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Comfort assessment for electric kick scooter decks

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Abstract.

The LEONARDO project, funded under the Horizon 2020 framework, is aimed at developing a new concept of micromobility electric vehicle combining the benefits of an e-kick scooter (rapid learning curve, stability) and those of a monowheel (greater agility). The goal is the development of a vehicle able to increase the consensus towards electric micromobility for enabling a relevant spread of this green transport solution, thanks to specific expedients like: (a) the possibility of exploiting an auxiliary battery pack to increase the path traveled by the vehicle; (b) a mass reduced to 10 kg, allowing to easily lift and move the vehicle to routinely encountered upper-level spaces (steps, the trunk of a vehicle, etc.). The weight reduction compared to similar vehicles necessarily involves the replacement or elimination of bulky components like suspension elements; for this reason, the deck must have intrinsic shock absorbing characteristics to maximize the rider comfort.

The objective of the present work is the identification of a class of decks for e-kick scooters that best meets the user comfort needs in an urban environment. To this end, experiments have been performed replacing the aluminium deck of a commercially available electric scooter with decks of different materials; the comfort offered by each deck has been measured compatibly with the ISO 2631:1997 standard on a closed test circuit, in correspondence of six different obstacles that the rider may tackle in a typical urban scenario. The results of the study, read in a statistical key by regressive methods and analysis of variance, evidence highest compatibility with maximum comfort criteria for the 11.5 mm thick bamboo deck; namely, the test campaign evidences how the maximum comfort for the rider can be obtained with a deck having a stiffness similar to that of bamboo. In this context, the bamboo deck lacking of shock absorbers demonstrates superior performance compared to aluminium decks equipped with suspensions for the same application, with a mass saving of approximately 65%. Special care should however be paid to the forces the deck could sustain: moving from an aluminium to a bamboo deck which is 20 times less stiff, forces decrease of only 20%. Overall, these highlights represent a comprehensive set of elements to pilot the design of micromobility vehicles, from both standpoints of comfort and resistance.

1. Introduction

Electric micromobility is currently seen as one of the major strategies to quickly achieve significant decreases of pollutants in urban environments within a limited time window, as the one dividing the European Commission from a reduction of 55% in greenhouse gases (2030 [1]). A mono-user, light transportation mean is the most appropriate traveling solution compared not only to alternatives like a combustion engine vehicle, but also to an electric passenger car: taking the latter as a reference, a micromobility vehicle significantly decreases the electric energy demand for transportation, an especially crucial point considering that non-sustainable sources accounted for more than 80% of the whole European production in 2020. In particular, the use of electric kick scooters (e-scooters) drastically increased in the last years, both in private and sharing contexts; it is additionally expected that the request for e-scooters will constantly increase by 25% each year until 2025 [2]. Most of travels by e-scooters

however typically substitute path otherwise covered by other sustainable transportation modes as walking [3], implying that a limited reduction on the number of circulating heavy, multi-user vehicles is currently observed. For these reasons, increasing the consensus towards micromobility solutions by users of other traditional vehicles is a priority to achieve a more sustainable transport system.

From the user perspective, e-scooter inadequacy as a transportation mean depends on two fundamental causes: the high mass and the reduced autonomy. A high mass (typical e-scooters on the market are down to 13 kg) discourages the user to carry the vehicle in its routine activities, being for instance less prone to lift and carry it to upper-level spaces (steps, trunk of a vehicle, etc.). Analogously, 85% of e-scooters are employed for less than one hour per day because of the limited energy stored in battery packs [4]. To this end, the aim of the LEONARDO project (MicrovehicLE fOr staNd-Alone and shAReD mOblity[1]) is twofold: to develop a microvehicle with a total mass lower than 10 kg and whose battery packs could be shared among the users in a battery sharing scheme; the vehicle implements a fixed battery pack, while an auxiliary battery pack can be picked up by the users at a recharging station to increase the traveled paths [5]. The vehicle is conceptualized so as to feature hybrid characteristics between an e-scooter and a monowheel, i.e., combining the rapid learning curve and the stability of an e-scooter with agility and capability to easily overcome road asperities of a monowheel (higher wheel diameter [6]).

Decreasing the mass of the vehicle requires renouncing to well-established concepts as shock absorbers, typically mounted on the front and/or rear wheels of an e-scooter. A deck with suitable properties in terms of vibration attenuation hence appears as the most feasible solution to decrease the vehicle mass without affecting the riding comfort for the user. From such standpoint, decks for e-scooters available on the market are mainly represented by aluminium structures that, without a shock absorber, are extremely stiff. A research by Koontz et al. [7] demonstrated that, in general, lighter and less stiff vehicle structures feature higher maneuverability and comfort for the user. Specific investigations on e-scooter motion have also been performed by Cano-Moreno et al. [2, 8] through simulations, determining that the use of less stiff shock absorbers and wheels could ameliorate the user experience from both health and comfort standpoints (the speed being the same). Nevertheless, the trip was simulated by random vibrations as prescribed within the ISO 8608:2016[2] standard, and did not investigated which types of obstacles in an urban environment could produce such oscillations; analogously, no information is available regarding the comfort experienced by the user when shock absorbers are excluded from the vehicle system. Nonetheless, $in-situ$ (on road) measurements could significantly differ from the results of simulation or lab tests, because conditions like the rider position and weight distribution can be fully accounted for only in real road contexts [9].

Based on such assumptions, the present study aims at analyzing the comfort provided on road by different decks in terms of material, while subjected to obstacles that can be typically encountered in urban contexts. Since these tests are required to pilot the design of an innovative vehicle concept, the forces discharged on the deck additionally require special attention. Vibrations and forces on the decks are hence monitored by an accelerometer and a load cell, respectively. The main reference for comfort assessment in the study is represented by the ISO 2631:1997[3] standard, while tests are performed on a closed circuit featuring several types of obstacle.

2. Materials and methods
The present Section introduces the fundamental elements enabling determination of comfort characteristics for different types of decks in diverse conditions. These elements are represented by comfort assessment methodologies, the experimental campaigns, and the procedures employed to analyze comfort data resulting from such experiments.

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[1] https://leonardoproject.eu/
[2] https://www.iso.org/standard/71202.html
[3] https://www.iso.org/standard/7612.html

2.1. Comfort assessment

Comfort assessment for a vehicle finds a valid reference in the ISO 2631:1997 regulation. The standard reports that diverse frequencies in the rider oscillations are associated with a different perceived comfort, from 0.4 Hz to 100 Hz. Hence, the acceleration must be filtered with a 0.4 Hz-100 Hz band-pass filter and appropriately weighted and expressed by the Root Mean Square (RMS) as follows:

$$a_{v_{ij}} = \sqrt{\frac{1}{B_j} \int_0^{B_j} a_{ij}^2(f) df} \tag{1}$$

$$a_{w_i} = \sqrt{\sum_j \left(W_j a_{v_{ij}} \right)^2} \tag{2}$$

Based also on the visualization of Figure 1, i is the considered direction among x, y, and z, $a_{ij}(f)$ is the i-th acceleration component in the j-th one-third octave band, B_j is the j-th one-third octave band, $a_{v_{ij}}$ the RMS acceleration value for the i-th direction in the j-th one-third octave band, W_i the weighting factor for the i-th one-third octave band given in specified tables and a_{w_i} the weighted acceleration value in the i-th direction. Composing a_{w_i} values in the three directions and considering a standing rider, the following equation is derived from the standard:

$$a_{TOT} = \sqrt{a_{w_x}^2 + a_{wy}^2 + a_{w_z}^2} \tag{3}$$

The standard indicates a_{TOT} as the main parameter to be considered for comfort assessment.

Figure 1. Visualization of the reference system according to ISO 2631:1997, considering the user in a standing position as in the case of an e-kick scooter rider.

2.2. Experimental campaign

2.2.1. Deck categories and evaluation of related stiffness   Experimental campaigns have been performed employing a commercial e-kick scooter that, in its original form, relies on an aluminum deck equipped with a shock absorber (ICEWHEEL E9sD); such deck has been identified as deck A_1. To pilot the choice of the deck category that best performs in terms of comfort provided to the user, diverse decks have been produced and replaced with the original on the e-kick scooter frame:

- The original aluminium deck, after removal of the shock absorber (**deck A_2**);

- A deck constituted of two layers of bamboo, one with the fibers disposed along x and the other along y (Figure 1); a fiber glass fabric is interposed between the layers and the deck has a total thickness of 11.5 mm (**deck B**);
- A deck made of eight maple sheets with an additional non-slip grip, with a thickness of 12.5 mm (**deck C**);
- A deck from three fir sheets alternated with plywood, with a thickness of 12.5 mm (**deck D**);
- A deck made of six fir sheets alternated with plywood, with a thickness of 25 mm (**deck E**);
- A deck made of three layers of curved bamboo obtained by vacuum resin bonding, with a thickness of 15 mm (**deck F**).

To characterize the various decks (some of which are visible in Figure 2), a three-point bending test was performed on a MTS 810 universal machine in displacement control, determining stiffness and modulus of elasticity. After preliminary three-point bending qualitative tests, decks D, E, and F have been discarded because of excessive fragility, very similar stiffness compared to deck A_2, and very similar stiffness to deck C, respectively. It was then assumed that the remaining decks represent three significantly different types of objects in terms of stiffness on which comfort analyses could be based.

Figure 2. Decks A_2, E, B, C (from left to right); deck E has been discarded from subsequent tests, because of high similarity with deck A_2 in terms of stiffness.

For the aluminium (A_2), bamboo (B), and maple (C) decks, maximum loads of 880 N, 870 N, and 1320 N were respectively applied without reaching the ultimate tensile strength. In each test, a length of support span of 400 mm was kept. In Table 1, the results of the three-point bending tests are reported for the three decks. Thickness of deck A_2 has not been reported because of its complex geometry.

Table 1. Values of the main considered variables for the three-point bending tests on the considered decks.

Deck	Thickness	Width	Maximum load	Maximum deflection
A_2 – Aluminium	/	145mm	1320N	0.43mm
B – Bamboo	11.5mm	200mm	880N	5.52mm
C – Maple	12.5	200mm	870N	4.72mm

The modulus of elasticity E is obtained from the classical relation that apply to beams subjected to bending moments:

$$E = \frac{L^3 \left(F_2 - F_1\right)}{4bt^3 \left(a_2 - a_1\right)} \tag{4}$$

where L is the length of support span, b the width of the specimen, t the specimen thickness, F_2-F_1 the load increase in the straight section of the load-deformation curve and a_2-a_1 the increase in deflection in the center line of the specimen (corresponding to F_2-F_1). The stiffness S is obtained from the following relation:

$$S = \frac{48EI}{L^3} \tag{5}$$

where I is the moment of inertia of the beam. Equations 4-5 assumes isotropic behaviour of the beam, condition that might be unsuitable for specific class of materials. Therefore, assuming F_2 and F_1 respectively corresponding to 80% and 10% of the maximum load, the following results are obtained:

- Deck A_2: Stiffness 3121.9 N/mm
- Deck B: Stiffness 161.8 N/mm – Modulus of elasticity 8531 MPa
- Deck C: Stiffness 184.1 N/mm – Modulus of elasticity 7762 MPa

Because of the complex shape of the aluminium deck A_2, the modulus of elasticity for the latter could not be calculated. Its stiffness has been consequently obtained based on the slope of the load-deformation curve from the bending test. The three stiffness values confirm that such decks cover a reasonably wide range of stiffness.

2.2.2. Test circuit   Based on the stiffness of each deck, differences in terms of comfort to the user are expected to emerge while riding on an urban context. Definition of a test circuit was hence required for comfort assessment of each deck. The circuit, closed to the traffic, should guarantee the presence of obstacles typically encountered in urban road environments. Several sections have been consequently considered including different types of obstacle, indicated in Figure 3 as follows:

1 Rough asphalt – $\mathbf{O_1}$;
2 Manhole without asperity – $\mathbf{O_2}$;
3 Manhole with asperity (slight gutter) – $\mathbf{O_3}$;
4 Ramp – $\mathbf{O_4}$;
5 Slight bump – $\mathbf{O_5}$;
6 Smooth surface – $\mathbf{O_6}$.

Between O_3 and O_4, a straight section with a homogeneous road surface of 45 m is present, in which maximum speed for the vehicle (25 km/h) could be achieved.

2.2.3. Instrumented vehicle   After stiffness characterization of the decks, their behavior in real road environments had to be tested in the closed circuit of Figure 3. Considering that comfort can be expressed by a superposition of accelerations on diverse directions based on the ISO 2631:1997 standard, the vehicle needed to be instrumented to acquire acceleration values. To this end, accelerations to which the decks are subjected while the rider is using the kick scooter have been acquired by a three-axis accelerometer mounted in the center of the deck, with vertical z axis facing upwards (opposite to gravity); the y axis of the accelerometer corresponds to the longitudinal direction of the vehicle, coherently with Figure 1. The accelerometer had a resolution of 80 mV/g and the sampling frequency was set to 1 kS/s. At each test,
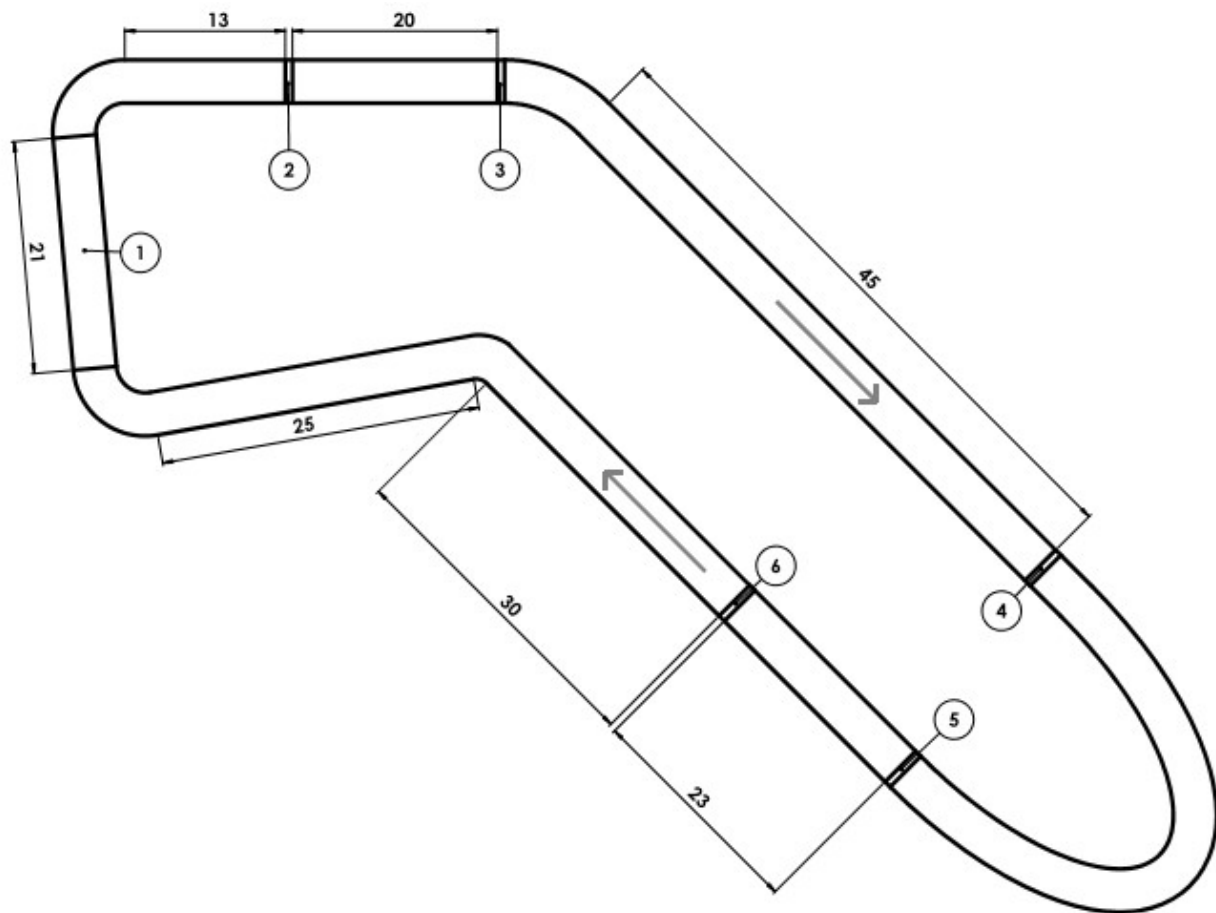
Figure 3. Considered circuit for the experimental campaigns; different sections in terms of road obstacles and distance among them are reported: rough asphalt (**1**), manhole without asperity (**2**), manhole with asperity (**3**), ramp (**4**), gutter (**5**), smooth surface (**6**).

a different deck was mounted on the e-kick scooter frame, i.e., A_1, A_2, B, C. The tests were carried out under the total mass (comprising user and overall mass of acquisition instruments) of 80 kg.

In addition, since forces discharging on the deck are fundamental in its design process (static and dynamic resistance), their monitoring is associated with fundamental highlights. Solely the forces to which the two most diverse decks in terms of stiffness are subjected were acquired along the circuit (i.e., A_2 and B), to evidence only major differences among the decks; accelerometer and load evaluations were performed in different tests. A load cell was hence mounted on a rigid panel, and interposed between the deck and the panel on which the rider stands. The load cell averaged the signals from four different strain gauges located at the vertices of the panel, with a sampling rate of 100 S/s. In Figure 4a, the load cell mounted between the panel and the deck is evidenced, with indication of the four strain gauges it is constituted of. Figure 4b depicts the vehicle ready for the acceleration test, in case of aluminium deck on which the accelerometer is mounted. Figure 4c evidences the vehicle ready for the load test, in which the mounted panel and the National Instruments© acquisition board (NI mod. 9291) are also shown.

2.3. Data analysis
Accounting for the indications included in the ISO 2631:1997 standard, the perceived comfort increases as a_{TOT} decreases, because the vibration energy transferred from the road to the rider reduces. It was hence first required to obtain the value of a_{TOT} for each test. A significance analysis was subsequently
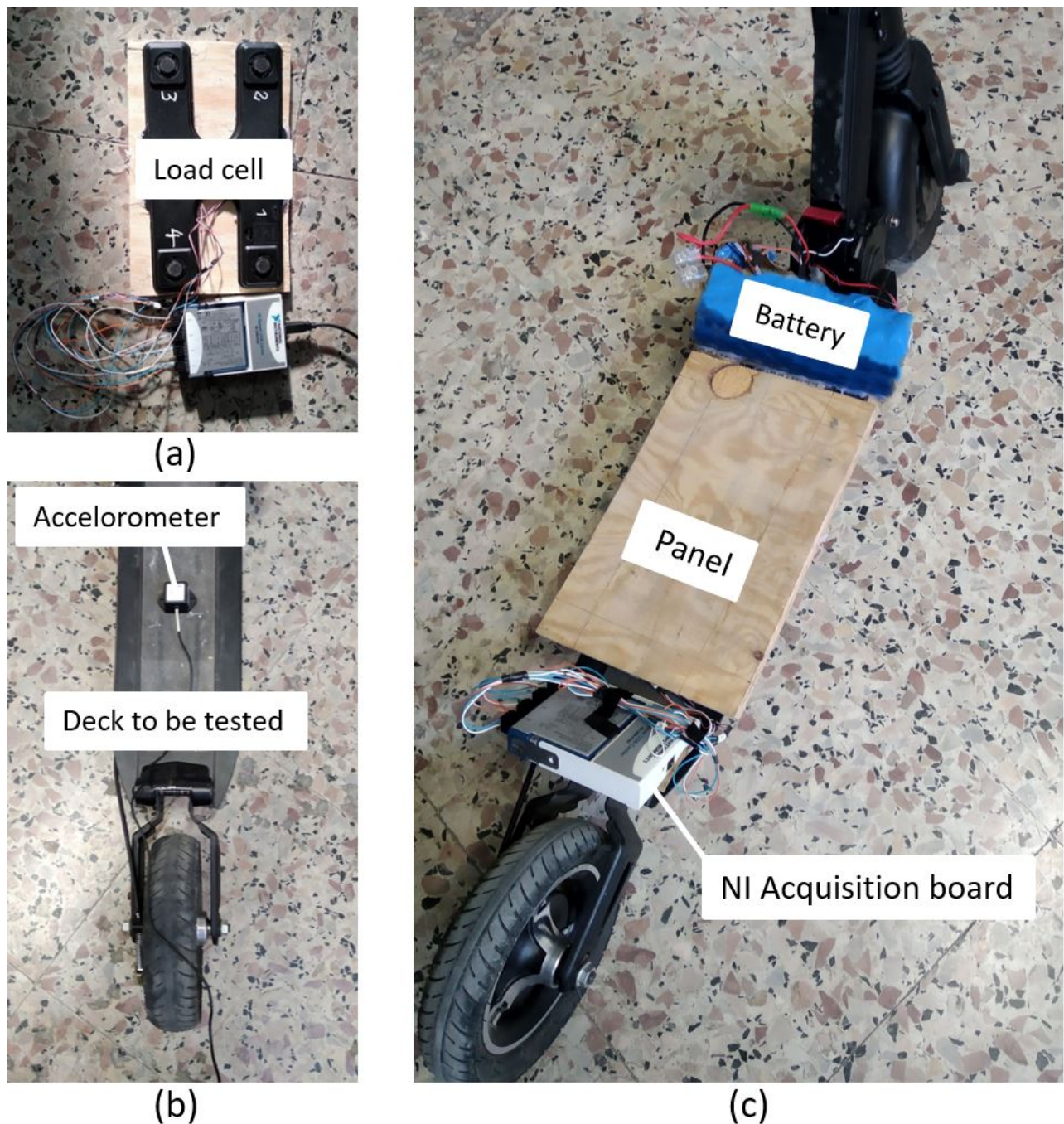
Figure 4. (a) Instrumented panel; (b) deck A_2 with the three-axis accelerometer; (c) deck A_2 with the instrumented plate.

necessary to determine the influence of the various decks on the provided comfort, the encountered obstacles being the same.

A program written in LabVIEW$^©$ was used for data acquisition. A post-processing program was also written in LabVIEW$^©$ to digitally filter acceleration data between 0.4 Hz and 100 Hz and obtain a_{TOT} in a specific time interval. The time intervals corresponding to each obstacle were isolated from the acquisition data. A systematic criterion was therefore established for a proper identification of the time

intervals: for O_1, an interval of 7 s was considered starting from the beginning of the circuit (progressive obstacle), while for all other obstacles an interval of 1 s was established, with a lower limit of 0.2 s before the absolute peak (or valley) corresponding to the obstacle and an upper limit of 0.8 s after. The time intervals for the load cells acquisition were analogously defined, and the corresponding load signals similarly processed.

Once obtained all the necessary data and processed as described above, a significance study was carried out by means of regression analysis by the Minitab$^©$ statistical software, for the determination of the parameters significantly influencing the comfort provided by the diverse decks. This was obtained by referring to an Analysis Of Variance (ANOVA) process.

3. Results and discussion

Table 2 summarizes the results of the ANOVA applied to the processed signals from the accelerometer; decks have been categorized based on their material, rather than on their value of stiffness: this is a requirement to compare the different decks (lacking a shock absorber) with deck A_1 (on which a shock absorber was implemented). A p-value lower than 0.05 for a variable is considered as an indicator of significant influence of such variable on a_{TOT}. In the analysis, deck A_1 and obstacle O_1 are used as the baseline deck and obstacle, respectively. It can be highlighted that, in terms of a_{TOT}, decks A_2 and C do not provide statistically significant differences compared to deck A_1. Instead, the use of the bamboo deck B has a statistically significant influence on the comfort perceived by the rider, independently on the type of encountered obstacle. Transversally, all types of obstacle significantly influence the comfort if compared to obstacle O_1. Nevertheless, a regression (odds ratio analysis) is also required to gain quantitative information regarding such an influence.

Table 2. Results of the ANOVA related to the parameter a_{TOT} (significant variables are highlighted by *).

Parameters	P-value
Constant	0.000*
Deck A1	-
Deck A2	0.119
Deck B	0.020*
Deck C	0.220
Obstacle O1	-
Obstacle O2	0.001*
Obstacle O3	0.000*
Obstacle O4	0.000*
Obstacle O5	0.000*
Obstacle O6	0.001*

The linear regression applied to the specific problem provides the following expression for a_{TOT}:

$$a_{TOT} = 7.10 + 0.0A_1 + 2.40A_2 - 3.73B - 1.86C + 0.00O_1 + 8.04O_2 + 8.85O_3 + \\ +12.96O_4 + 12.88O_5 + 7.62O_6 \tag{6}$$

where the categorical variables A_1, A_2, B, and C represent the different decks, while the categorical variables from O_1 to O_6 the obstacles of the test circuit. In the equation, these categorical variables gain

a value of 1 if the variable is taken into account, 0 otherwise. Since the coefficient related to deck B is the lowest among all decks, it can be derived that the parameter a_{TOT} reaches a minimum when deck B is employed in the experiment, i.e., maximum comfort. Deck C also provides a low value of a_{TOT}, but its statistical non-significance (Table 2) does not allow to assess its superiority compared to the aluminium deck with shock absorber. The same applies to the aluminum deck without shock absorber (A_2), that provides the highest values of a_{TOT} on average but influences a_{TOT} in a statistically non-significant way. In addition, obstacles O_2 and O_3 similarly affect the values of a_{TOT}, as well as O_4 and O_5. Nonetheless, Equation 6 features a high goodness-of-fit, with an adjusted value of R^2 equal to 84.9%.

Figure 5 depicts various graphs that highlight the difference in terms of comfort between the worst and the best deck based on the coefficients of Equation 6, i.e., respectively A_2 and B. It is derived that the bamboo deck provides the highest comfort in whichever condition, in particular in case of the progressive obstacle (O_1). Influence of the deck category on additional parameters has been considered in the analysis, e.g., value and number of the acceleration peaks in different directions; nevertheless, the main effect of the deck reflects on the a_{TOT} parameter. No further information is hence provided on such parameters.

For what regards the forces discharged on the deck, graphs are presented in Figure 6 regarding the same decks of Figure 5. It can be seen that the values of both maximum force and standard deviation force for the bamboo deck are lower than those for the aluminium one, if averaged among all cells. This is independent of the considered obstacle; however, the maximum force can reach values of 1400 N in a single cell, despite the 80 kg mass of the rider considered in the experiments. This obviously depends on the position of the rider centre of mass with respect to the deck centre. Even if stiffness for the bamboo deck is almost 20 times lower than that of aluminium, the maximum force to which the deck is subjected is only 20% lower on average. These results provide fundamental highlights for the design phase of a bamboo deck (or a deck with analogous stiffness), in terms of forces that can be admitted in transient regimes. Considering that the bamboo deck approximately accounts for 0.6 kg instead of 1.7 kg for the assembly constituted of the aluminium deck and suspension, this solution entails a mass decrease of 1.1 kg (65%).

4. Conclusions

The present work assessed the comfort provided by different types of deck to the rider for the design of an innovative electric kick scooter solution, in which mass is limited by the absence of shock absorbers. The primary reference for comfort assessment was the ISO 2631:1997, that considers the root mean square of accelerations along three axis as the main comfort indicator. Each frequency component of the acceleration signal is differently perceived by the rider, so that a frequency weighting on the signals was performed following the standard. The forces discharged on the deck were also acquired by a load cell, fundamental to define the maximum stress the deck will sustain in transient regimes.

The results demonstrated that the bamboo deck outperforms other types of considered decks, independently of the obstacles which can be encountered by the vehicle in a typical road environment (rough asphalt, manholes, etc.). More in general, based also on the results from a linear best-fitting process, the highest comfort is provided by decks with low stiffness; a linear fit is sufficient to more than adequately describe the comfort provided by the deck (R^2=84.9%). Special care must be however paid towards the forces acting on the deck: experiments demonstrated that, even if the stiffness lowers of 20 times, the maximum forces on the deck would only decrease of about 20%.

The results provide suggestions to design a deck which can be light while preserving its comfort characteristics compared to decks implementing shock absorbers. Several types of obstacles have been considered which are typically found in urban roads; therefore, the obtained indications represent a comprehensive set of elements which can be employed to pilot the design phase of future, lighter micromobility solutions.
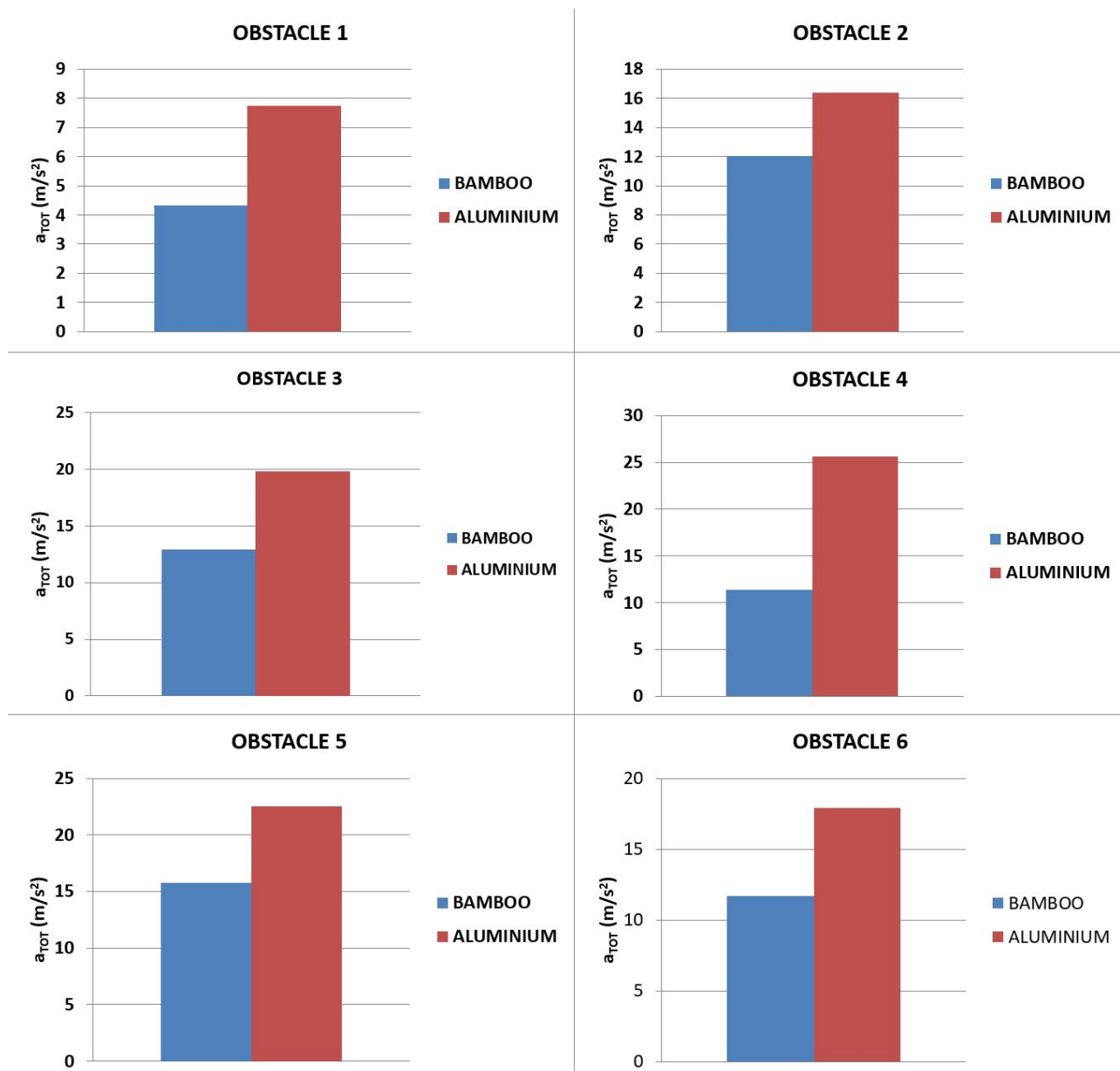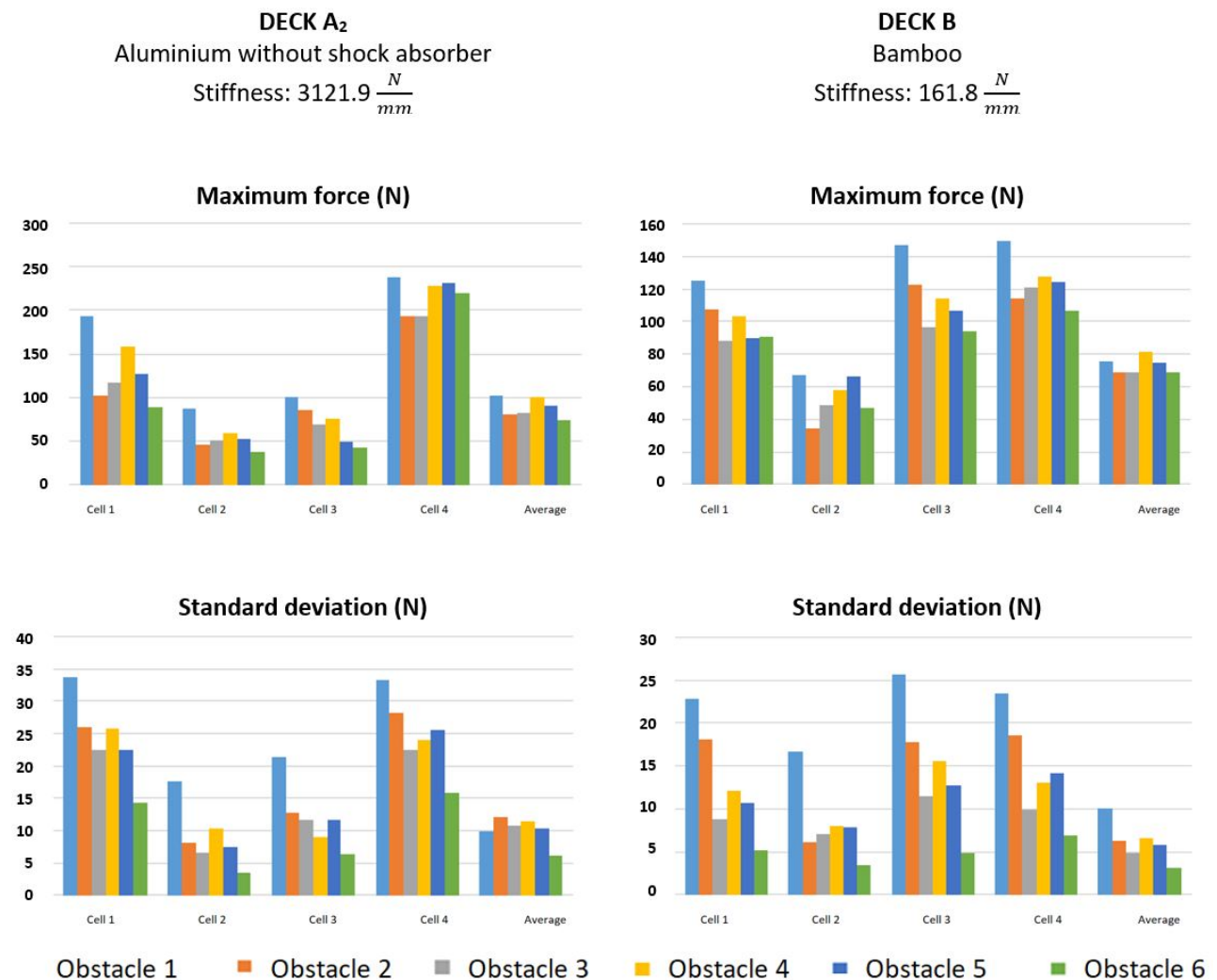
Figure 5. Comparison between the parameter a_{TOT} associated with deck A_2 (aluminium without shock absorber) and B (bamboo).

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DECK A₂
Aluminium without shock absorber
Stiffness: $3121.9 \frac{N}{mm}$

DECK B
Bamboo
Stiffness: $161.8 \frac{N}{mm}$

Figure 6. Comparisons between the two most distant categories of deck in terms of stiffness, as a function of maximum force and standard deviation of the force acting on each of the four cells (and corresponding average).

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