front wheels than rear wheels were available for testing. To compare a larger wheel sample, only the front wheels were included in the selection. Nevertheless, the factorial design includes both the front and the rear wheels as one factor. The hypothesis was that the front and rear wheel dynamics are similar. The preload difference between the front and the rear wheel due to the cyclist's weight distribution on the bike does not have a significant effect on dynamic behavior [18]. Therefore, the lowest or highest transmitting front wheel should also be the lowest or highest transmitting rear wheel.

The fork transmission ranking was done by comparing the VIB variation at the brake hoods between different forks (Table 2). Each fork was tested 6 times in a random order. The same cyclist, frame, wheel set, stem and handlebar were used for all tests. The tire pressure was set at 8 bars.

The frame transmission ranking was obtained by comparing the VIB variation at the brake hoods and the seat

Table 2 Components tested for the fork factor

Name	Steering column material	Blades and crown material	Total mass (g)
Easton EC90SL	Carbon	Carbon	360
Cervélo FK30 SL	Carbon	Carbon	340
Cervélo TT Wolf	Aluminum	Carbon/ Aluminum	600
Look HSC 5 SL	Carbon	Carbon	320
Specialized Roubaix FACT	Carbon	Carbon	414

Table 3 Components tested for the frame factor

Name	Material	Size	Top tube length (cm)	Total mass (g)
Masi Gran Criterium	Steel	56	56.5	2,240
Focus Culebro	Aluminum	XL	56.0	1,920
Merlin Agilis	Titan	M	55.5	1,540
Specialized Comp Roubaix	Carbon	L	56.5	1,340
Cervelo R3	Carbon	56	56.4	1,070
Cervelo R5ca	Carbon	56	56.4	800

Table 4 Components tested for the stem factor

Name	Material	Length (mm)	Total mass (g)
3T ARX-PRO	Aluminum	110	132
3T ARX-LTD	Carbon	110	126
FSA OS-99 CSI	Aluminum wrapped with Carbon	110	141

Table 5 Components tested for the handlebar factor

Name	Material	Width (cm)	Total mass (g)
3T Ergonova Pro	Aluminum	44	260
FSA K-Wing	Carbon	44	240
3T 4GXL	Aluminum	44	290
3T THE	Aluminum	44	340
3T Ergonova LTD	Carbon	44	190

post using different frames (Table 3). The frame size was the size given by the frame manufacturer. The top tube length was the horizontal distance between the head tube and top tube junction to the seat tube (or its prolongation). The total mass included the bottom bracket and the seat post clamp. Each frame was tested 7 times in a random order. The VIBs were measured in force, acceleration and power at the stem and the seat post. The same cyclist, fork, wheel set, stem and handlebar were used for all tests. The tire pressure was set at 8 bars.

The stem transmission ranking was done by comparing the VIB variation at the brake hoods using different stems (Table 4). The stem length was the distance between the center of the fork and the handlebar attachment. The same stem length was tested to ensure that the cyclist's position does not change during the comparison. Therefore, the length effect was not assessed in this study. The total mass included all the stem's screws. Each stem was tested 6 times in a random order. The same cyclist, frame, fork, wheel set and handlebars were used for all tests. The tire pressure was set at 8 bars.

The handlebar transmission ranking was done by comparing the VIB variation at the brake hoods between different handlebars (Table 5). The width was the overall dimension of the handlebar. Every handlebar was tested 5 times in a random order. The same cyclist, frame, fork, wheel set and stem were used during these tests. The tire pressure was set at 8 bars.

2.3 Factorial design plan

Once the (−) and (+) levels of each factor (bicycle component) were defined, the factorial design was conducted. To assess the relative contribution of the bicycle components, the VIB level for each factor combination was measured. A sample combination is: wheels (−) with the fork (−), frame (+) and handlebar (−). Even though five factors were considered in the selection, only four were included in the factorial design: wheels, fork, frame and handlebar. The stem is excluded from the factorial design because no significant difference was measured between the tested stems. This exclusion is explained in the factor selection results and analysis (presented in Sect. 3a–b).

The factorial design used was a 2^4 factorial performed in 4 blocks (measurement session) with 2 replicates completely randomized for a total of 32 combinations (Table 6). The experiment design was made of blocks of 8 combinations to ensure that testing was performed in a relatively short time frame (about 2 h including assembly and disassembly). Dividing up the test in this way minimizes the tester's level of fatigue, as well as any natural variations in dynamic behavior and other time-dependent phenomena that could alter the measurements.

Two techniques were used to increase the degree of freedom of the analysis and therefore increase the statistical power: the combinations were replicated twice and only the effect of the main factor and two-factor interactions were included in the analysis [27].

Table 6 2^4 factorial design in 4 blocks and 2 replicates combination matrix used to assess the relative contribution of bicycle components on VIB

Run order	Block 1				Block 2			
	Wheels	Fork	Frame	Handlebar	Wheels	Fork	Frame	Handlebar
Replicate 1								
1	(−)	(−)	(+)	(−)	(−)	(+)	(−)	(+)
2	(+)	(−)	(+)	(+)	(+)	(+)	(+)	(+)
3	(+)	(−)	(−)	(−)	(+)	(−)	(+)	(−)
4	(−)	(+)	(+)	(+)	(+)	(+)	(−)	(−)
5	(+)	(+)	(−)	(+)	(−)	(−)	(−)	(−)
6	(+)	(+)	(+)	(-)	(+)	(−)	(−)	(+)
7	(−)	(+)	(−)	(−)	(−)	(−)	(+)	(+)
8	(−)	(−)	(−)	(+)	(−)	(+)	(+)	(−)
Replicate 2								
9	(−)	(−)	(+)	(−)	(+)	(+)	(+)	(+)
10	(+)	(+)	(−)	(+)	(−)	(−)	(−)	(−)
11	(−)	(−)	(−)	(+)	(+)	(+)	(−)	(−)
12	(+)	(−)	(−)	(−)	(+)	(−)	(−)	(+)
13	(+)	(+)	(+)	(−)	(−)	(+)	(+)	(−)
14	(+)	(−)	(+)	(+)	(+)	(−)	(+)	(−)
15	(−)	(+)	(+)	(+)	(−)	(−)	(+)	(+)
16	(−)	(+)	(−)	(−)	(−)	(+)	(−)	(+)

3 Results and analysis

The experimental results are separated in two parts. Part (a) presents the results from the factor level selection tests and these results are analysed in part (b). Part (c) presents the results of the factorial design based on the factor level selection made in part (b). The factorial design results are analysed in Part (d).

3.1 Factor levels selection results

The significant levels (p value) of the three measurands were calculated by means of an ANOVA (analysis of variance) at the measurement points for each factor levels selection test (Table 7). When the p value was below 0.05, a significant difference of VIB between the bicycle's components tested was concluded.

The ranking of the wheels, the fork, the stem and the handlebar was similar for both the left and right brake hoods, so to be concise, the result of only one brake hood is presented here. The VIB comparison between the front wheels at the brake hoods shows a significant difference for P_{VIB} (Fig. 5). The VIB comparison between the forks at the brake hoods shows a significant difference for F_{VIB} and P_{VIB} at the left brake hood (Fig. 6) but at the right brake hood, the difference is significant only for P_{VIB}. The VIB comparison between the frames at the stem and seat post shows a significant difference for all three measurands at both measurement points (Figs. 7, 8). The stem VIB comparison does not show any significant difference at either brake hoods for all measurands (Fig. 9). The VIB comparison between the handlebars made at the right and

Table 7 p value of the factor levels selection tests

Factor	Measurement point	p value for a_{VIB}	p value for F_{VIB}	p value for P_{VIB}
Wheel	Left brake hood	0.164	0.115	0.000
	Right brake hood	0.208	0.084	0.000
Fork	Left brake hood	0.280	0.017	0.000
	Right brake hood	0.201	0.263	0.000
Frames	Stem	0.000	0.007	0.000
	Seat post	0.000	0.016	0.003
Stem	Left brake hood	0.967	0.644	0.282
	Right brake hood	0.611	0.402	0.298
Handlebar	Left brake hood	0.115	0.001	0.000
	Right brake hood	0.038	0.000	0.000

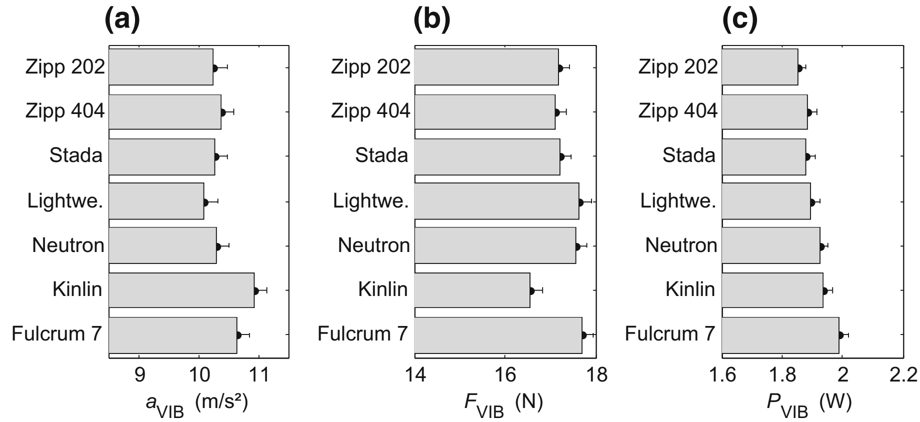

Fig. 5 Wheel VIB measurements at the right brake hood, uncertainty bars are at a confidence level of 95 %

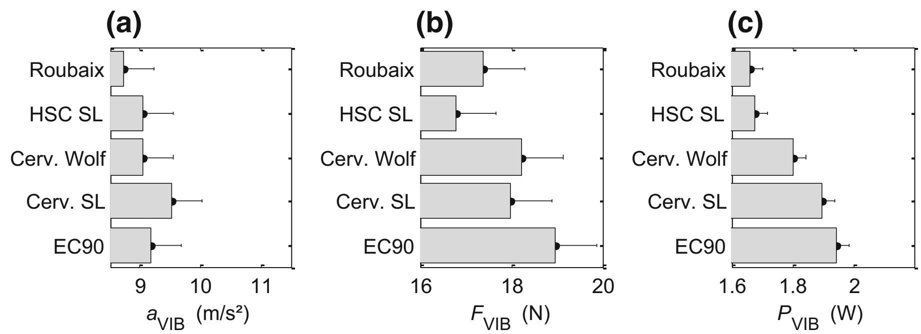

Fig. 6 Forks VIB measurements at the left brake hood, uncertainty bars are at a confidence level of 95 %

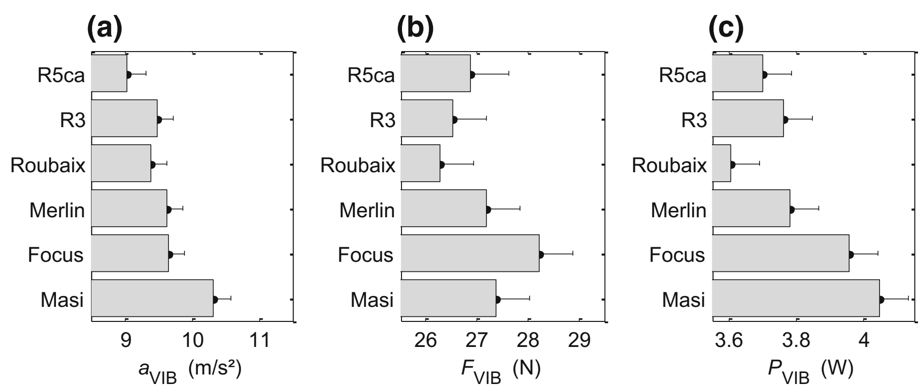

Fig. 7 Frames VIB measurements at the stem, uncertainty bars are at a confidence level of 95 %

the left brake hood shows a significant difference for all three measurands at the brake hoods except for a_{VIB} measured at the left brake hood (Fig. 10).

3.2 Factor levels selection analysis

The objective of this section was to select the lowest and highest transmitting component for each factor. These selected components will be respectively, the (−) and (+) level. The selection is summarized in Table 8. The wheel level selection was based on P_{VIB} values because it is the only measurand that has a significant impact on both measurement points (Table 7). The lowest transmitting wheel is the Zipp 202 and the highest is the Fulcrum 7 (Fig. 5c). Like the wheel selection, the fork level selection was based on absorbed power P_{VIB} values because it is the only measurand that has a significant impact on both measurement points (Table 8). The lowest transmitting fork is the Specialized Roubaix Fact and the highest transmitting fork is the Easton EC90SL (Fig. 6c).

The frame level selection was based on all three measurands and both measurement points because they all present significant differences (Table 7). As seen on Figs. 7 and 8, the Cervélo R5ca is the lowest transmitting frame at 4 measurands out of a total of 6 and the Masi Gran Criterium is the highest transmitting frame at 4 measurands

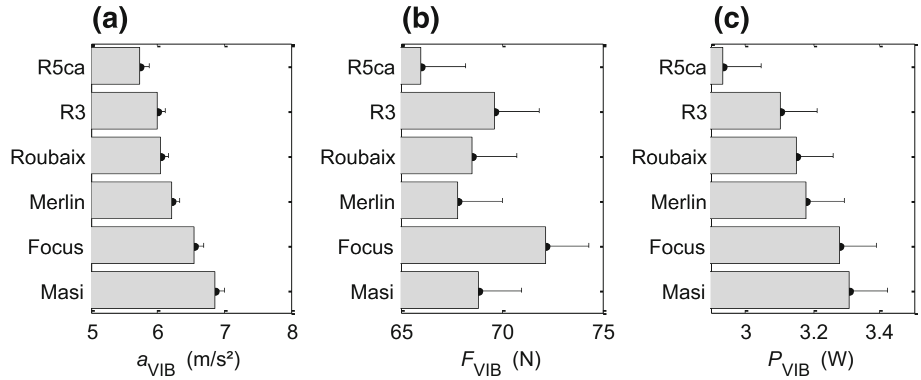

Fig. 8 Frame VIB measurements at the seat post, uncertainty bars are at a confidence level of 95 %

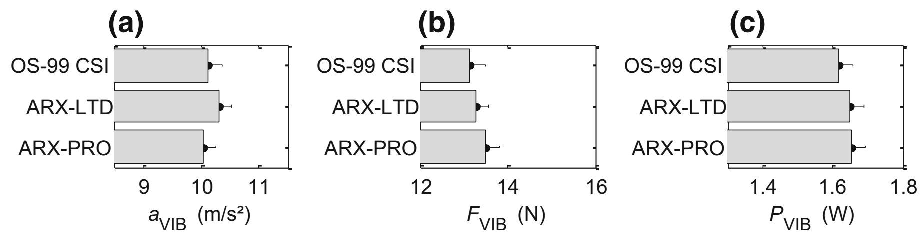

Fig. 9 Stem VIB measurement at the right brake hood, uncertainty bars are at a confidence level of 95 %

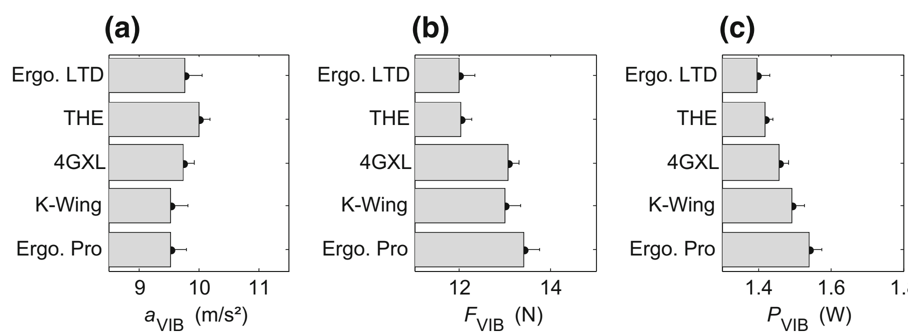

Fig. 10 Handlebar VIB measurements at the right brake hood, uncertainty bars are at a confidence level of 95 %

Table 8 Factors level selection

Factor	(–) level	(+) level
Wheels	Zipp 202	Fulcrum 7
Forks	Specialized roubaix fact	Easton EC90SL
Frame	Cervélo R5ca	Masi gran criterium
Stem	Excluded from the factorial analysis	
Handlebar	3T Ergonova LTD	3T Ergonova PRO

out of a total of 6. These frames are therefore, the (−) and (+) level for the frame factor.

The stem factor was excluded from the factorial design because no significant difference in VIB can be made between the tested stems (Table 7). Therefore, no level could be selected and it is very unlikely the stem factor makes a major contribution to the VIB since no difference was measured between the stems tested.

The handlebar level selection was based on the measurands presenting a significant difference on both measurement points, i.e. a_{VIB}, F_{VIB} and P_{VIB} at the right brake hood and F_{VIB} and P_{VIB} at the left brake hood (Table 7). The 3T Ergonova LTD and the 3T Ergonova Pro are respectively, the lowest and highest transmitting handlebars except for the a_{VIB} at the right brake hood. They will be respectively, the (−) and (+) level for the handlebar factor.

The power absorbed by the cyclist (P_{VIB}) seems to be the most consistent measurand because it allows the lower *p* value in the factor levels selection (Table 7). It is also the only measurand that presents the same result at the left and right brake hoods in the factorial design.

3.3 Factorial design results

The standardized effect of each factor (bicycle component) and component interaction (expressed by the symbol "/")

are represented with Pareto charts for each measurand. In these charts it is also possible to assess the VIB variation percentage explained by the sum of the more influential components and their interaction. Discrepancies between the effect of the factors' ranking at the left and right brake hoods are explained by the asymmetric dynamic behavior of the cyclist. These discrepancies are mainly seen on factors with a lower effect on the VIB.

With regard to the a_{VIB} at both brake hoods, the 2 most influential factors are the same, i.e. the fork and wheels (Fig. 11). At the left brake hood, all the components and interactions have a significant effect on a_{VIB} accepted for the handlebars, wheels/fork and wheels/handlebar interactions; and the effects of the first 6 factors and interactions (from fork to fork/handlebar, Table 9) account for 82 % of the a_{VIB} variation measured. At the right brake hood the results are slightly different: in addition to the fork and wheels, only the wheel/fork interaction and the handlebar have a significant effect on a_{VIB} and these 4 factors and interaction effects (Table 9) account for 66 % of the a_{VIB} variation.

With regard to the F_{VIB} at the brake hoods, the handlebars and fork are the 2 factors with the greatest influence (Fig. 12). All factors have a significant effect on F_{VIB}, whereas the interactions do not, except for two: the wheels/fork interaction at the left brake hood and the fork/frame interaction at the right brake hood both have an effect on the F_{VIB}. The effects of the first 4 factors and interaction (Table 9) account for 80 % of the F_{VIB} variation measured at both brake hoods, and the effects of the first 5 factors and interactions (Table 9) account for 82 % of the F_{VIB} variation.

With regard to the P_{VIB} at the brake hoods, the handlebars and fork are also the 2 most influential factors (Fig. 13). At the left brake hood, only the handlebar interactions (fork/handlebar, wheels/handlebar and frame/handlebar) do not have a significant effect on P_{VIB} and the effects of first 5 factors and interaction (Table 9) explain 83 % of the P_{VIB} variation measured at the left brake hood. At the right brake hood, the wheels/fork, frame/handlebar and fork/handlebar interactions do not significantly affect the P_{VIB}; and the first 4 factors (Table 9) account for 81 % of the P_{VIB} variation measured at the right brake hood.

With regard to the a_{VIB} at the seat post, the wheels and frame are the 2 factors with the greatest influence (Fig. 14). In addition to these factors, only the wheels/frame and fork/frame interactions have a significant effect on a_{VIB} and the effects of the 3 first factors and interactions (Table 9) account for 87 % of the a_{VIB} variation.

In regard of F_{VIB} at the seat post, the wheels and wheels/frame interactions are the 2 factors with the most influence and the only ones with a significant effect on F_{VIB} (Fig. 15). The effects of these factors account for 48 % of the F_{VIB} variation measured at the seat post (Table 9).

For the P_{VIB} at the seat post, the wheels and frame are the two factors with the greatest effect (Fig. 16). In addition to these, the wheel/frame interaction is the only other factor with a significant effect on P_{VIB} and the effects of these 3 factors account for 81 % of the P_{VIB} variation at the seat post (Table 9).

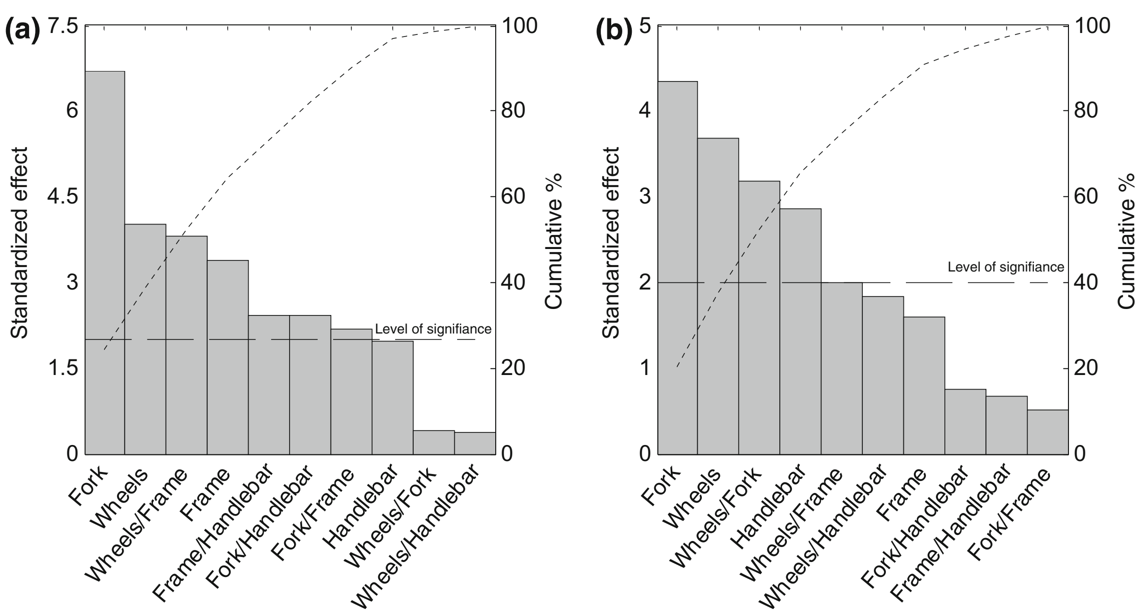

Fig. 11 Pareto Chart, standardized effects and cumulative effects of the bicycle components on a_{VIB} **a** at the left brake hood; **b** at the right brake hood; the factors above the level of significance have a p value below 0.05

Table 9 Component ranking contribution explaining at least 80 % of the VIB variations at 5 % significance for each measurement point

Measurement point	a_{VIB}			F_{VIB}			P_{VIB}		
		cumul %	*p* value		*cumul %*	*p* value		*cumul %*	*p* value
Left Brake Hood	Fork	24	0.000	Handlebar	27	0.000	Handlebar	29	0.000
	Wheels	39	0.000	Fork	52	0.000	Fork	55	0.000
	Wheels/Frame	52	0.000	Frame	70	0.000	Frame	67	0.000
	Frame	65	0.001	Wheels/Fork	80	0.016	Wheels	78	0.000
	Frame/Handlebar	73	0.019				Wheels/Fork	83	0.006
	Fork/Handlebar	82	0.019						
Right Brake Hood	Fork	20	0.000	Handlebar	26	0.000	Handlebar	31	0.000
	Wheels	37	0.001	Fork	49	0.000	Fork	55	0.000
	Wheels/Fork	52	0.003	Fork/Frame	62	0.000	Wheels	70	0.000
	Handlebar	66	0.006	Frame	73	0.000	Frame	81	0.000
				Wheels	82	0.003			
Seat Post	Wheels	42	0.000	Wheels	30	0.000	Wheels	40	0.000
	Frame	70	0.000	Wheels/Frame	48	0.013	Frame	71	0.000
	Wheels/Frame	87	0.000				Wheels/Frame	81	0.000

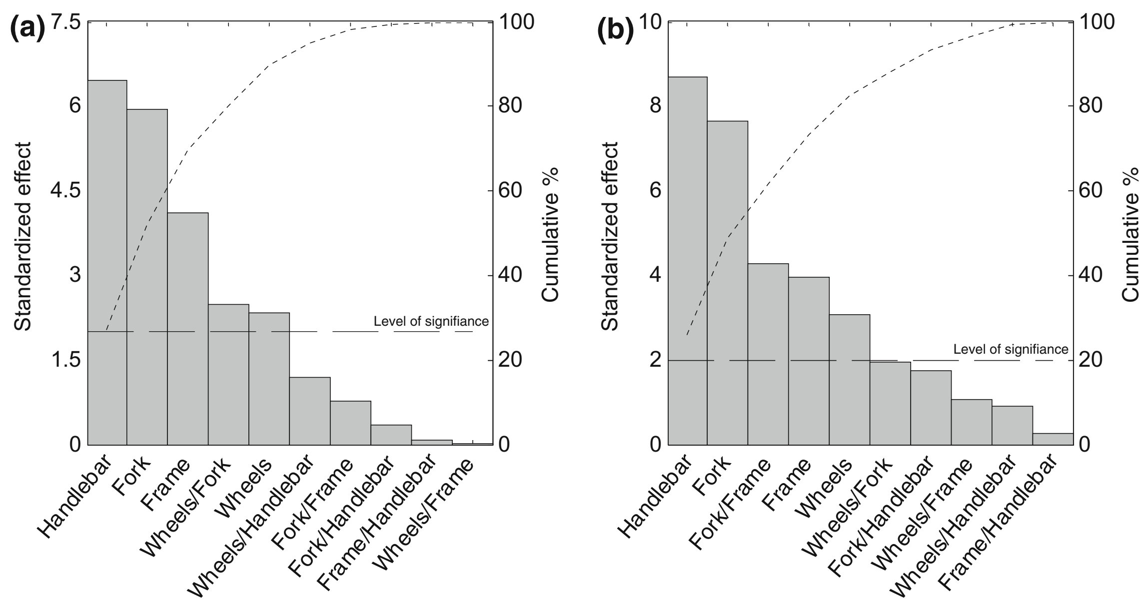

Fig. 12 Pareto Chart, standardized effects and cumulative effects of the bicycle components on F_{VIB} **a** at the left brake hood; **b** at the right brake hood; the factors above the level of significance have a *p* value below 0.05

3.4 Factorial design analysis and discussion

Determining the predominant factors (bicycle components) on the VIB is not trivial because these depend on the measurement point and the measurand considered. At the brake hoods, for example, the fork and wheels are the most influential factors for a_{VIB}, but for F_{VIB} and P_{VIB} it is the handlebar and the fork. Only the fork is one of the most influential factors for each measurand at the brake hoods.

For F_{VIB} and P_{VIB} at the brake hoods, the handlebar and the fork account for approximately, 50 % of all the variations. This shows their predominance on these measurands. It is only for P_{VIB} that all 4 factors explain at least 80 % of the variation on P_{VIB}. This enables us to assume that component interactions can be neglected when the power absorbed by the cyclist is used to measure VIB.

For a_{VIB} and P_{VIB} at the seat post, the wheels are always the most influential factors following by the frame. For F_{VIB}, the wheels/frame interaction is the second most

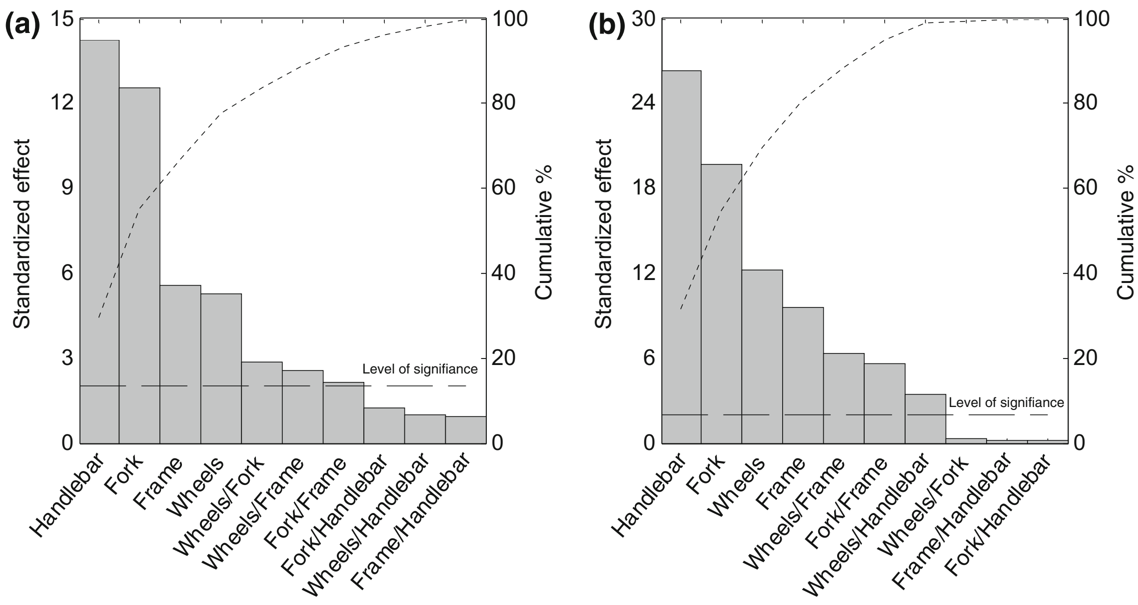

Fig. 13 Pareto Chart, standardized effects and cumulative effects of the bicycle components on P_{VIB} **a** at the left brake hood; **b** at the right brake hood; the factors above the level of significance have a p value below 0.05

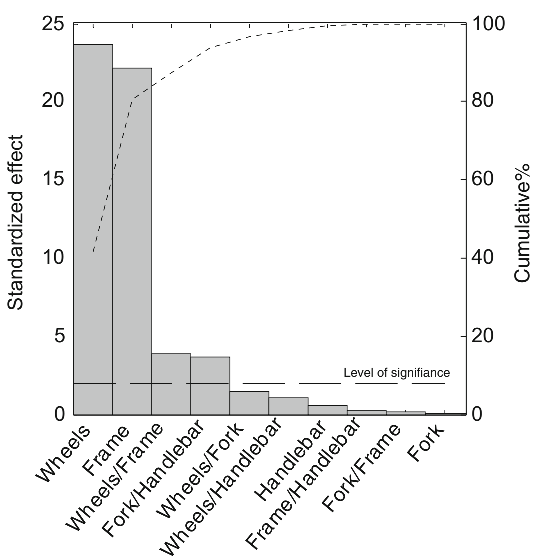

Fig. 14 Pareto Chart, standardized effects and cumulative effects of the bicycle components on a_{VIB} at the seat post; the factors above the level of significance have a p value below 0.05

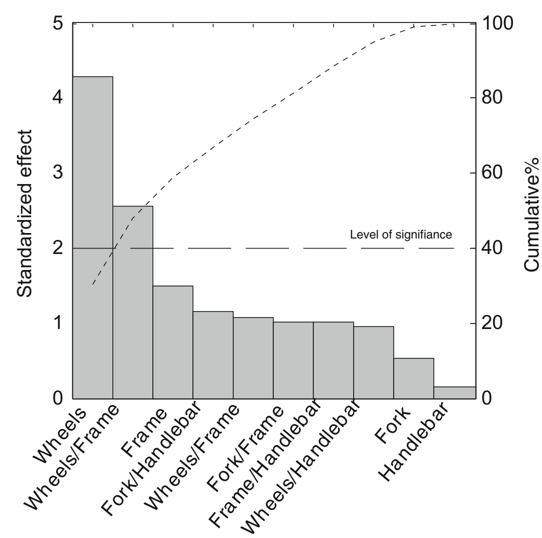

Fig. 15 Pareto Chart, standardized effects and cumulative effects of the bicycle components on F_{VIB} at the seat post; the factors above the level of significance have a p value below 0.05

influential factor and this interaction is the third factor for the other measurands.

For a_{VIB} and P_{VIB} at the seat post, the wheels and frame account for approximately, 70 % of the VIB variation and the wheels/frame interaction only account for 17 and 10 %, respectively, of the VIB variation. That indicates that the wheels and frame are the predominant factors for these measurands.

Regarding the P_{VIB} which was the most consistent measurand in the factor selection, two main conclusions can be made: the handlebar and the fork are the predominant bicycle components for the VIB level at the hands (brake hoods); and the wheels and frame are the predominant bicycle components for the VIB level at the buttocks (seat post). This means it is important to select a lower-transmitting pair of wheels and frame to reduce the VIB at the seat post. But this does not mean that the other bicycle

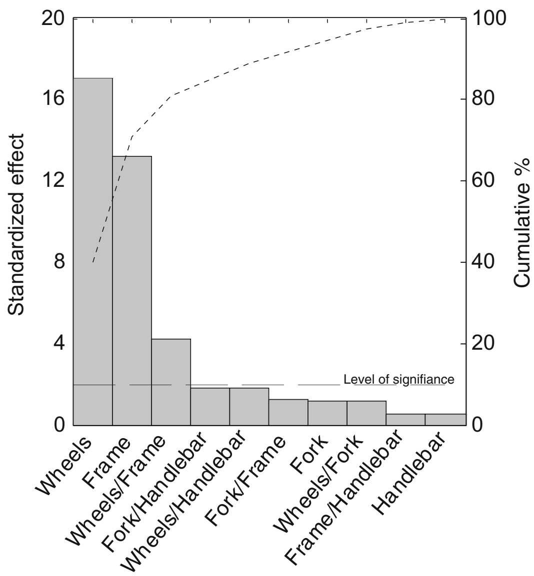

Fig. 16 Pareto Chart, standardized effects and cumulative effects of the bicycle components on P_{VIB} at the seat post; the factors above the level of significance have a p value below 0.05

components do not have any effect. It only means that considering the components tested in this study, it is the wheels and the frame that have the greatest effect on the P_{VIB} at the seat post. The same statement can be made with regard to the brake hood results.

Therefore, to reduce the P_{VIB} at the brake hoods, it is not useful to change the frame if the bicycle is not already equipped with a lower-transmitting fork and handlebar mount, because changing these two components should have a more significant effect on P_{VIB} than changing the frame.

The relative contribution of each bicycle component to the VIB depends on the component selection. The authors strongly believe that the selections used in this paper are representative of the components used by most cycling enthusiasts. Therefore, the results are accurate but do not include the effect of an unusual component such as a suspension fork or frame.

4 Conclusion

The aim of this study was to investigate the relative contribution of the bicycle components on the VIB. To achieve this objective, the bicycle was divided into its 5 main components. Four of these bicycle components were used as factors for a factorial design experiment. For each bicycle component, the lowest and highest transmitting components were defined and used to establish the level for the factors in the factorial design. The selection and factorial analysis were based on 3 measurement points (left and right brake hood and seat post) and 3 different measurands (acceleration, force and power).

The factor levels selection and factorial design results show that the power absorbed by the cyclist is the most consistent of the three measurands to quantify the VIB. According to the P_{VIB} the handlebar and the fork have the greatest effect on VIB at the brake hoods, whereas the wheels and frame have the greatest effect on the VIB at the seat post. The aim of this paper was not to explain the reason behind the preponderance of these components on the VIB. Nevertheless, these results provide valuable insight as to which components must be evaluated to improve dynamic comfort.

The methods proposed here could also be used to assess any new component designed to improve comfort. The same methodology could also be used to assess the effect of the cyclist's position on the VIB by conducting a factorial design using different stem and frame sizes. As mentioned in the introduction, the use of the VIB as a measurand of comfort should be validated by further study. Investigation on the VIB threshold that a cyclist can feel could also be useful to help bicycle companies improve their products.

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