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RESEARCH PAPER

Statistical Analysis of the Vibrations Transmitted From an Electric Kick Scooter to Riders

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Abstract

In recent years, micro-vehicles have been increasingly involved in urban mobility following the actual trend towards light, more affordable, and eco-friendly means of transportation. Among this vehicle category, the electric kick scooters (e-scooters) represent the most popular example driven by app-based sharing mobility services. Despite the positive implications, poor safety requirements and issues of discomfort are also related to this new segment. The recent spread of e-scooters is motivating the scientific community in investigating performance and ride comfort, in the attempt of improving vehicle design and safety regulations. The aim of this study is to evaluate e-scooter vibrations in driving in a realistic environment, constituted by bike path with seven speed bumps. Fourteen healthy young participants (seven males and seven females) are asked to conduct the test at two different constant velocities (5 km/h and 25 km/h). Accelerations are acquired at the main human body segments as well as on the e-scooter. The assessment is based on identifying maxima and root mean squares from signal time histories. A non-parametrical statistical analysis is performed focusing on vibrations transmitted from vehicle to human body, e-scooter velocity, and some rider's characteristics such as gender, mass, dominant arm, and dominant foot. Root mean squares and tests at low velocity generally underline a larger number of significant differences. Moreover, the parameter which mostly influences the system is the rider's mass. Overall, the proposed methodology proves to be an efficient tool to investigate the vehicle-rider vibrational influence.

Keywords Urban personal mobility · Micro-vehicles · E-scooter · MIMU · Statistical analysis · Vibrations

Introduction

In the last few years, urban mobility is experiencing an increasing popularity of electric micro-vehicles (e-MVs) [1–3]. The spread of this segment can be framed into the trend towards more affordable, light and eco-friendly vehicles [4]. Despite being topologically different from each other, some common characteristics of e-MVs are the extreme compactness and the integration into the vehicle chassis of an electric wheel motor assisting the ride. The reduced dimensions, also guaranteed by the presence of small wheels and often by foldability, simplify the portability and the storage in limited spaces such as workplaces and urban apartments. Among e-MVs, electric kick scooters are probably the most popular vehicles since their introduction in metropolitan areas as sharing services [5, 6]. In this way, the so called "last-mile gap" caused by urbanisation can be smoothened by integrating personal and shared e-scooters with public transport system [7].

A fundamental aspect, which clearly distinguishes e-scooters from other two-wheeled vehicles (traditional bikes, mopeds and motorbikes), is the stand-up riding posture. The lack of the saddle, together with the adoption of small tyres, impacts on manoeuvrability, stability, and ride comfort [8]. In particular, the capacity to filter vibrations caused by road unevenness and transmitted to the user has always represented a crucial factor in vehicle design. As carried out for bicycles [9], passenger cars [10], and heavy-duty trucks [11], specific vibrational analyses should also be extended to the new electric micro-vehicle category. Since the recent advent of e-scooters, related literature focused on vibrations effects on human health and comfort is still in progress. Vella et al. [12] investigated the longitudinal dynamics

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exploiting experimental testing and lumped parameter models to highlight the influence of rider kinematics in the braking manoeuvre. Arslan et al. [13] developed a simplified multibody model to study the vehicle response climbing small bumps. Asperti et al. [14, 15] analysed the vertical dynamics taking into account the impedance of the rider and focusing on ride comfort and road holding capability. Boglietti et al. [16] conducted an experimental comparison in terms of ride comfort between an e-scooter and an e-bike driving on homogeneous road surfaces. Brunner et al. [17] analysed the behaviour of the rider performing common manoeuvre in a controlled indoor testing facility. Cafiso et al. [18] focus the attention on ride comfort and safety in relation to the road maintenance. In [19], Cano et al. presented a comfort analysis varying the speed, road surface and riders. The same authors presented a multibody model in [20, 21], suggesting a methodology based on ISO standards for the vibration assessment.

Compared to traditional motorised vehicles, a peculiarity of the e-scooter/human system is the shifting of the inertia ratio towards the rider. Accordingly, the human motion analysis becomes a key point for a complete understanding of the system dynamics. The recent diffusion of micro electro-mechanical systems has encouraged the adoption of wearable technologies such as magnetic-inertial measurement units (MIMUs) for the tracking of human motion in many contexts. Once MIMUs are fixed on body segments, the human movement can be quantitatively characterized by collecting data from the triaxial accelerometer, gyroscope, and magnetometer embedded in each sensor [22]. Considering different mobility scenarios [23, 24], wearable inertial sensors represent an advantageous solution because they are low-cost, portable, easy to wear, and minimally invasive. In addition, their possibility to be used out of laboratory constraints encourages human motion tracking directly in real environments. The electric kick scooters have only recently become widespread means of transportation. Scientific community has just approached this research topic, so related studies are still in progress, especially the interactions between the vehicle and the rider. Accordingly, this research proposes to assess vibrations monitoring both vehicle and riders. To do so, piezo-electric tri-axial accelerometers are mounted on the vehicle while wearable MIMUs are worn by the rider. Hence, accelerations are monitored on the vehicle, at the interface between the e-scooter and the rider, and on selected human body segments. Fourteen healthy young participants characterised by a limited expertise with e-scooters are involved in the experimental campaign. On-road tests consist of driving on a bike path characterised by seven speed bumps, at two different constant velocities. Statistical analysis is performed on the acquired signals for different e-scooter velocities and rider's characteristics, considering absolute maxima and root mean squares of the acceleration norms. A special emphasis is given to the study of vibrations transmitted from vehicle to humans, considering the handlebar-to-forearms and the deck-to-shanks contributions.

The article is organized as follows. First, test procedure is described, focusing on participants characteristics and sensor setup. Then, the data processing is presented, highlighting the methodology followed for assessing the parameters of interest and the developed statistical analysis. Finally, the main results are discussed.

Sensor Setup and Test Procedure

Participants

This study is approved by the Local Institutional Review Board. All procedures are conformed to the Helsinki Declaration. A power analysis is performed prior to the experiment to define the number of participants [25]. Considering that the sternum is the most representative human segment in terms of inertial contribution, the absolute maximum of sternum acceleration [g] is selected as the main outcome to calculate the sample size. The following equation (Eq. (1)) allows the computation of the minimum number of necessary samples:

$$n = \left(\frac{Z_{1-\frac{\alpha}{2}} + Z_{1-\beta}}{\Delta} \right)^2 \sigma^2 \quad (1)$$

where $\alpha = 0.05$ is the level of significance, $\sigma = 0.38$ g is the standard deviation [24], $\Delta = 0.3$ g is the minimum relevant difference [24], $P = 0.8$ is the power level. Since the computed minimum number of subjects is equal to $n = 12.58$, fourteen healthy young participants (seven males and seven females) are recruited for the experiment, after giving their written informed consent. Four inclusion criteria are considered: (i) age between 20 and 35 years old, (ii) no declared neurological disorders, (iii) no musculoskeletal diseases in the last 5 years, and (iv) no previous expertise with the e-scooter. Population characteristics are reported in Table 1. Three participants (21%) are left-handed while only one participant is ambidextrous. Apart from two participants, the whole population has the dominant hand aligned with the dominant foot. Indeed, twelve participants (86%) are characterized by the right dominant foot. Eight participants (57%) prefer to use the dominant foot for the push off. Tandem foot

Table 1 Characteristics of participants

Participants	Age [years]	Gender	Mass [kg]	Height [m]	BMI [kg/m^2]	Dominant hand	Dominant foot	Forward foot	Push off	Position
01	26	M	96	1.80	29.6	Both	Right	Both	Right	Parallel
02	25	F	61	1.73	20.4	Left	Right	Right	Left	Tandem with back toes forward
03	26	F	58	1.64	21.6	Right	Right	Left	Right	Tandem with back toes angled
04	24	F	50	1.63	18.8	Right	Right	Left	Right	Tandem with back toes angled
05	28	M	80	1.70	27.7	Right	Right	Right	Left	Tandem with back toes angled
06	31	F	60	1.67	21.5	Left	Left	Right	Left	Tandem with back toes forward
07	28	F	54	1.58	21.6	Right	Right	Left	Right	Tandem with back toes forward
08	28	F	60	1.77	19.2	Right	Right	Right	Left	Tandem with back toes forward
09	32	M	83	1.80	25.5	Right	Right	Right	Left	Tandem with back toes forward
10	27	M	63	1.73	21.0	Right	Right	Right	Left	Tandem with back toes forward
11	31	M	95	1.85	27.6	Left	Left	Both	Left	Parallel
12	29	M	57	1.73	19.0	Right	Right	Both	Left	Parallel
13	25	M	65	1.78	20.5	Right	Right	Left	Right	Tandem with back toes forward
14	29	F	55	1.65	20.2	Right	Right	Both	Right	Parallel
Mean (standard deviation)	27.8 (2.5)	-	66.9 (15.1)	1.7 (0.1)	22.5 (3.6)	-	-	-	-	-

position is preferred by ten participants (71%) with respect to parallel foot position (29%) [24]. All the participants who adopt the tandem foot position place the push off foot behind the other one, which can be aligned (70%) or angled (30%) with respect to the vehicle longitudinal axis.

Instrumentations

The experimental setup is reported in Fig. 1. The e-scooter involved in the experimental campaign is the commercial vehicle Aprilia ESR2.

The inertial system (Opal™ APDM, USA) adopted for the experiment consists of five wireless magneto-inertial measurement units (MIMUs) containing a tri-axial accelerometer (range ± 200 g), a tri-axial gyroscope (range ± 2000 °/s), and a tri-axial magnetometer (range ± 8 Gauss). Inertial sensors are fixed on participants' forearms, sternum, and shanks through bands supplied by the APDM kit. Each unit is positioned paying attention to the alignment of its x-axis with the longitudinal axis of the corresponding segment. The communication between MIMUs and a PC is guaranteed via Bluetooth. Data are acquired through the proprietary software Motion Studio™ (APDM, USA), with a sampling frequency of 200 Hz.

Four Kistler IEPE accelerometers are placed on the electric scooter: one accelerometer is at the top of the steering column, one accelerometer is on the deck under the feet, two accelerometers are in correspondence of the front and rear wheel centres. The nominal sensitivity is 100 mV/g, the acceleration range is ± 50 g, and the frequency response is linear (± 5%) from 1 to 5000 Hz. The vehicle velocity is estimated starting from the front wheel angular velocity measured by a proximity sensor clamped at the vehicle front suspension system. The accelerations and the angular velocity are synchronously acquired at 3200 Hz, by means of Siemens SCADAS XS acquisition system.

The synchronization between Opal and SCADAS acquisition systems is achieved through an analogue trigger signal at the begin of each acquisition.

Experimental Tests

Participants are asked to drive the e-scooter at two velocities (5 km/h and 25 km/h) on a bike path characterised by seven bumps (in Fig. 2). The velocity is kept constant activating the cruise control modality before reaching the bumps. Each participant repeats the test six times for each velocity. Preliminary to the test series, participants familiarise in driving the vehicle for 15 minutes.

Data Processing

The data processing here presented is applied for each test. The vibration assessment is conducted on the basis of acceleration norms, absolute maxima (Max) and root mean squares (RMS). The experimental signals acquired on the e-scooter are aligned according to the vehicle reference system (Fig. 1). For the MIMUs on the rider, the gravitational acceleration is removed at each time step from the measured values. The time interval to be assessed is triggered based on the filtered vertical acceleration ($\ddot{z}_{fw}$) of the front wheel, using a low-passband filter with cut-off frequency of 40 Hz for tests at 5 km/h and 120 Hz for tests at 25 km/h. Figure 3 graphically represents the procedure adopted for the identification of the time interval.

After identifying the climbing phase on the first bump by the front wheel (first peaks highlighted by black asterisks in Fig. 3), two different time intervals are isolated (coloured bands in Fig. 3):

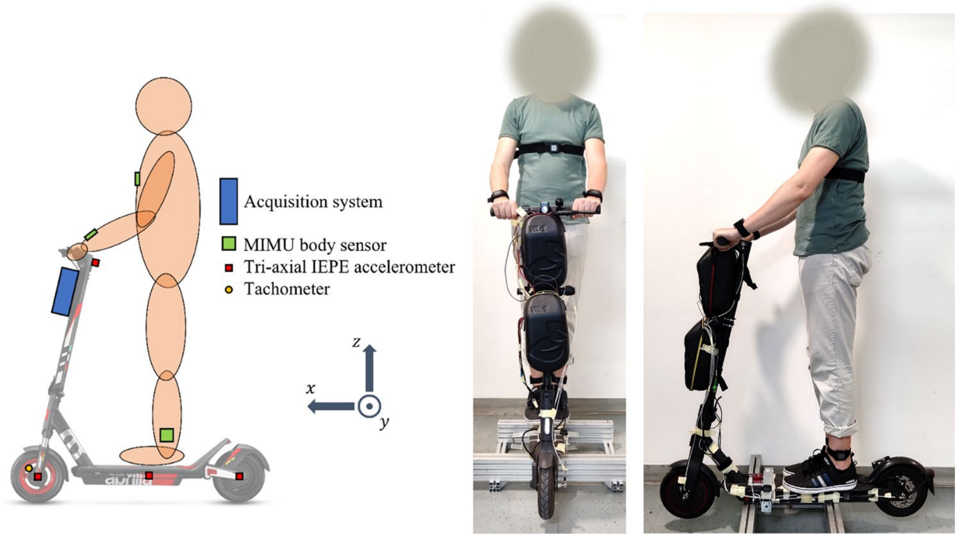
- light green band (from T_1 to T_2), corresponding to the whole-time history related to the manoeuvre, used for the computation of the norm RMS;
- dark green band (from T_3 to T_4), corresponding to the front wheel crossing the second bump, used for the computation of the norm Max.

The norm of accelerations, hereinafter named n, is computed for all the MIMUs on the rider and the accelerometers mounted on the e-scooter deck and handlebar (Eq. (2)).

$$n_i = \sqrt{\ddot{x}_{s,i}^2 + \ddot{y}_{s,i}^2 + \ddot{z}_{s,i}^2} \tag{2}$$

where i stands for the measuring point (i.e., deck, handlebar, right and left forearms, right and left shanks, sternum) and $\ddot{x}$, $\ddot{y}$ and $\ddot{z}$ are the acceleration components along the sensor axes. Values of Max and RMS are calculated according to Eq. (3).

Fig. 1 Experimental setup



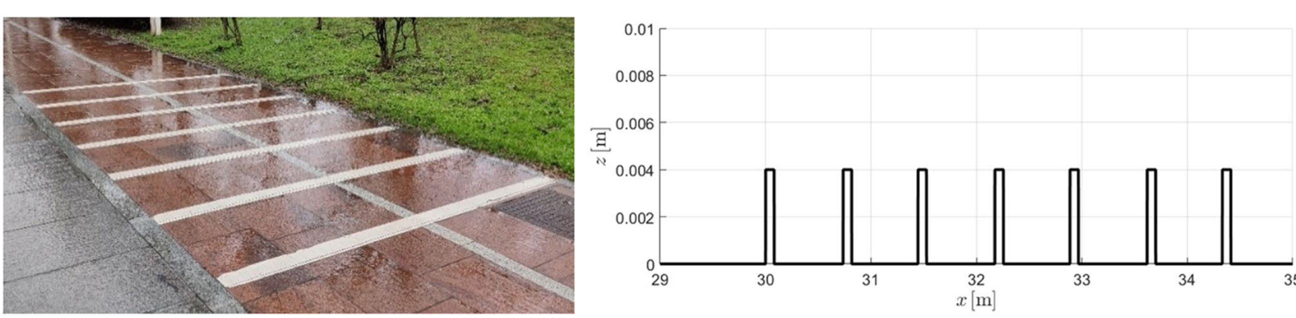


Fig. 2 Bike path with bumps

$$\begin{cases} \mathrm{RMS}_i = RMS(n_i) & T_1 \le t \le T_2 \\ \mathrm{Max}_i = Max(n_i) & T_3 \le t \le T_4 \end{cases} \tag{3}$$

Intra-subject averaged values of Max and RMS are computed for each velocity. Statistical analysis is conducted grouping the results according to several factors such as vehicle velocity, gender, mass, dominant arm, forward foot, and vibrations transmission from vehicle to human body. The application of the Shapiro–Wilk test (2-tails, significance level: $\alpha = 0.05$) certifies the non-normal distribution of data, imposing a non-parametric statistical analysis. The tests described below are executed considering both Max and RMS values.

- The Mann–Whitney U test (2-tails, significance level: $\alpha = 0.05$) is performed between the values related to the two e-scooter velocities (5 km/h and 25 km/h) considering all participants together.
- The Mann–Whitney U test (2-tails, significance level: $\alpha = 0.05$) is first performed comparing the following males' and females' anthropometric data: mass, height, and BMI. Then, the same test is conducted comparing males' and females' values for each measuring point and each velocity.
- Participants are divided into three groups based on their body mass: low (mass < 60 kg), medium (60 kg ≤ mass < 80 kg), high (mass ≥ 80 kg). Then, the Friedman test followed by a post-hoc Mann–Whitney U test (two-tailed, significance level: $\alpha = 0.05$) is performed.
- Participants are divided into two groups based on their dominant arm (right and left). The Mann–Whitney U test (2-tails, significance level: $\alpha = 0.05$) is conducted, for each measuring point and each velocity.
- Participants are divided into two groups based on their forward foot (right or left). The Mann–Whitney U test (2-tails, significance level: $\alpha = 0.05$) is performed for each measuring point and each velocity.
- The Friedman test followed by a post-hoc Wilcoxon signed-rank test (two-tailed, significance level: $\alpha = 0.05$) is performed for right forearm, left forearm, and steering at each velocity. The same tests are executed for right shank, left shank, and deck at each velocity.

Results and Discussion

In this section, results are presented and discussed through bar diagrams. Statistically significant differences are highlighted through a single ($p \le 0.05$) or double ($p \le 0.01$) asterisk.

Max and RMS values of the norm acceleration at both velocities are reported in Figs. 4 and 5, respectively. Considering both Max and RMS values, the increase of e-scooter velocity produces a very significant increase in the acceleration of all segments ($p << 0.01$), apart from the Max values of the sternum.

Differences between males' and females' Max and RMS values at 5 km/h are reported in Figs. 6 and 7, respectively. Differences between males' and females' Max and RMS values at 25 km/h are reported in Figs. 8 and 9, respectively. Considering results at 5 km/h, females' accelerations are significantly higher for deck ($p = 0.04$ for Max, $p = 0.02$ for RMS) and handlebar ($p = 0.01$ for Max, $p = 0.04$ for RMS). Moreover, the same trend involves the right shank ($p = 0.03$ for Max, $p = 0.03$ for RMS) and the left shank ($p = 0.04$ for Max). Considering results at 25 km/h, no statistically significant differences can be found between males and females. These results suggest that the gender influences the riding attitude at low vehicle velocity.

Differences among Max and RMS values related to different riders' mass at 5 km/h are reported in Figs. 10 and 11, respectively. Differences among Max and RMS values of acceleration related to different riders' mass for 25 km/h are reported in Figs. 12 and 13, respectively. Considering results at 5 km/h, acceleration values are inversely proportional to the mass of participants. Indeed, statistically significant differences can be observed between the first and the third group, both for Max values ($p = 0.04$ for the handlebar, $p = 0.03$ for the right forearm, $p = 0.02$ for the right shank)

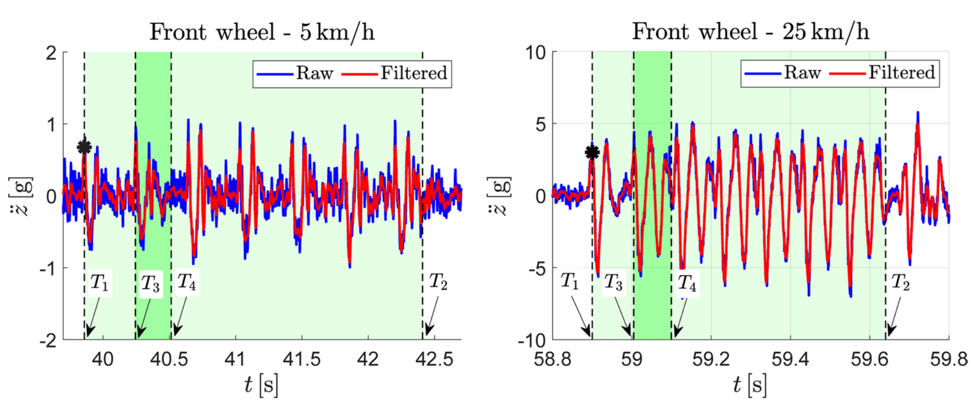


Fig. 3 Front wheel vertical acceleration at 5 (left) and 25 (right) km/h

and RMS values ($p = 0.03$ for the handlebar, $p = 0.02$ for the right forearm, $p = 0.02$ for the left forearm, $p = 0.02$ for the right shank, $p = 0.02$ for the left shank). Considering results at 25 km/h, almost no statistically significant differences are found. All these results are in line with the previous gender analysis. Indeed, the first group (mass < 60 kg) is tendentially composed of females, while the third one (mass ≥ 80 kg) is composed of males. Accordingly, the mass of the rider influences the riding attitude when the e-scooter velocity is low. The analyses performed clustering participants based on their dominant arm or their forward foot do not highlight statistically significant differences for both Max and RMS values at both velocities.

Max values related to handlebar and forearms (left) and deck and shanks (right) are reported in Fig. 14, considering all the participants. Differences among RMS values related to handlebar and forearms (left) and deck and shanks (right) are reported in Fig. 15. Considering the vibrations transmitted from the e-scooter to the rider upper body (left panels of Figs. 14 and 15), the values of the right forearm at 5 km/h are significantly higher than the values of the handlebar both for Max ($p << 0.01$) and RMS ($p << 0.01$) values. Focusing on results at 25 km/h, the right forearm values are significantly higher than the values of the left forearm both for Max ($p = 0.04$) and RMS ($p << 0.01$) values. These results suggest that human joints are stiffer when the e-scooter moves at

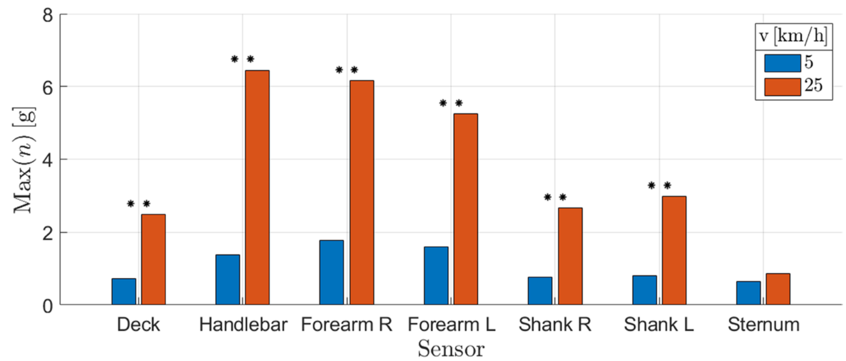


Fig. 4 Max values comparing e-scooter velocities

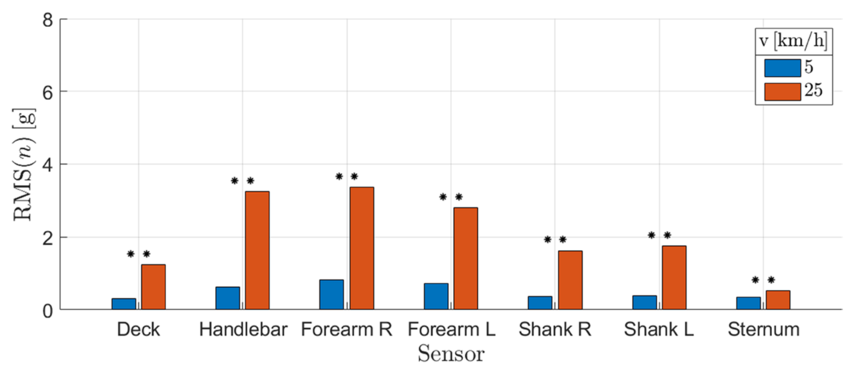


Fig. 5 RMS values comparing e-scooter velocities

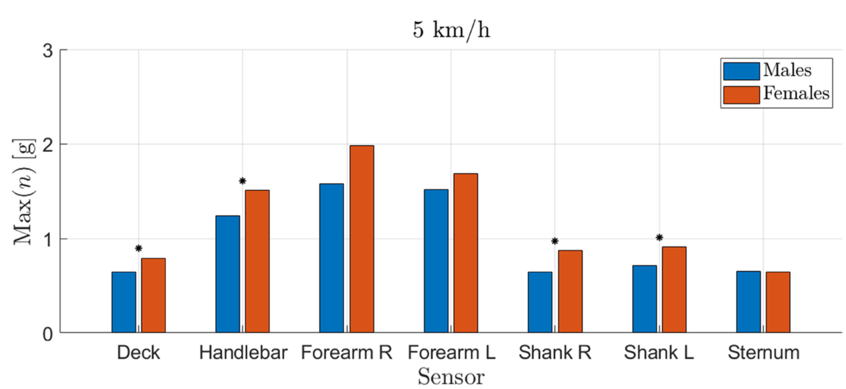


Fig. 6 Max values comparing males and females at 5 km/h

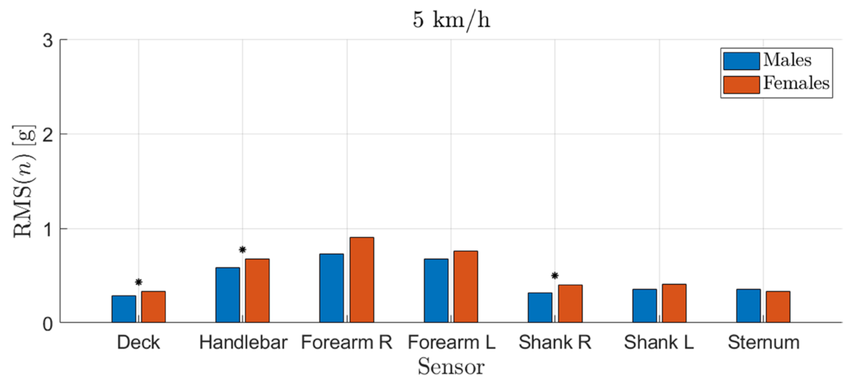


Fig. 7 RMS values comparing males and females at 5 km/h

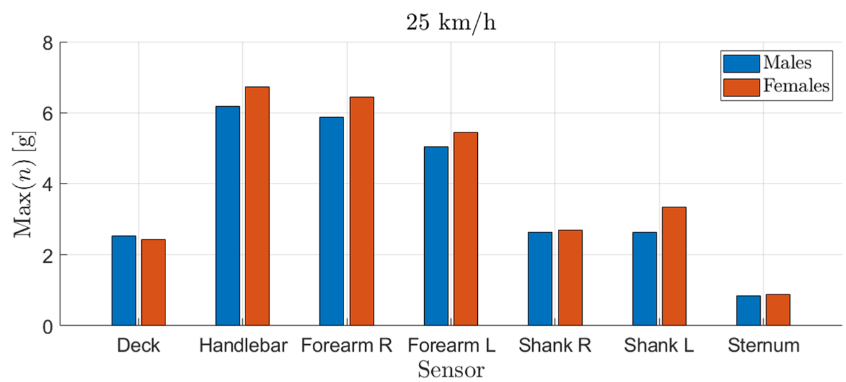


Fig. 8 Max values comparing males and females at 25 km/h

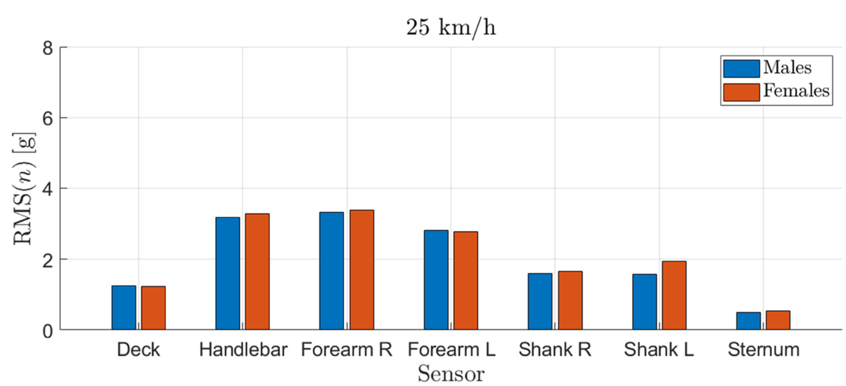


Fig. 9 RMS values comparing males and females at 25 km/h

lower velocity. On the contrary, when the e-scooter velocity is higher, the acceleration decreases from the handlebar to the forearms. Moreover, at 25 km/h the difference between right and left forearms can be due to the presence of the accelerator and braking lever respectively on the right and left side. It is supposed that the rider instinctively tends to be less rigid on the left side, in correspondence of the braking lever. Considering the vibrations transmitted from the e-scooter to the rider lower body (right panels of Figs. 14 and 15), deck values are always lower than shank values for both Max and RMS. Statistically significant differences occur in correspondence of RMS values ($p << 0.01$ between deck and left shank at 5 km/h, $p = 0.02$ between deck and right shank at 25 km/h, $p << 0.01$ between deck and left shank at 25 km/h). This trend can be due to the ankle response to vibrations coming from the deck. Moreover, left shank values are always higher than right shank values even though no statistically significant differences occur. This aspect can be related to the dominant foot of participants (86% right dominant foot).

Power Spectral Density (PSD) of handlebar and forearms vertical acceleration and of deck and forward shank vertical acceleration at 5 (left) and 25 (right) km/h are computed in Matlab® and reported in Figs. 16 and 17, respectively.

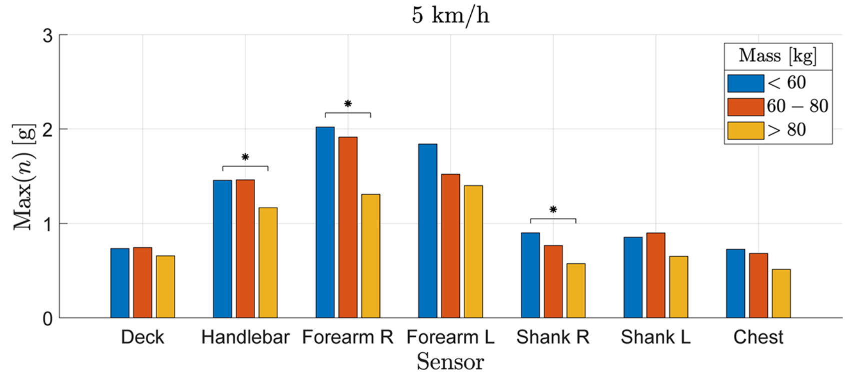


Fig. 10 Max values at 5 km/h grouped according to the participants' mass

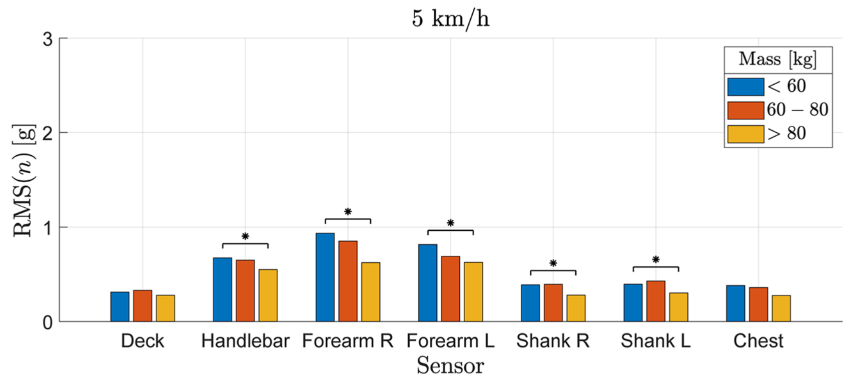


Fig. 11 RMS values at 5 km/h grouped according to the participants' mass

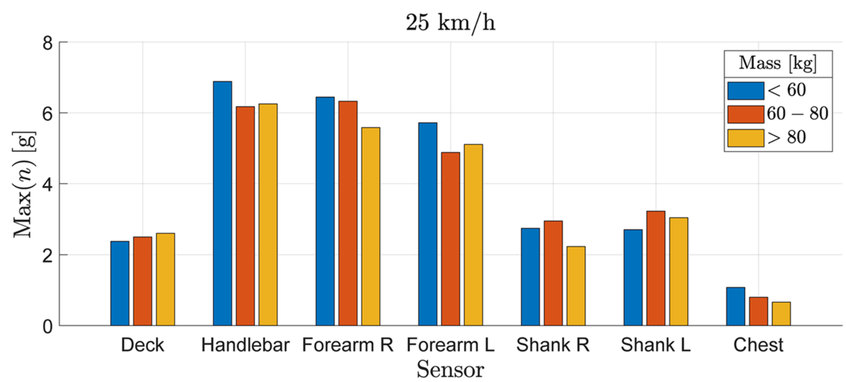


Fig. 12 Max values at 25 km/h grouped according to the participants' mass

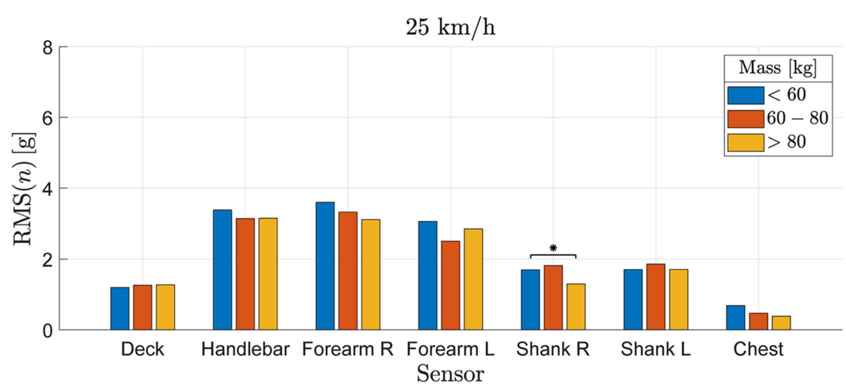


Fig. 13 RMS values at 25 km/h grouped according to the participants' mass

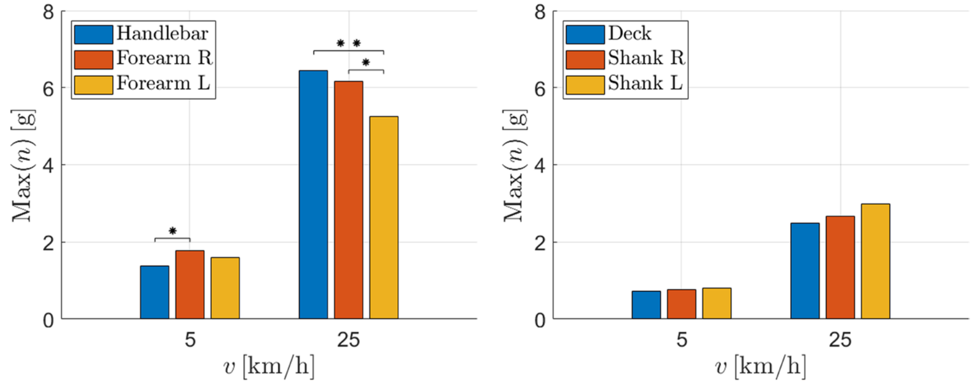


Fig. 14 Analysis of transmitted vibrations (*Max*) on handlebar-to-forearms (left) and deck-to-shanks (right)

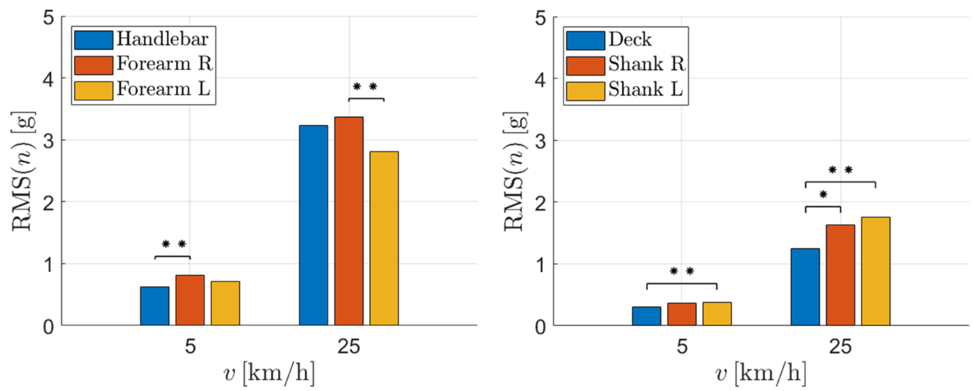


Fig. 15 Analysis of transmitted vibrations (*RMS*) on handlebar-to-forearms (left) and deck-to-shanks (right)

Inter-subjects average (coloured lines) and standard deviation (coloured bands) values are reported. In addition, the frequency related to the spatial distance between consecutive bumps (f_b) and its multiples are reported with black dashed dot lines. The primary frequency is computed as follows (Eq. (4)):

$$f_b = \frac{v}{\Delta x} \tag{4}$$

where v is the vehicle velocity and Δx is the distance between two consecutive bumps. Since Δx is equal to 0.71m, $f_b \approx 2$ Hz when v is equal to 5 km/h and $f_b \approx 10$ Hz when v is equal to 25 km/h.

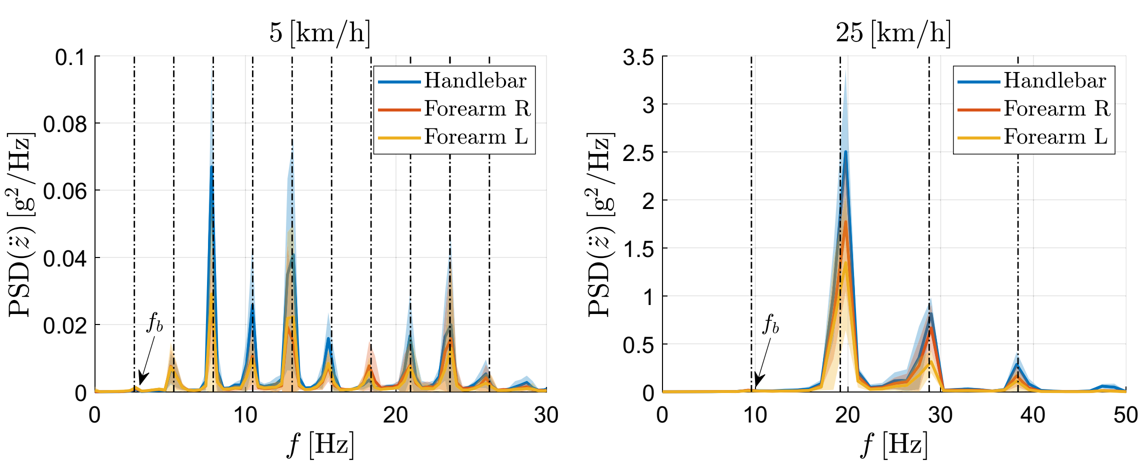


Fig. 16 *PSD* of handlebar and forearms vertical acceleration at 5 (left) and 25 (right) km/h

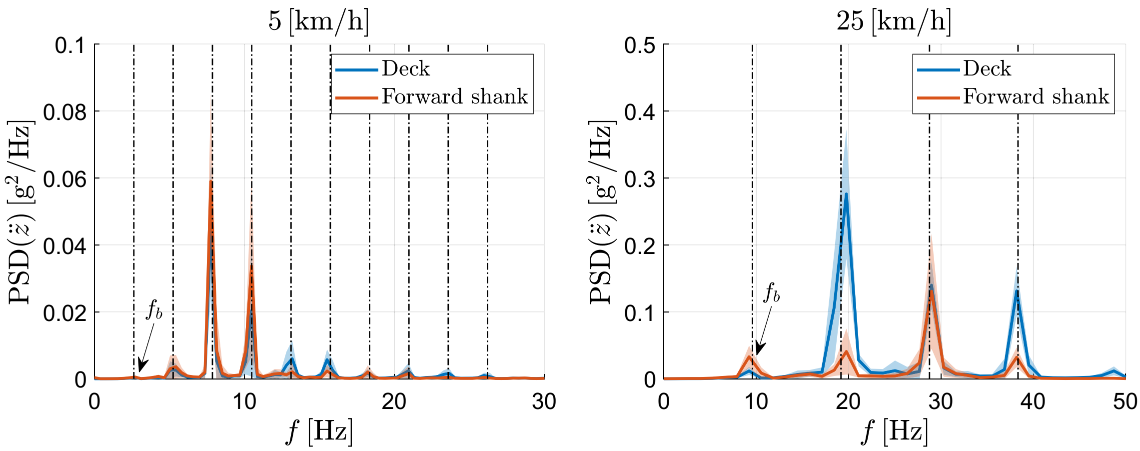


Fig. 17 *PSD* of deck and forward shank vertical acceleration at 5 (left) and 25 (right) km/h

Independently of the considered body district and the e-scooter speed, there is correspondence in frequency domain between e-scooter and rider signals. Hence, all frequencies visible on the e-scooter are also present on the human body with similar amplitude. The small standard deviation related to the rider and to the vehicle highlights the repeatability of tests and the homogeneous behaviour of the riders. The different amplitudes in correspondence of super harmonics could depend on the natural frequencies of the system constituted by vehicle and rider."

Conclusions

The purpose of this research work is assessing how vibrations affect e-scooter riding and vibrations transmitted from vehicle to human body, focusing on the effects of some rider's characteristics such as gender, mass, dominant arm, and dominant foot. The proposed methodology is based on estimating the vibrations on both vehicle and rider through the computation of Max and RMS accelerations. Accelerometers and MIMUs prove to be suitable tools since the reduced riding invasiveness and the possibility to test realistic manoeuvres.

Statistically significant differences are generally highlighted more in RMS values than in Max ones. For this reason, they prove to be more adequate for this kind of analysis. In addition, differences are more evident at low vehicle velocity. Results demonstrate that the mass of the rider is a parameter affecting the system vertical dynamics. On the contrary, left and right segments are characterized by similar vibration levels independently of the dominant upper and lower limb.

The human body response to vehicle vibrations depends on the e-scooter velocity. In detail, at low velocity, the accelerations measured at the rider's limbs are higher than the e-scooter accelerations. On the contrary, at high velocity, forearm accelerations are lower than the handlebar accelerations. Differences detected between right and left forearm accelerations can be due to the positioning of e-scooter commands.

Current efforts are devoted to studying e-scooter motion and rider's behaviour driving on different surfaces such as asphalted and pavé roads. The analysis can also be extended to a wider population to increase the statistical impact of results, considering different ranges of users in terms of age and expertise.

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Data Availability The raw experimental data used in the present paper are available from the corresponding author upon request for research purpose.

Declarations

Conflict of Interest On behalf of all authors, the corresponding author states that there is no conflict of interest.

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References

1. Boglietti S, Barabino B, Maternini G (2021) Survey on e-powered micro personal mobility vehicles: exploring current issues towards future developments. Sustainability 13:3692
2. Reck DJ, Martin H, Axhausen KW (2022) Mode choice, substitution patterns and environmental impacts of shared and personal micro-mobility. Transp Res D Transp Environ 102:103134
3. Zagorskas J, Burinskienė M (2019) Challenges caused by increased use of e-powered personal mobility vehicles in European cities. Sustainability 12:273
4. Bozzi AD, Aguilera A (2021) Shared E-scooters: a review of uses, health and environmental impacts, and policy implications of a new micro-mobility service. Sustainability 13:8676
5. Almannaa MH, Ashqar HI, Elhenawy M, Masoud M, Rakotonirainy A, Rakha H (2021) A comparative analysis of e-scooter and e-bike usage patterns: findings from the City of Austin, TX. Int J Sustain Transp 15:571–579
6. Leoni J, Tanelli M, Strada SC, Savaresi SM (2022) Assessing e-scooters safety and drivability: a quantitative analysis. IFAC-PapersOnLine 55:260–265
7. Butler L, Yigitcanlar T, Paz A, Areed W (2022) How can smart mobility bridge the first/last mile gap? Empirical evidence on public attitudes from Australia. J Transp Geogr 104:103452
8. Paudel MP, Fah F, Yap Y (2021) Front steering design guidelines formulation for e-scooters considering the influence of sitting and standing riders on self-stability and safety performance. Proc Inst Mech Eng Part D: J Automobile Eng 235:2551–2567
9. Lépine J, Champoux Y, Drouet J (2016) A laboratory excitation technique to test road bike vibration transmission. Exp Tech 40:227–234
10. Vella AD, Vigliani A, Tota A, Lisitano D (2020) Experimental ride comfort analysis of an electric light vehicle in urban scenario. SAE Technical Paper 2020-01-1086. https://doi.org/10.4271/2020-01-1086
11. Velmurugan P, Kumaraswamidhas LA, Sankaranarayanasamy K (2014) Whole body vibration analysis for drivers of suspended cabin tractor semitrailer. Exp Tech 38:47–53
12. Vella AD, Vigliani A (2022) Research on the Longitudinal dynamics of an Electric Scooter. SAE Int J Veh Dyn Stab NVH 7:35–51
13. Arslan E, Uyulan Ç (2022) Analysis of an e-scooter and rider system dynamic response to curb traversing through physics-informed machine learning methods. Proceedings of the Institution of Mechanical Engineers, Part D: Journal of Automobile Engineering 237(7):1555–1571. https://doi.org/10.1177/09544070221100111
14. Asperti M, Vignati M, Braghin F (2022) Modeling of the vertical dynamics of a kick e-scooter on distributed road irregularity. In: Advances in Dynamics of Vehicles on Roads and Tracks II: Proceedings of the 27th Symposium of the International Association of Vehicle System Dynamics, IAVSD 2021, August 17–19, 2021, Saint Petersburg, Russia, Springer, pp 1070–1080
15. Asperti M, Vignati M, Braghin F (2021) Modelling of the vertical dynamics of an electric kick scooter. IEEE Trans Intell Transp Syst 23:9266–9274
16. Boglietti S, Ghirardi A, Zanoni CT, Ventura R, Barabino B, Maternini G, Vetturi D (2022) First experimental comparison between e-kick scooters and e-bike's vibrational dynamics. Transp Res Procedia 62:743–751
17. Brunner P, Löcken A, Denk F, Kates R, Huber W (2020) Analysis of experimental data on dynamics and behavior of e-scooter riders and applications to the impact of automated driving functions on urban road safety, In: 2020 IEEE Intelligent Vehicles Symposium (IV), IEEE, pp 219–225
18. Cafiso S, Di Graziano A, Marchetta V, Pappalardo G (2022) Urban road pavements monitoring and assessment using bike and e-scooter as probe vehicles. Case Stud Constr Mater 16:e00889
19. Cano-Moreno JD, Cabanellas Becerra JM, Arenas Reina JM, Islán Marcos ME (2022) Analysis of e-scooter vibrations risks for riding comfort based on real measurements. Machines 10:688
20. Cano-Moreno JD, Marcos MI, Haro FB, D'Amato R, Juanes JA, Heras ES (2019) Methodology for the study of the influence of e-scooter vibrations on human health and comfort. In: Proceedings of the Seventh International Conference on Technological Ecosystems for Enhancing Multiculturality, pp 445–451
21. Cano-Moreno JD, Islán ME, Blaya F, D'Amato R, Juanes JA, Soriano E (2021) E-scooter vibration impact on driver comfort and health. J Vib Eng Technol 9:1023–1037. https://doi.org/10.1007/s42417-021-00280-3
22. Digo E, Pastorelli S, Gastaldi L (2022) A narrative review on Wearable Inertial sensors for human motion tracking in industrial scenarios. Robotics 11:138
23. Wang P, Yi J, Liu T (2019) Stability and control of a rider–bicycle system: analysis and experiments. IEEE Trans Autom Sci Eng 17:348–360
24. Garman C, Como S, Campbell I, Wishart J, O'Brien K, McLean S (2020) Micro-mobility vehicle dynamics and rider kinematics during electric scooter riding. SAE Technical Paper 2020-01-0935. https://doi.org/10.4271/2020-01-0935
25. Digo E, Panero E, Agostini V, Gastaldi L (2021) Gait parameters of elderly subjects in single-task and dual-task with three different MIMU set-ups. In: 2021 IEEE International Symposium on Medical Measurements and Applications (MeMeA), IEEE, pp 1–6

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