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Evaluation of human body kinematics while riding electric kick scooter

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Abstract. The recent popularity of electric kick scooters, as affordable, eco-friendly, and lightweight vehicles, places them on the spotlight of urban mobility. The upright riding position, along with the vehicle's low mass, necessitates a thorough understanding of the entire system, including human motion analysis. The aim of the present study is to evaluate the impact of some electric kick scooter and rider characteristics on the rider kinematics in a real driving scenario. Fourteen healthy young participants are recruited for the experimental campaign. The on-road tests consist of driving on seven speed bumps at two different constant speeds. During the tests, the angular motion of selected human body segments and the pitch motion of the electric kick scooter are monitored: these magnitudes are used to conduct a statistical analysis focusing on the influence of vehicle speed and rider's gender, mass, and forward foot. Overall, results suggest that the dynamics around the medio-lateral axis of both the vehicle and the human body is influenced by the riding speed, the gender, and the mass. Moreover, a symmetrical foot position on the deck promotes greater rider stability.

Keywords: Personal urban mobility, Micro-vehicles, Electric standing scooter, Rider, MIMU, Statistical analysis.

1 Introduction

The recent advent of electric micro-vehicles (e-MVs) in some urban areas of the world is justified by the global trend towards more affordable and eco-friendly vehicles [1]. Electric kick scooters (e-scooters) stand out for popularity both in the context of personal mobility vehicles (PMVs) and sharing mobility services [2]. Differently from other two-wheeled vehicles, e.g., traditional bikes and mopeds, e-scooters are characterized by the up-right riding posture of the user, which, combined with small tires, influences maneuverability and stability [3]. Moreover, because of the vehicle's low weight, the rider's inertia is predominant in the entire dynamic system. These peculiarities have led the scientific community to focus attention on the ride comfort and safety of this new kind of vehicle. Boglietti et al. conducted an experimental comparison between the e-scooter and the e-bike in terms of vibrations [4]. Asperti et al. showed the effect of rider's impedance on the vertical dynamics of the e-scooter through lumped parameter models [5, 6]. Arslan et al. developed a simplified multibody model to study the vehicle response due to small bumps [7], whereas Cano et al. presented a multibody model for the vibration assessment [8]. The influence of rider motion in the emergency braking maneuver was analyzed with lumped parameter [9] and detailed multibody [10] models by Vella et. al. The dynamic behaviour of e-scooter/rider system is investigated through operational modal analysis in [11].

As underlined by the above-mentioned studies, a complete comprehension of the whole system composed of the vehicle and the rider relies significantly on human motion analysis. Considering that the e-scooter mobility occurs outdoors, a suitable system to track human motion is represented by wearable magnetic-inertial measurement units (MIMUs). Indeed, MIMUs are low-cost, portable, easy to wear, minimally invasive, and appropriate to be used out of laboratory constraints [12, 13]. MIMUs fixed on human body segments allow to quantitatively characterize the movement by collecting data from the triaxial accelerometer, gyroscope, and magnetometer embedded in each sensor [14]. A previous study involving fourteen healthy young participants driving an e-scooter on a bike path characterized by seven speed bumps, at two different speeds is presented in [15]. Accelerations monitored on selected human segments and on the vehicle at the interface with the rider were exploited to investigate vehicle-human body transmissibility for different e-scooter speeds and rider's characteristics.

The present study aims to evaluate the impact on angular motion of the vehicle and the human body while driving on speed bumps at constant speed. In detail, a statistical analysis of the angular velocities, recorded in [15], is conducted focusing on the influence of vehicle speed and riders' gender, mass, and foot positioning on the e-scooter deck.

The article is organized as follows. The experimental campaign is described in the second section focusing on the sensor setup, testing protocol, and signal processing. The main outcomes coming from the statistical analysis on rider's kinematics are reported in the third section. The main conclusions are drawn in the fourth section.

2 Experimental campaign

In this section, the experimental campaign already discussed in [15] and exploited to collect the angular velocities of the vehicle and of the rider's segments is summarized. The driving tests are conducted by fourteen healthy subjects, equally distributed in terms of gender, without experience driving e-scooters. The main characteristics of the riders involved in the analysis are reported in Table 1.

Table 1. Characteristics of the participants in the experimental campaign

Characteristics	*Average*	*Standard deviation*
Age [years]	27.8	2.5
Body mass [kg]	66.9	15.1
Height [m]	1.70	0.10

The 21% of the subjects is left-handed and the 86% of the subjects is characterized by the dominant hand aligned with the dominant foot.

2.1 Sensor setup and test procedure

The vehicle used for the on-road tests is Aprilia ESR2, which is equipped with suspension systems and 10-inch pneumatic tires. The instrumentations involved in the experimental part of the activity is shown in the left panel of Fig. 1.

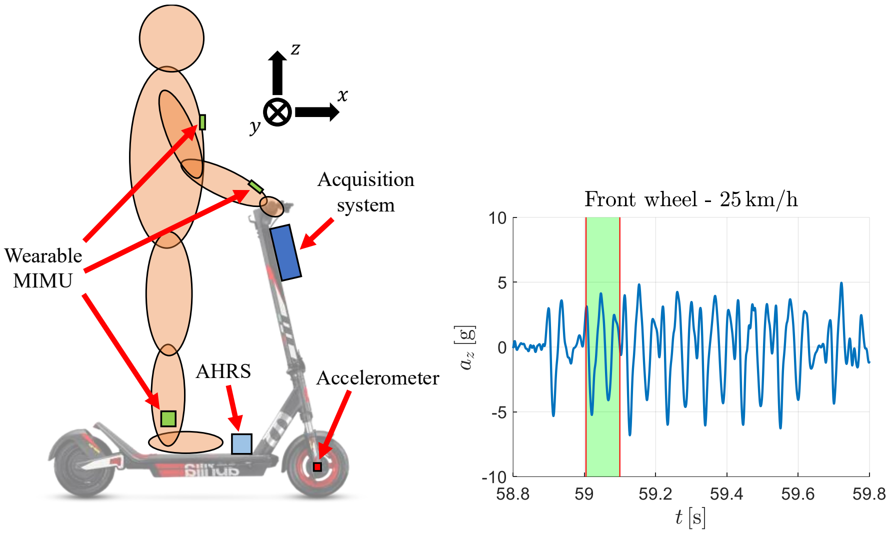

Fig. 1. Sensor setup (left panel) and time interval identification for the analysis based on the vertical acceleration of the front wheel (right panel)

Five wearable magneto-inertial measurement units (MIMUs) produced by Opal$^{\text{TM}}$ APDM are used for collecting the angular velocities (ω) of selected human body segments. The five sensors are fastened in correspondence of the sternum (ST), the right and left forearms (R-FA/L-FA) and the right and left shanks (R-SH/L-SH). The signal logging is obtained via Bluetooth through Motion Studio$^{\text{TM}}$ APDM software.
The measurements coming from the vehicle are managed by Siemens SCADAS XS acquisition system: this system is fixed on the steering column of the e-scooter. SBG Ellipse-A Attitude Heading Reference System (AHRS) is used to monitor the angular velocities of the deck (DE): it is connected to Siemens SCADAS XS via CAN protocol. A triaxial Kistler IEPE accelerometer is mounted in correspondence of the front wheel. Signals acquired by Opal$^{\text{TM}}$ APDM and Siemens SCADAS XS are triggered at the beginning of each acquisition and aligned in time domain during the post-processing.

The tests consist of driving the e-scooter on a bike path characterized by seven speed bumps at 5 km/h and 25 km/h, which correspond to the minimum and maximum vehicle speeds allowed by the electric motor and vehicle control system. Each rider tested both vehicle speeds six times.

2.2 Signal processing

The statistical analysis is conducted considering the absolute maxima (Max) of the angular velocities around the medio-lateral axis of the human body segments and the angular velocity of the e-scooter deck around the y-axis in correspondence of the second speed bump. Maximum angular velocity values are averaged for each body segment, as well as for values recorded on the front wheel. The component of the acceleration along the z-axis of the front wheel is used to identify the time history of interest (the green band in the right panel of Fig. 1 corresponds to the second bump).

The non-normal distribution of data certified by the application of the Shapiro–Wilk test (2-tails, significance level: $\alpha = 0.05$) imposes a non-parametric statistical analysis. The following tests are executed on Max values of the angular velocities. The Mann–Whitney U test (2-tails, significance level: $\alpha = 0.05$) is performed grouping the acquisitions according to the following factors: e-scooter speeds (5 km/h and 25 km/h), riders' gender, and riders' forward foot. The Friedman test followed by a post-hoc Mann–Whitney U test (two-tailed, significance level: $\alpha = 0.05$) is performed dividing participants into three groups based on their body mass: low ($M < 60$ kg), medium (60 kg $\leq M < 80$ kg), high (M $\geq$ 80 kg).

3 Results and discussions

Overall, statistically significant differences are denoted with a single asterisk when the p-value (p) is equal to or lower than 0.05 and with a double asterisk when (p) is equal to or lower than 0.01 (stronger significant differences). Max values of the medio-lateral angular velocities of the human body segments and the pitch velocity of the vehicle are reported in Fig. 2 comparing the two tested vehicle speeds. Since there are strong statistically significant differences ($p << 0.01$) between 5 km/h and 25 km/h for all measuring points, it can be deduced that the e-scooter speeds impacts in a relevant way on the dynamics around the medio-lateral axis of both vehicle and human. Forearms and sternum are the most involved segments. Comparing right and left forearms, a slight difference in the maximum can be detected and it is more evident at 25 km/h than at 5 km/h. On the contrary, right and left shanks do not show relevant differences.

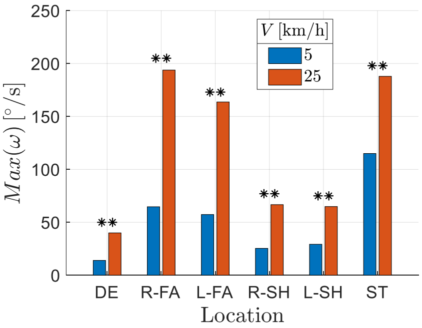

Fig. 2. Maxima of the angular velocities comparing the vehicle speeds

Differences between males' and females' *Max* values at 5 km/h (left panel) and 25 km/h (right panel) are reported in Fig. 3. Overall, females have higher *Max* values than males, except for the left forearms at 25 km/h. The only statistically significant difference occurs for the deck at 5 km/h ($p << 0.01$). The gender difference can be especially appreciated for forearms and sternum.

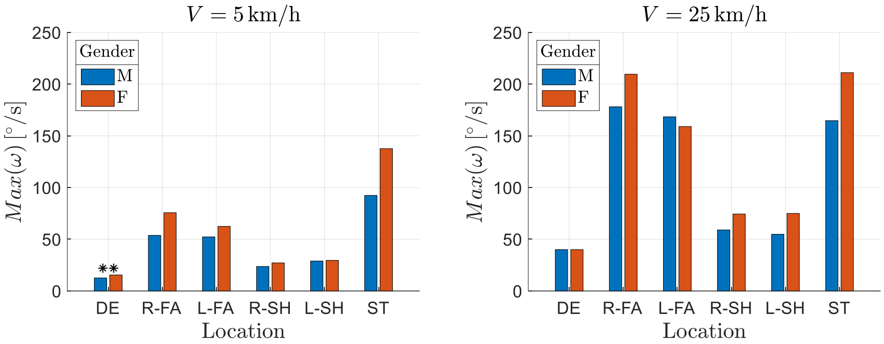

Fig. 3. Maxima of the angular velocities comparing the genders (M: males, F: females) for 5 km/h (left panel) and 25 km/h (right panel)

The influence of the riders' mass at 5 km/h (left panel) and 25 km/h (right panel) is represented in Fig. 4. Results show a decreasing trend with increasing mass considering the sternum and the deck. However, this trend is statistically significant only for the deck at 5 km/h ($p << 0.01$).

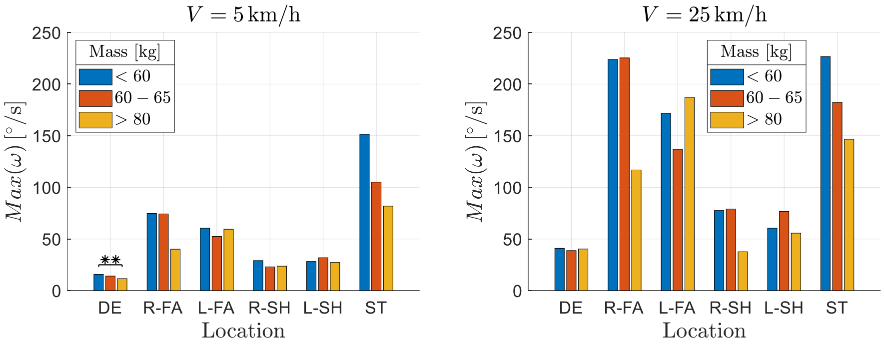

Fig. 4. Maxima of the angular velocities comparing the categories of body mass for 5 km/h (left panel) and 25 km/h (right panel)

Max values of angular velocity at 5 km/h (left panel) and 25 km/h (right panel) based on the position of the forward foot are reported in Fig. 5. The deck is not particularly influenced by the side of the forward foot at both e-scooter speeds. Overall, at 5 km/h, the value associated to "paired" feet is always the lowest one, because a symmetrical position results in a smaller oscillation. In detail, there is a statistically significant difference between the forward foot denoted as "paired" and "left" for the right forearm

($p = 0.03$) and the right shank ($p << 0.01$). This aspect can be explained considering that riders with a left forward foot tend to rotate the right-side segments more. At 25 km/h the situation is similar, except for the left forearms, which is influenced by the presence of the e-scooter brake. Comparing right and left sides, even if in absence of statistically significant differences, the *Max* value associated to the right side is always lower than the one of the left side (except for the left shank at 5 km/h and 25 km/h, and the sternum at 25 km/h). This trend can be justified considering that the dominant foot of the tested population is almost always the right one and hence the left side is exposed to greater oscillations.

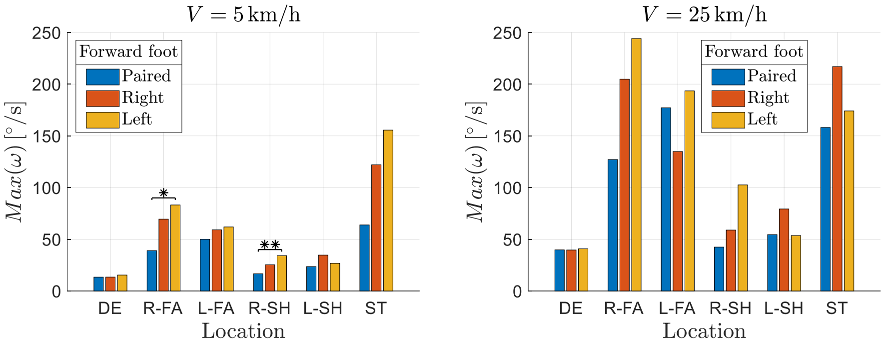

Fig. 5. Maxima of the angular velocities comparing the forward foot of the rider for 5 km/h (left panel) and 25 km/h (right panel)

4 Conclusions

The aim of this study is to evaluate how some e-scooter and rider characteristics influence the whole system kinematics in terms of angular motion.

As well as for vibrations analysis performed in [15], differences are more evident at low vehicle speed. While for accelerations the influence of gender is more evident for the lower body, in this case females' higher values of angular velocity mainly involve the upper body. In accordance with the vibrational analysis, maximum angular velocities are inversely proportional to the mass of participants. In contrast to accelerations, the impact of the forward foot on angular velocities is relevant.

Results suggest that the dynamics around the medio-lateral axis of both the vehicle and the human is influenced by the e-scooter and the rider characteristics. In detail, the e-scooter speed and the riders' gender impact on the human upper body (forearms and sternum).Reduced angular oscillations and a stronger stability of the rider are improved when the rider's mass increases and feet are paired on the e-scooter deck.

Overall, this research work demonstrates the predominance of the rider's inertia on the entire dynamic system, enhancing the importance of considering the human body motion for ride comfort and safety analyses with this vehicle category. Moreover, the developed protocol proves to be suitable for a complete understanding on human body response while driving the e-scooter in urban scenarios.

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