Gender Differences in Injury Severity in Pedestrian–E-Scooter Collisions: A Simulation Study Using Multi-body Tools

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Abstract. The adoption of electric micromobility, encouraged by the sustainability goals of the Agenda 2030, has revolutionized urban transportation, although it often preceded the development of appropriate regulations and infrastructure. In Italy, ISTAT data show a concerning increase in accidents involving electric scooters, many of which include pedestrians. This study fills a gap in scientific research: the lack of biomechanical analyses that consider gender differences. Using a multibody simulation environment, 120 impact scenarios involving e-scooters and pedestrians are investigated, with variations in mass, impact angles, and speed. The outcomes are assessed through the HIC (Head Injury Criterion) index to determine the severity of head injuries. The study highlights that initial speed is the main factor determining injury severity, and that anthropometric differences between men and women significantly influence the dynamics of falls and the extent of impact with the ground.

Keywords: E-scooter · Pedestrian · HIC · Multi-body · Gender Differences · Micromobility

1 Introduction

In recent years, environmental impact has become a significant issue. To combat this problem, the United Nations Organization has adopted a global legislative framework, the Agenda 2030 [1], which defines 17 Sustainable Development Goals (SDGs) to be pursued by 2030.

Among the various objectives, this legislative framework certainly aims to encourage reducing pollution, given the use of private vehicles such as cars, to the detriment of a mobility defined as sustainable.

A transport system is considered sustainable when it provides easy access to places, goods, and services that cater to different societal groups and future generations, while

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O. Gervasi et al. (Eds.): ICCSA 2026 Workshops, LNCS 16765, pp. 471–483, 2027.
https://doi.org/10.1007/978-3-032-30536-7_30

ensuring the health and safety of the population. The key element is awareness, with citizen engagement through alternative suggestions to encourage lifestyle changes. Sustainable mobility has developed from this foundation, promoting travel by micro-mobility devices such as e-scooters and electric bikes, as well as walking and shared vehicles like car and bike sharing. In this context, urban micromobility has become a transformative approach in both developed and developing cities [2]. Electric scooters, in particular, symbolize this shift. These modes of transport are especially suited to short journeys, thanks to their convenience, versatility, and ease of use. However, the increase in micromobility has not kept pace with the development of adequate regulations and infrastructure suitable and safe for such vehicles. Many cities introduced electric scooters before establishing policies on their use in circulation zones, maximum speeds, and the required protective gear. Studies indicate that most e-scooter users do not wear helmets, even at moderate or high speeds [3].

However, this increases the risks users face on their journeys and raises the likelihood of collisions with other road users. E-scooters, compared to other micromobility modes, expose drivers to greater risk due to their intrinsic characteristics, such as smaller wheels, a higher center of gravity, and limited braking stability [4]. An additional factor increasing the risk of injury for scooter riders is the low helmet use rate; studies from various regions show helmet use below 10% among e-scooter riders [5–7]. The low rate of helmet use confirms the high incidence of head injuries, as documented by emergency services.

Furthermore, the use of such modes of transport has increased interactions with pedestrians, especially in shared areas. Numerous studies show that, recently, there has been a significant increase in pedestrian injuries following impacts with micromobility devices [8–10].

Data on accidents involving these road users underscore the importance of ensuring their safety.

In Italy, ISTAT data from 2023 [11] report a total of 3,365 accidents involving electric scooter drivers, with 3,195 injuries and 21 deaths. These figures are higher than in 2022, which recorded 2,929 accidents, 2,787 injuries, and 16 fatalities. Many of these accidents involve collisions with pedestrians, including 182 injured, one pedestrian hit, and one pedestrian killed. Of the 3,173 accidents recorded in 2023, approximately 1,573 involved vulnerable road users, with more men than women affected. Despite increasing safety concerns, scientific insights into the dynamics of micromobility and pedestrian collisions remain limited, with most data originating from injury reports rather than biomechanical or simulation research.

Unlike motor vehicles, electric scooters often come into contact with a pedestrian's limbs or torso before they start to fall. This contact leads to the development of a rotary moment that generates unusual falls, different from those generated by the auto-pedestrian contact.

Furthermore, the handlebars and frame of these vehicles have rigid surfaces that could hit parts of the pedestrian's body before the e-scooter even falls, increasing the risk of injury.

Once established, it is crucial to thoroughly analyze the body's kinematics and the relative impact velocities that pedestrians experience in accidents involving mobility

vehicles. While conventional empirical data are available, the development of simulation-based methods to better understand injury mechanisms is highlighted. As a result, details like the direction of impact, the gender of the scooter rider, the pedestrian's gender, and the passenger's posture are often overlooked.

While some studies examine how impact direction affects user injuries, there is a lack of analysis of how anthropometric parameters such as body mass, height, center of gravity position, and segmental mass distribution influence outcomes.

Most standardized simulations and crash tests use male anthropometric models (50th percentile), often ignoring important biomechanical differences between men and women, like body mass distribution, neck muscle endurance, and height. These factors directly influence head movement and injury results [12, 13]. These limitations underscore the need for research that systematically examines micromobility collision mechanisms and assesses injury severity in controlled settings.

This study seeks to address this gap by examining how the HIC (Head Injury Criterion) index varies in scooter-pedestrian impacts using the Virtual Crash multibody simulation environment [14]. It aims to quantify how gender-based anthropometric differences affect TBI severity, offering new insights to help create more inclusive safety standards.

2 Materials and Methods

The present research, therefore, aims to investigate whether and what differences exist in the severity of injuries sustained by vulnerable users following impact. In particular, the investigation focuses on potential differences in injury severity between men and women. The type of impact investigated is a collision between an e-scooter driver and a pedestrian, based on the need highlighted by recent years' accident data.

Therefore, it was decided to investigate the dynamics of collisions between these two vulnerable road users. In the technical literature, the most relevant parameter for assessing the pedestrian's injury is the HIC (Head Injury Criterion) [15–18].

This criterion, to assess head injuries, which are the most serious injuries to the body following an accident, is based on the measurement of the actual head deceleration after impact (see Eq. 1).

$$HIC = \max\left[(t_2 - t_1) \bullet \left(\frac{\int_{t1}^{t2} a(t)dt}{t_2 - t_1}\right)^{2.5}\right] \tag{1}$$

Where:

-a represents the acceleration over the time interval;

-t_2 and t_1 represent the time interval that maximizes the average deceleration.

The equation proposed above can be simplified as a mass-spring model (see Eq. 2) [19]:

$$HIC = K * V^{2.5} \tag{2}$$

Where:

-K is a constant of proportionality equal to 33.93;

-V is the maximum velocity of impact (m/s);

Using the AIS scale, HIC values (dimensionless) can be converted to assess the likelihood of serious injury [20]. This probability can be evaluated through the following relationship for AIS4 (see Eq. 3).

$$Probability\ of\ injury = \frac{1}{\left[1 + \exp\left(\left(\frac{4{,}9+200}{HIC}\right) - 0,00351 \bullet HIC\right)\right]} \tag{3}$$

This relationship uses the maximum head-to-ground impact velocity from crash test simulations to estimate HIC values. The HIC values are then used to assess the likelihood of severe TBI (Traumatic Brain Injury) using the AIS (Abbreviated Injury Scale; see Fig. 1). This establishes a relationship between the vehicle's collision speed and the likelihood of severe head injuries.

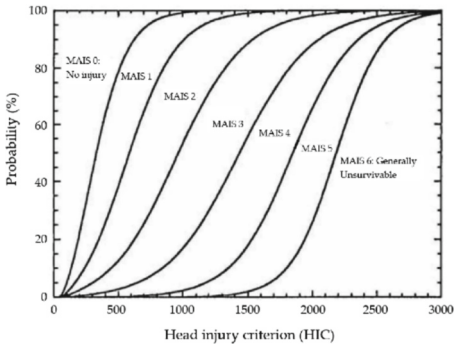

Fig. 1. Prasad–Mertz probability curves for a specific injury at a given HIC value [21].

Therefore, to estimate the HIC sustained by users involved in an accident, it is necessary to know the head's speed at impact.

To know this magnitude, a multi-body simulation software, such as Virtual Crash, was used in the present research [14].

Virtual Crash is a well-known, moment-based crash reconstruction software widely used in car accident research and by law enforcement agencies in Europe and America. The software is based on Kudlich–Slibar rigid-body impulse models [22] and uses a mixed Euler-Runge-Kutta numerical integration method [23]. Importing diverse models, such as CAD models of vehicles, pedestrians, terrain, and obstacles, enables the most accurate reconstruction of the working environment.

The software uses 13 ellipsoidal objects connected by joints to create a ragdoll model of cyclists and pedestrians, with shape, size, and weight adjustable. Changes in mechanical properties, such as joint stiffness, damping, and posture, can create a realistic human model. The models have been adapted to replicate the postures of e-scooter riders and pedestrians.

This software enables the development of a sensitivity analysis with a low computational burden; for this reason, it was used in the present research.

However, since Virtual Crash is a software based on rigid models, it is necessary to validate its outputs against those from more sophisticated finite element software.

D'Apuzzo et al. [24] investigated the impact between a scooter driver and an SUV, developing the simulation using Virtual Crash. They then compared the HIC results with those presented by Ptak et al. [25], obtained by implementing the same simulations in Madymo. Madymo is a finite element software that goes beyond the rigid model simplification provided by Virtual Crash. A comparison of the HIC values showed a strong correlation, leading to the identification of a more critical case history involving a frontal impact in which deformations play a fundamental role. In this case, the HIC value from the Virtual Crash software, despite being notably different from Madymo's, is very high. This suggests an inherent criticality of the Greater scenario that exceeds the more accurately reconstructed one.

Therefore, in any case, the HIC values obtained would allow for safety considerations.

Despite these limitations, Virtual CRASH offers significant advantages for studying collisions in the micromobility field. It enables systematic variation of parameters such as velocity, mass, angle, and anthropometry, thereby isolating the effects of each factor on injury severity. In addition, it provides kinematic outputs, such as head velocity, impact time, and center of mass motion, which are essential for calculating injury metrics, such as the criterion for head injury.

The methodology is first and foremost based on the definition of the influential variables to be considered.

It was decided to analyze the influence of the following characteristics:

- Type of e-scooter with different masses;
- Speed of the scooter driver;
- Type of pedestrian hit, distinguished in terms of gender;
- Type of scooter driver, distinguished in terms of gender;
- Types of impact angles.

The choice of electric scooter type fell on the typical micromobility vehicle used in urban areas. The substantial difference among the types chosen in the simulations concerns mass. From the analysis of the literature [26–28] and from the mobility reports shared, also by sharing companies, it was possible to identify characteristic masses of these vehicles: 12, 15, and 20 kg, which respectively indicate different types of material, i.e., carbon fiber, aluminum, and steel.

As for the height and orientation of the handlebars, they are adjusted in the Virtual Crash software (see Fig. 2) to accommodate typical riding postures, ensuring that both male and female riders adopt realistic positions.

As regards permitted speed limits, the Highway Code D.L. 2021 [29] provides a maximum of 20 km/h, while in pedestrian areas it drops to 6 km/h.

Particular attention should be paid if you use a sharing scooter. These vehicles are equipped with a GPS tracking system that connects to the company's network via the application installed on the user's mobile phone. These applications automatically limit vehicle speed to 6 km/h when users enter an area marked on the GPS as a pedestrian area, as required by Legislative Decree 2021.



Fig. 2. Model of e-scooters in Virtual Crash software.

The technical data sheets for the scooters showed that the maximum speed ranges from 25 to 30 km/h.

As for the angles of impact selected for the simulations, they correspond to:

-0° = frontal impact;

-0° off-center = off-center frontal impact;

-90° = side impact;

-180° = rear impact;

-180° off-center = off-center rear impact.

These directions were chosen because they represent real, standard, and observed collision configurations in shared spaces between pedestrians and micromobility.

Frontal impacts typically occur when a scooter rider approaches a pedestrian head-on, while offset impacts occur when a pedestrian tries to avoid an approaching scooter rider. Side impacts often happen at intersections or when pedestrians are in the path of an approaching e-scooter.

As defined in the Introduction, a specific gap in the current research concerns the analysis of any differences, in terms of harmfulness, between users involved in accidents based on gender.

This aspect appears essential, as differences in mass, height, and the position of the center of gravity can influence the outcomes of collisions. Generally, women have lower mass and stature than men, which could alter the extent of rotation during impact and, consequently, influence the timing and severity of head impacts with the ground.

As for the Virtual Crash software, it uses 13 ellipsoidal objects connected by joints to create a ragdoll model of cyclists and pedestrians, with adjustable shape, size, and weight. Mechanical properties, such as joint stiffness, damping, and postures, can be modified to obtain a more realistic human model. The models have been adapted to replicate the postures of scooter drivers and pedestrians.

To evaluate the anthropometric proportions, referring to the male and female dummies to be considered, the type of "adult" dummy was examined, and, based on literature analysis, the proportions were deduced.

For male models, the height is about 1.75 m, and the mass is about 75 kg. The women's models were configured with a height of 1.62 m and a mass of 62 kg [30–34].

Once these variables were defined, 120 simulations were performed in the Virtual Crash software (see Table 1).

Table 1. Parameters and variables considered for the impact scenarios.

E-scooter weight (kg)	E-scooter speed (km/h)	Impact Angle (°)	Pedestrian Gender	Rider Gender
12 15 30	6 15 20 30	0 180 90 0 off 180 off	Male Female	Male Female

From the simulations, the time history of the head speed experienced by the subjects involved in the accident (see Fig. 3) was obtained, which, when applied to the Head Injury Criterion, enabled the HIC to be evaluated.



Fig. 3. Head speed time history experienced by the e-scooter rider and the pedestrian in the Virtual Crash.

3 Analysis of Results

From the simulations, it was possible to analyze the impact mechanism on the users' heads. As far as pedestrians are concerned, there is an impact mechanism that includes two phases:

- Primary impact with the electric scooter: in this type of impact, the effect on the pedestrian's lower limbs first occurs. However, depending on the scooter model, the first contact may also affect the pelvis and/or torso. This impact then determines the trajectory of the pedestrian's torso as it is rotated and translated, shifting the center of mass relative to the feet.
- Secondary impact with the ground: following the first impact, the head touches the ground, and it is precisely this impact that determines the most severe HIC values.

The kinematics of the scooter rider's head follow a similar principle. When the rider is destabilized, the body can be thrown over the handlebars or to the side, resulting in a secondary impact with the ground.

As previously mentioned, the focus of the present research is to investigate whether and how gender difference affects the severity of injuries sustained as a result of impact. For this purpose, the HIC values, respectively for pedestrians and riders, obtained from the combinations of simulations described above, were correlated. In particular, for the pedestrian, the HIC correlation is shown in Fig. 4.

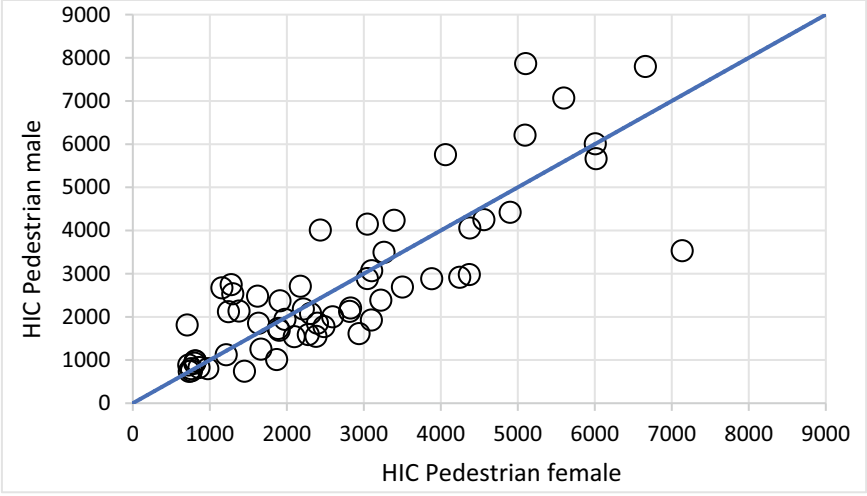

Fig. 4. HIC comparison between male and female pedestrians for electric scooter impacts.

The data show a general positive correlation, although there are substantial differences. There is significant dispersion around the bisector, indicating that the biomechanical response to impact differs substantially between the two genera.

The trend shows that, under the same accident conditions, male pedestrians have higher HIC values than women. This evidence could depend on the height and center of mass; even among pedestrians, the man is taller. This condition could, in the event of a fall, expose the head to impacts with the ground of greater kinetic energy.

Having ascertained this, we intend to investigate how the initial impact variables, set as simulation conditions, can influence the pedestrian's injury, differentiated by gender.

To investigate this, a correlation matrix (see Fig. 5) is presented that, using Pearson coefficients, allows examination of the relationships between the input variables and the Head Injury Criterion (HIC) injury index, calculated separately for male and female subjects.

The results show that the initial speed is the parameter most strongly correlated with HIC for both subjects, with Pearson correlation coefficients of 0.61 and 0.54 for the male and female pedestrians, respectively. Therefore, this highlights a slightly greater sensitivity of male pedestrians to changes in speed.

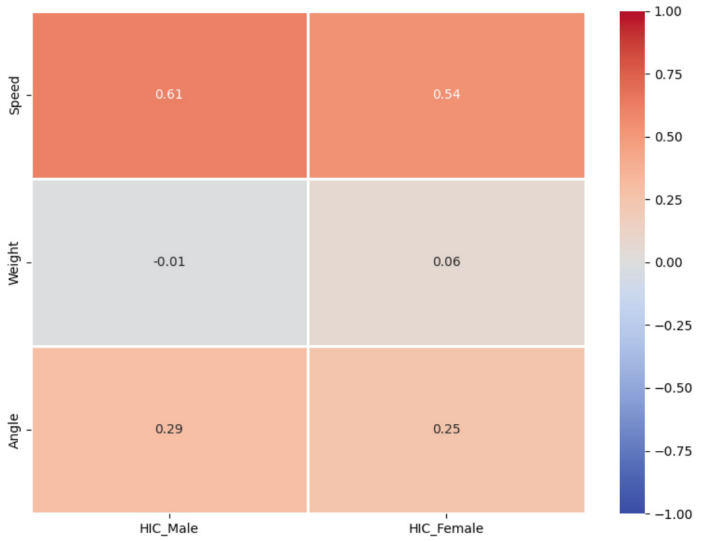

Fig. 5. Correlation matrix between impact parameters (speed, weight, and angle) and Head Injury Criterion (HIC) for male and female models.

As for the weight of the vehicle (in this case, an e-scooter), there is little correlation for both male and female pedestrians, with Pearson coefficients of −0.01 and 0.06, respectively.

The angle of impact, on the other hand, shows a modest correlation, similar for both sexes, suggesting a secondary effect.

Therefore, differences can be observed between male and female pedestrians, but for both, the vehicle's initial speed is a significant factor in the injuries sustained.

From the results obtained, it was therefore decided to investigate in greater depth the link between vehicle speed and the outcomes of injuries suffered by pedestrians, men and women (see Fig. 6).

What can be seen is that, in general, as speed increases, HIC values also increase markedly, confirming the strong relationship between speed and the severity of injuries sustained by pedestrians in impact events, as shown in the literature.

More specifically, at low speeds (5–15 km/h), there is an overlap between men and women. At higher speeds between 20 and 30 km/h, however, women begin to record higher HIC values than men.

It is therefore emphasized that this parameter should be investigated to understand the intrinsic variability it can generate across different simulation scenarios.

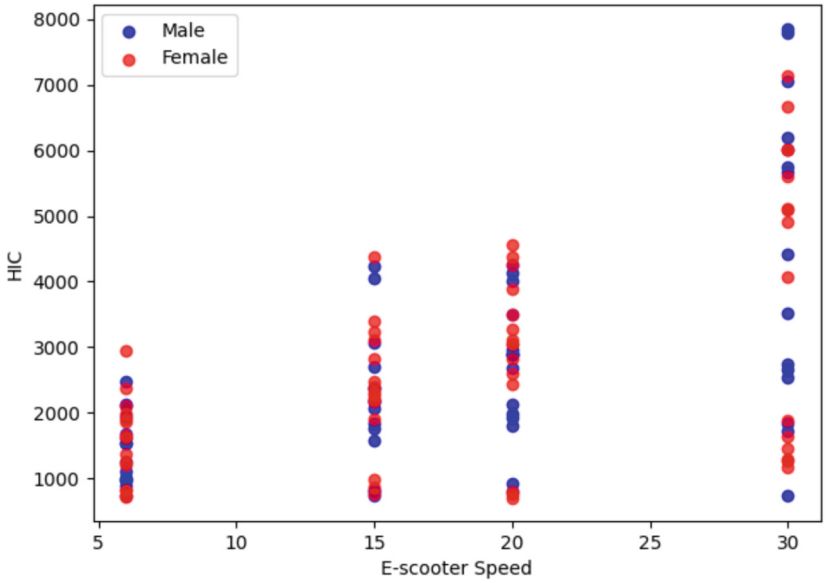

Fig. 6. Correlation between Speed and Head Injury Criterion (HIC) for male and female models.

4 Conclusion

The present work aims to investigate the influence of gender differences on the harm subjects suffer as a result of an impact. ISTAT data show that accidents involving micro-mobility vehicles are growing and, above all, that among the various vehicles, electric scooters account for a significant share. In addition, there are worrying data on collisions between drivers of these vehicles and pedestrians. This has led to a focus on this type of accident.

To determine the severity of the injury sustained by the subjects as a result of the impact, the Head Injury Criterion was used, which is expressed as the HIC. This criterion bases the severity of the recorded injury on the speed of the impact sustained by the subjects involved. To determine this magnitude, 120 simulations were conducted using the Virtual Crash accident reconstruction software. The simulations vary according to different boundary conditions: the gender of the subjects involved, the vehicle's initial speed and weight, and the angles of impact.

The analysis focused on the pedestrian figure. First of all, it was clear that the gender difference influences the outcome of the clash, with men recording greater injuries than women. This probably happens because men are taller, which exposes their heads to a greater fall with higher kinetic energy. Therefore, biomechanical gender differences influence the injuries sustained.

Having ascertained this, it was decided to investigate how the various input conditions could, or could not, influence the severity of the injury.

It was found that vehicle speed is the parameter most strongly correlated with HIC for both genders, with Pearson correlation coefficients of 0.61 for males and 0.54 for females. However, a significant fact that emerges, for higher speeds, is that the trend is reversed: women suffer greater injuries than men. This underlines a particular intrinsic criticality in some impact scenarios.

In contrast, the vehicle's mass (12, 15, or 20 kg) has almost no effect on injury severity.

This research, therefore, not only underlines the need to consider gender differences for these types of studies but also supports the effectiveness of speed restrictions, such as the 6 km/h limit, in pedestrian areas, to drastically reduce the risk of permanent or fatal trauma.

The gender differences considered in this study are limited to anthropometric parameters (mass and height), since Virtual Crash employs rigid-body multibody models that do not allow detailed biomechanical characterization of tissue properties or neck stiffness.

Future developments include investigating the influence of gender differences on injuries sustained by scooter drivers and implementing new simulations that include other modes of micromobility.

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