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A computational investigation of the dynamic factors governing severity of head injury to pedestrians involved in e-scooter collisions

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ABSTRACT

A rapid rise in the popularity of e-scooters has brought forth an increasing number of e-scooter-related conflicts, crashes, and injuries to pedestrians in many cities. There is a pressing need to understand the factors influencing the severity of injury to pedestrians involved in e-scooter collisions. This paper investigates the dynamics of e-scooter-pedestrian collisions and presents a new method for relating the probability of severe head injury to collision speed in e-scooter-pedestrian collisions. A total of 160 computer simulations representing different collision scenarios have been analyzed. Our results have shown that e-scooter speed is the main determinant of the severity of pedestrian head injury. E-scooter speed ranging from 10 to 15 km/h is found to be critical for pedestrian safety as the probability of severe head injury rises rapidly within this speed range. Moreover, an e-scooter-pedestrian collision is more likely to cause severe head injury to the pedestrian than a bicycle-pedestrian collision within the same speed range. It has also been found that the weight of the e-scooter and the direction of impact do not have a strong influence on the collision metrics, especially on the probability of severe head injury. The study has also investigated the post-collision fall mechanism for different pedestrian profiles and the influence of different impact angles. Finally, some recommendations have been proposed, including a speed limit of not more than 11 km/h for e-scooterist on shared paths where the likelihood of pedestrian and e-scooter conflicts is higher. The recommendations could help authorities develop legislation for safe micro-mobility.

Introduction

The emergence of lightweight, portable, and battery-assisted Personal mobility devices (PMD), especially e-scooters, offers a new mode of transportation for short-distance commuting (Ma et al., 2021; Rose & Richardson, 2009). This new mode of transportation is often referred to as Micromobility (Che et al., 2020). As half of the daily trips are less than 5 miles (Heineke et al., 2019), PMDs like e-scooters can provide an alternative to replace such short-distance travel by other motor vehicles (Fearnley, 2020). Therefore, PMDs like e-scooters have been viewed as a prominent solution to reduce congestion and bridge the current gap in the current transportation system known as the first and last mile problem (Fearnley, 2020; Levy, 2010; Schellong et al., 2019; Yang et al., 2020). Moreover, the concept of shared mobility, where battery-operated vehicles like e-scooters can easily be rented through a smartphone, has changed the urban mobility landscape (Bieliński & Ważna, 2020). Companies like Lime, Bird, and Scoot, are operating shared e-scooter services in many cities like Frankfort, Paris, California, Portland, and Berlin (Adeyemi, 2019).

The availability, ease of use, smaller form factor, and portability are some of the key design aspects that are driving the popularity of e-scooters among riders (Bloom et al., 2021; Button et al., 2020; Che et al., 2020; Dhillon et al., 2020). Many crowded cities and downtowns, where congestion is a prevalent problem, have adopted shared or privately owned e-scooters to commute faster and with ease. The cost-effective pricing of e-scooter sharing services has made the e-scooter a more affordable transportation alternative. Moreover, e-scooters are a recent addition to the transportation system. Therefore, they are viewed as a modern and innovative mode of transportation that gives a sense of independence and freedom and therefore appeals to many individuals. As a result, a large number of people intend to or are persuaded to try e-scooter (Guo & Zhang, 2021). Thus, social, economic, and psychosocial factors have contributed to a rapid rise in the popularity of these e-scooters. As a result, millions of trips have been reported to be

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completed using e-scooters within a short period (Basky, 2020).

Furthermore, the aftermath of the recent pandemic has had an accelerated influence on the adaptation of e-scooters as a means of transportation, as reported by many published articles. A large number of London commuters opted for an e-scooter instead of trains and buses during the pandemic (Sandle, 2020). Similar observations have been made in Portugal (Dias et al., 2021) and Turkey (Bagdatli & Ipek, 2022). Another research from Texas, USA, has found that the e-scooter trip length has increased during the pandemic(Dean & Zuniga-Garcia, 2023; Mehzabin Tuli et al., 2022). In fact, about 30 to 40 percent of the riders selected e-scooters for trips that would otherwise be made using private automobiles in major cities US cities (Fearnley, 2020).

However, the increasing popularity of e-scooters has also brought forth a number of challenges. Despite many governments promoting the micro-mobility and safe use of e-scooters, there has not been a fair share of equity and accessibility among disadvantaged communities such as racial and ethnic minorities and low-income populations (Aman et al., 2021). Moreover, another research in Italy has highlighted a gender gap among e-scooter riders where almost 89 % women did not use the e-scooter; as a result, the e-scooter ridership is purely male-dominant (Campisi et al., 2021). One of the possible causes for this gender bias is the perceived safety of riding an e-scooter on the current infrastructure. With the new policy to make micro-mobility and e-scooter more accessible to all genders and disadvantaged communities, the number of e-scooter riders is likely to increase further. Therefore, the risk of conflicts and crashes involving e-scooters is very likely to increase with the increasing population of e-scooter riders. This is evident from the alarming number of collisions and injuries involving e-scooters over the past few years (Ma et al., 2021; Zagorskas & Burinskienė, 2020).

The major challenges are the conflicts due to sharing the space and the significantly understudied rideability of e-scooters compared to other vehicles like cars, motorcycles, and bicycles. Furthermore, the speed of the e-scooters is regulated between 15 km/h to 25 km/h in many European and Asian cities. However, Texas city in the USA, has a speed limit of 32 km/h (20 mph) for e-scooters. To put this into perspective, the average pedestrian speed is 5 km/h, and the average motor vehicle speed is 40–50 km/h (Garman et al., 2020). Moreover, Greece and Poland allow e-scooter on pavements. Similarly, Singapore and some cities in Australia and America allow e-scooters on either shared paths or sidewalks, which could increase the scooterists' conflicts with pedestrians.

Considering the speed difference and vulnerability of the e-scooter riders with heavy motor vehicles on the road, some cities have allowed e-scooters on the sidewalk, bicycle paths, or shared paths (Basky, 2020; Garman et al., 2020). This step has reduced the conflict or possibility of potential road collisions between motor-vehicle and e-scooter riders; however, e-scooter-related conflicts and collisions with other users, such as pedestrians, are increasing (Badeau et al., 2019). Unlike the conventional bicycle users with whom vulnerable road users, i.e., pedestrians, have been sharing the space for an extended period, the pedestrian's perceptions and behavior are yet to be fully adapted to the sudden emergence of e-scooters (Che et al., 2020). Therefore, there have been increasing concerns regarding conflicts, and the risk pedestrians perceive from e-scooter riders on the sidewalk, bicycle paths, and shared paths (Beck et al., 2020; Cicchino et al., 2020; Comer et al., 2020; James et al., 2019). Researchers from the USA have reported that a majority of the e-scooter related crashes (about 58 %) occur on the sidewalk or footpaths compared to 23 % of crashes on the road (Cicchino et al., 2021a). With the increasing number of conflicts and collisions, injuries and some fatalities associated with the use of e-scooters have also been reported in news media (Bahl, 2019; Kate, 2020; Lim) and journal articles (Cicchino et al., 2021b; Liew et al., 2020).

Most of the published information is related to injury statistics and heavily relies on the retrospective data record maintained by emergency departments or hospitals (Badeau et al., 2019; Bloom et al., 2021; English et al., 2020; King et al., 2019; Mayhew & Bergin, 2019; Siman-Tov et al., 2017; Trivedi et al., 2019). A few articles also studied the cause of crashes, riding behavior, and rider and pedestrians' perception of e-scooters (Comer et al., 2020; Haworth & Schramm, 2019; Health, 2019; James et al., 2019). Further studies have shown approximately 20 individual injuries per 100 K e-scooter trips (Bekhit et al., 2020; County, 2019; Health, 2019). Bird (Bird, 2019), a shared e-scooter operator, also reported 23 injuries per million kilometers. Another report from the Portland bureau of transportation (E-scooter findings report, 2018) suggested approximately 136 collisions per million kilometers. Similarly, about 70 e-scooter collisions per million kilometers, which is about eight times higher than for bicycles, have been estimated in Denmark (Fearnley, 2020). Surprisingly, 600 injuries per million trips have been reported in New Zealand (Ioannides et al., 2022). Another Research from Singapore has reported that the severe injury rate is 3 times higher in motorized personal mobility devices, including e-scooters, compared to non-motorized devices (Tan et al., 2019). A comparison of injuries per million-kilometer data from multiple sources for bicycles and e-scooter suggested that e-scooter injuries can be almost double-digit higher than bicycle injuries (Buehler & Pucher, 2017; Health, 2019; E-scooter findings report, 2018). Furthermore, a study in the Journal of the American Medical Association (JAMA) reported a rise of 222 % in e-scooter related injuries before the arrival of shared e-scooter in 2014 and after the rental e-scooter started to roll on the roads in 2018 (Basky, 2020).

Although the collisions and injury data may vary depending on the location of the study, the analysis has shown a similar trend of a rapid increase in e-scooter related collisions and injuries in Australia, the UK, New Zealand, Singapore, and the USA (Basky, 2020; Beck et al., 2020; Liew et al., 2020; Mayhew & Bergin, 2019; Namiri et al., 2020). Moreover, the head and upper extremities are the most common body parts suffering from injuries (English et al., 2020; Wüster et al., 2020). Furthermore, a survey study from the USA by Namiri et al. (Namiri et al., 2020) reported that nearly one-third of the patient could suffer head injuries, double the number of head injuries sustained by bicycle collisions. Similarly, James et al. (James et al., 2019) reported that 72 % of pedestrians and 47 % of e-scooter riders believe that riding e-scooter on the sidewalk puts pedestrians at health risk. Moreover, data from the USA, UK, Israel, Australia, and Germany has suggested that about 10 % of the total e-scooter related collisions are reported to involve pedestrians (Bloom et al., 2021; Sikka et al., 2019; Siman-Tov et al., 2017; Störmann et al., 2020; Trivedi et al., 2019). Notably, pedestrians are said to suffer more severe injuries when hit by the e-scooter (Siman-Tov et al., 2017; Yang et al., 2020).

Due to the growing concerns and debate about e-scooter safety performance, and the increasing number of collisions, e-scooters started to suffer a set-back by the end of 2019, leading to strong restrictions on their use (Ma et al., 2021; Schellong et al., 2019). However, e-scooters are still allowed in many cities, and concerned authorities are constantly monitoring and revising the legislation. There is a pressing need to understand the conflicts that result in collisions and the factors that influence the severity of injury to pedestrians involved in e-scooter collisions. However, there is little published literature that provides insight into the collision dynamics, injury mechanisms, and factors that influence injury severity during a pedestrian vs. e-scooter collision. Most of the research has been based on archived data from hospitals or emergency departments. There is a lack of detailed analysis of e-scooter and pedestrian interactions, especially during a collision, which is important for proposing new policies and building shared paths for safer mobility in the future.

This paper presents a dynamic analysis of e-scooter and pedestrian collisions. The main aim of this paper is to establish a scientific rationale for relating the severity of pedestrian head injuries to the speed of e-scooter and pedestrian collisions, and to develop a basis for speed limits on crowded shared paths. Collisions are analyzed based on the indices like throw distance, peak head velocity before impacting the ground, head injury criterion (HIC), and probability of severe head injury. In addition, the paper also presents a detailed study of the collision mechanism and the influence of parameters like speed, pedestrian height and weight, vehicle weight, and impact on the severity of the injuries. One of the main objectives of this study is to establish a safe speed limit for e-scooter by examining the injury mechanisms and severity of the injury of pedestrians.

Method

We have used a multi-body dynamic software called Virtual Crash (VirtualCrash) to create various scenarios and simulate the e-scooter and pedestrian collision. Virtual Crash is an accident reconstruction software that is based on well-known impulse-moment principle. Virtual Crash results have been validated against international references such as Research Input for Computer Simulation of Automobile Collisions (RICSAC) and Japan Automobile Research Institute (JARI), as well as other staged experiments, and has been found to have good agreement with experimental results (Becker et al., 2015; Coufal & Semeia, 2014; Hoxha et al., 2017; Sovreski et al., 2017; VirtualCrash, 2021a). Moreover, Virtual Crash has been successfully used in motor vehicle collision research as well as by law enforcement authorities in Europe and America. The software is based on the Kudlich-Slibar rigid body impulse model and uses mixed Euler and Runge-Kutta numerical integration methods (VirtualCrash, 2021b).

Human body models

Virtual Crash uses a multi-body model of rider, and pedestrian using 13 ellipsoidal objects are used to define different body parts, as shown in Fig. 1. The body parts are connected by joints to create ragdoll human models. The software adjusts the shape, size, and weight of each body part based on the weight and height of the human model. Furthermore, the software also allows changing the posture, joint stiffness, and damping parameters to make a realistic human model. The human model does not react to the impact by extending the hand or using other body parts to deliberately break the fall. Therefore, the model can be considered a passive human model. Most importantly, it should be noted that the human model does not include biomechanical properties like tissue or bone properties. However, the model preserves the anthropomorphic properties of the human body. Such multi-body models have been successfully used by various computational software like MADYMO (GuideDogs, 2021; Searle, 1993) and PC Crash (Moser et al., 1999; Traets) to study the fall mechanisms and impact kinematics.

In this computational analysis, two different pedestrian profiles that are different in weight and height were selected. The two pedestrian profiles resembled an adult and a child. The weight and height of these two profiles are based on the mean values of the Singapore population (Ministry of Health (Singapore). Singapore National Health Surveillance Survey, 2013). The details of the pedestrian profiles are listed in Table 1.

Table 1
Anthropomorphic parameters of pedestrian profiles.

Parameters	Pedestrian profiles	
	Pedestrian profile 1	Pedestrian profile 2
Resemblance	Adult (Age: 18–30 years)	Child (Age: 7–12 years)
Height (m)	1.73	1.367
Mass (kg)	69.20	34.70
Body width (m)	0.460	0.365
Center of mass height (m)	1.094	0.862

E-scooter model

Three E-scooter models of different masses were considered in this analysis. The lightest E-scooter has a 12.5 kg weight, followed by 20 kg, 25 kg, and 30 kg e-scooters. The corresponding inertial properties of the e-scooter models associated with their weights have also been considered. The resemblance of the e-scooter model in Virtual Crash with the similar commercial model of an e-scooter is illustrated in Fig. 2. Although the e-scooter has a retrofitted seat, it can accommodate a standing rider. The geometrical and mass-related details of the e-scooter model are listed in Table 2.

Collision scenarios

This computational study represents a scenario where an e-scooter and pedestrian collides on a level road. In each simulation. the e-scooter moves at a pre-defined speeds while the pedestrian is maintained stationary. To maintain a constant relative speed between the pedestrian and the e-scooter, no brake was applied before the collision. Four metrics, (i) pedestrian's throw distance, (ii) peak head-ground impact velocity, (iii) Head Injury Criterion (HIC) value, and (iv) probability of severe head injury, have been used to analyze the e-scooterist-pedestrian collisions quantitatively. Moreover, the orientations of the pedestrians were changed to analyze the effect of impact directions on the fall mechanism and collisionmetrics.

Here, the head throw distance is defined as the forward distance the head traveled between the initial position before the collision and the final position after the collision. Similarly, the peak head velocity is defined as the maximum velocity with which the head impacts the ground due to the collision. From the simulation, the pedestrian's head throw distance and peak head-ground impact were extracted. Typical results of pedestrian throw distance, and peak head-ground impact velocity obtained from Virtual Crash are shown in Fig. 3.

It should be noted that this investigation is trying to study the worst-case scenario where the pedestrian's head hits the ground with the maximum possible velocity. In this scenario, the pedestrian collapses immediately after being hit by the e-scooter. In real life, pedestrians often use their hands to break a fall; however, in this study the

Fig. 1. (a) Ragdoll model to represent human subjects and (b) Ragdoll model after adding realistic-looking exterior.

Fig. 2. E-scooter model (left- actual e-scooter mode, right- Virtual Crash model).

Table 2
E-scooter design parameters.

Parameters	Unit	Values
Vehicle weight	kg	12.5
Wheelbase	m	1.017
Handlebar height	m	1.121
Saddle height	m	0.9

pedestrian's body model is passive and does not react to the impact with their hands. A similar approach has been used by Posirisuk et al. (Posirisuk et al., 2022) in their study of e-scooters and pothole interaction. Nonetheless, human models were adjusted to replicate pedestrians and the standing posture of e-scooterist. The joints are defined accordingly to represent the realistic movement of the human body. As a result, the neck can snap forward and backward, but bend backward movement knees and elbows are restricted. In addition, the software's default coefficient of restitution value of 0.1 is used for the human body.

Impact direction

All the impacts studied here are head-on impacts meaning that the e-scooter hits the pedestrian along the centerline. Four impact directions; 0- degree, 90-degrees, 180-degrees, and 270-degrees, have been considered in this study. The directions are based on the orientation of the pedestrian with respect to the e-scooter, as illustrated in Fig. 4.

Impact speed

In this study, the e-scooter-pedestrian collision speed is varied from 10 km/h to 30 km/h in increments of 5 km/h.

Contact characteristics

In Virtual Crash, the body parts of the pedestrians of the riders are connected by the ragdoll joints, and the user can adjust the stiffness and the damping of the joints. However, in this study, the default value of joint stiffness and damping in Virtual Crash has been used. The default value of joint stiffness and damping allows the human model to hold the posture until it encounters surface or colliding objects. Thereafter, the posture is released, and the human body acts as a flaccid body similar to the Articulated Total Body (ATB) used in many vehicle crash tests. This method has been found to work reasonably well in simulations to study the overall motion of the human body in various crash tests (Virtual-Crash, 2021a). Besides human body joint parameters, contact characteristics such as coefficient of friction (COF) and wheel adhesion coefficient have been carefully selected based on previously published literature. The parameters and their values are listed in Table 3.

Mathematical formulation

Head Injury Criterion (HIC) and Abbreviated Injury Scale (AIS 4) have been used to assess the severity of head injuries. The HIC is a measure of the likelihood of head injury caused by an impact. The HIC values have been related to the AIS scale, which is a coding system for classifying and describing the severity of injuries. The HIC and probability of a severe head injury (AIS 4) are calculated using equations (1)

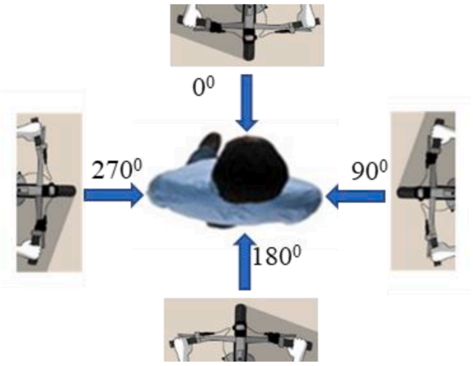


Fig. 4. A top view illustration of e-scooter and pedestrian collision directions.

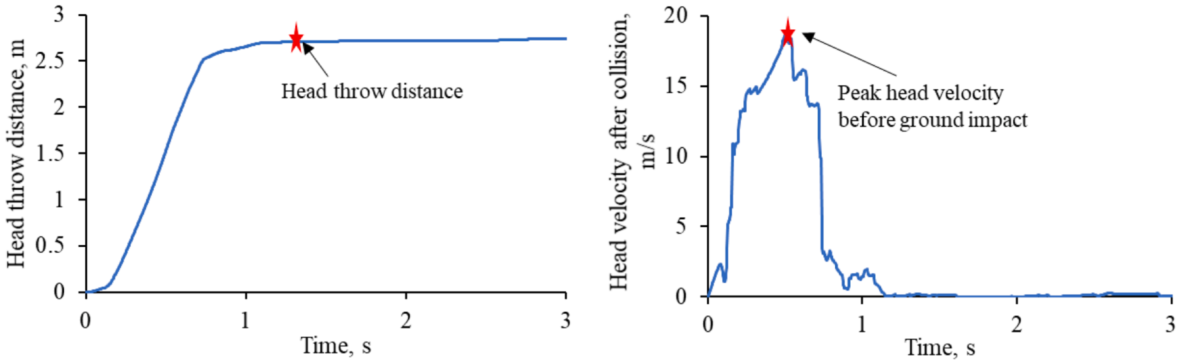


Fig. 3. A typical illustration of data obtained from Virtual Crash.

Table 3
Parameters used in e-scooter and pedestrian collision.

Human parameters	Reference	Selected values*
Joint stiffness	Default value Virtual crash	2 N/m
Joint damping	Default value Virtual crash	0.1 Ns/m
Human-ground coefficient of friction	Wood (Wood & Simms, 2000) and Han (Han & Brach, 2001)	0.8
Vehicle-ground coefficient of friction	Batista (Batista, 2008), Lin (Lin et al., 2012),	0.5
Wheel adhesion coefficient	Leng (Leng et al., 2021)	0.78

* Selected values are closer to the values in the reference literature.

(Hutchinson et al., 1998) and 2 (Berkowitz, 2001), respectively.

$$\mathrm{HIC} = \max\left[(t_2 - t_1)\cdot\left(\frac{\int_{t_1}^{t_2} a(t)\mathrm{d}t}{t_2 - t_1}\right)^{2.5}\right] \tag{1}$$

Probability of severe head injury = 1/ [1 + exp ((4.9 + 200/HIC)-0.00351 x HIC)] (2).

The standard HIC formula, equation (1), has been modified by considering a simple mass-spring model of the impact, as detailed in reference (Gao & Wampler, 2009). The modified formula for estimating the HIC values can be written as:

$$\mathrm{HIC} = K^{*}\mathrm{v}_1^{2.5} \tag{3}$$

The modified equation related HIC value to impact velocity using a proportionality constant (K). The proportionality constant was calculated to be 33.9 based on the experimental results of a human dummy fall on a dry asphalt surface (Fanta et al., 2012). In this way, we are able to quickly estimate the HIC values based on the maximum head-ground impact velocity.

We would also like to highlight that the main contribution of this study is the development of a simplified methodology to correlate impact velocity to the probability of head injury, identifying the factors that influence the injury severity and a detailed study of the injury mechanism for e-scooter and pedestrian collisions. The method that we have formulated for relating the e-scooter-pedestrian collision speed to the probability of severe head injury to the pedestrian is shown in Fig. 5. For each collision scenario parameters such as collision speed, the pedestrian profile, impact directions and e-scooter weight are set, and the simulations are run. The maximum head impact velocity of pedestrian's head is extracted from the simulation and is used to calculate the HIC value using equation (3). Thereafter, an AIS curve is used to relate

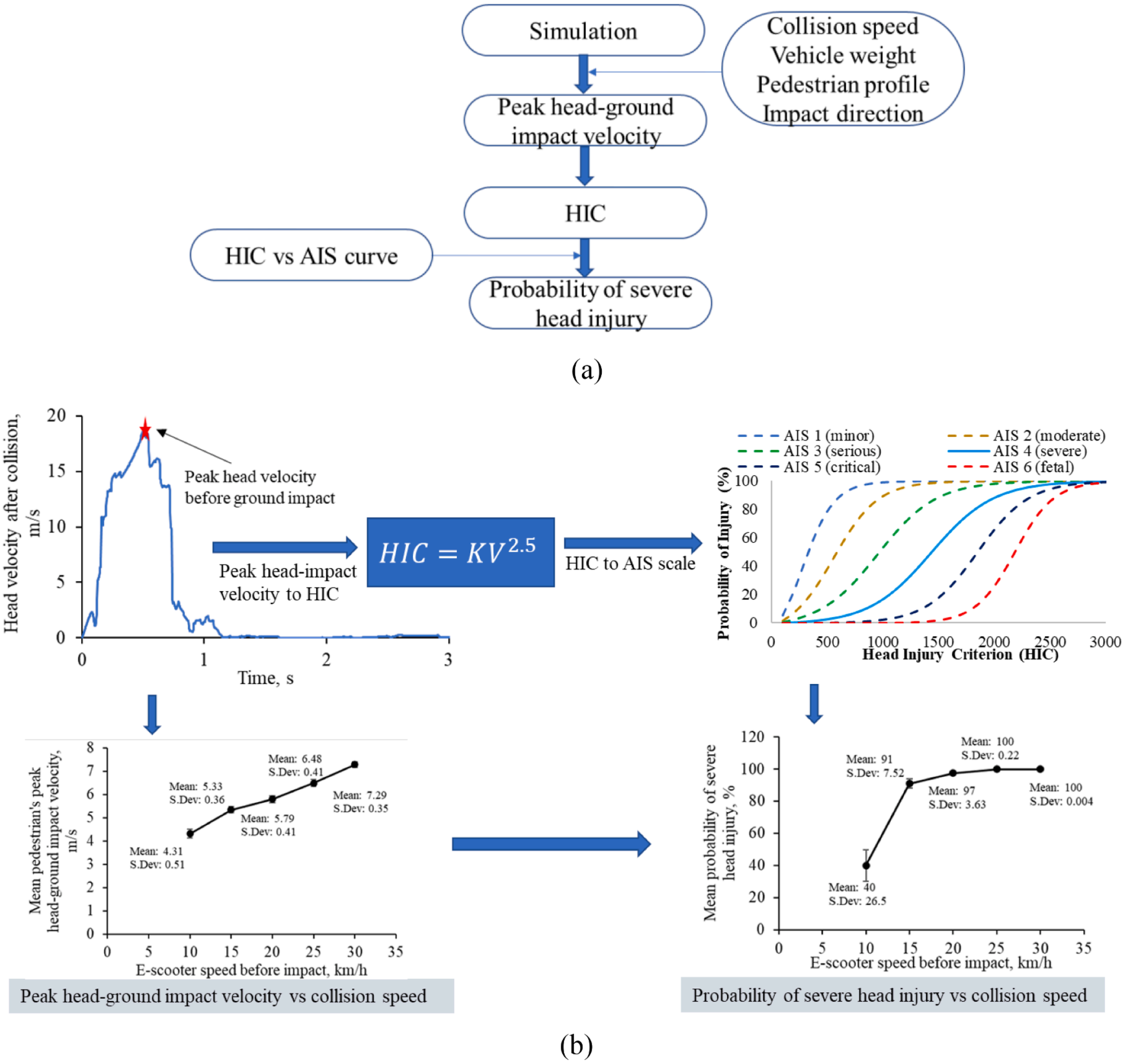


Fig. 5. A representation of the overall methodology adopted for analysis: (a) calculation of probability of severe head injury (b) methodology for relating collision speed with probability of severe head injury.

the HIC and the probability of severe head injury. Thus, a relation between collision speed and probability of severe head injury to pedestrian can be established. This method enables to recommend a speed limit for e-scooterist on narrow and shared paths based on the probability of severe head injury to the pedestrian.

Results and discussion

Validation of Virtual Crash model and fall mechanism

The challenge in this study is the lack of relevant data from published articles. We have used two approaches, based on the limited available data and information, for preliminary validation of the results obtained from the Virtual Crash. The first approach is to quantitatively compare the outcome of e-scooter and pedestrian collision in terms of throw distance, head impact velocity, HIC value, and injury severity using some available data. The second approach is to use the crash test videos obtained from different sources and compare the fall mechanism of pedestrians after colliding with the e-scooter predicted by the Virtual Crash simulation.

In a pedestrian and e-scooter crash test conducted by Union Technique de l'Automobile du motorcycle et du Cycle (UTAC) Millbrook (GuideDogs, 2021; Winchcomb, 2022), an adult pedestrian was reported to be thrown by 3.45 m when struck by an e-scooter at 25 km/h. Moreover, as cited on Parliamentary Advisory Council for Transport Safety (PACTS), UK report (Winchcomb, 2022), the test showed that, based on the head injury criterion (HIC), there is a 90 % probability of fatal injury when a pedestrian's head collides with the ground after being struck by an e-scooter at 25 km/h. This 90 % probability of fatal head injury corresponds to a more than 98 % probability of severe head injury.

For a similar scenario, Virtual Crash has predicted a throw distance of 3.153 m throw distance. The difference between the dummy test and the Virtual Crash result is about 9 %. This difference can be justified by comparing the height of the Virtual Crash human model with a 95th percentile adult ATB model. The height of the pedestrian model in Virtual Crash is 1.73 m, whereas a 95th percentile ATB has a height of 1.91 m. As the head of the bicyclist and e-scooterist human model in crash tests has been found to follow a trajectory like a projectile (Werner et al., 2001), the pedestrian model with greater height will have more throw distance. In addition, Virtual Crash predicted a 99 % probability of severe head injury for pedestrian and e-scooter collision at 25 km/h which is comparable to the value reported by PACTS (Winchcomb, 2022).

Moreover, Fig. 6 compares the peak head-ground impact velocity and the corresponding the HIC value obtained from Virtual Crash using equation (1), with similar crash data obtained from the literature (Hajiaghamemar et al., 2015; Moure-Guardiola et al., 2020; Playsafe, 2016; Saczalski et al., 1976; Zhang et al., 2009). Due to a lack of HIC data for pedestrians involved in e-scooter collisions, relevant data from human dummy and headform drop tests were considered for comparison. It can be noted from the figure that Virtual Crash results are similar to the crash data considered for comparison.

Similarly, Fig. 7 presents a comparison between the Virtual Crash simulation model and video of e-scooter-pedestrian crash tests using dummies. For comparison, time steps after the e-scooter collide with the pedestrian have been considered. As can be seen in both the simulation and the dummy test video, the first impact on the pedestrian is near the waist and comes from the e-scooter handlebar. Thereafter, the rider's and pedestrian's bodies collide. As the impact from both the handlebar and rider-pedestrian body collision is above the pedestrian's center of mass, the pedestrian starts to fall toward the ground. Although the pedestrian's fall mechanism in the dummy test video and Virtual Crash simulation are similar, the scooter rider's fall mechanism is different. This can be attributed to the fact that the rider's hands were tied to the handlebar in the experiment, which restricted the forward motion of the rider.

The virtual crash simulations were compared with two additional dummy crash tests (Hess, 2020; RCAR, 2020), as shown in Fig. 8. Pedestrians' fall mechanisms in both videos and Virtual Crash simulations are largely similar. In Fig. 8 (a), both rider model has a walking posture which contributed to a different fall mechanism of the rider. The rider's body rotated after collision with the pedestrian in the dummy test due to walking posture, whereas the rider falls forward without rotation in Virtual Crash simulation. However, both the crash test and Virtual crash simulation have predicted a sideways fall of the pedestrians. Similarly, in the case of the 90-degree child pedestrian and e-scooter crash test, the wheel contacts the child pedestrians first; after that, the child leans toward the e-scooters and collides with the handlebar before falling forward. Virtual Crash simulation has clearly illustrated this falling mechanism of child pedestrians. Again, the differences in the fall mechanism of the e-scooter rider in the Virtual Crash simulation and the crash test videos are attributed to the rider's initial posture.

The authors would like to acknowledge that we could not present more detailed validation due to a lack of published literature and data. However, comparisons of throw distance, HIC values, injury severity, and fall mechanism of child and adult pedestrians at various collision directions and velocity with crash experiments have provided a preliminary validation for Virtual Crash simulations.

Parametric analysis

It should be noted that the results presented in this section are based on multiple levels of speed, pedestrian profiles, e-scooter weight, and impact directions. Statistical values like mean, standard deviation, and confidence intervals have been presented in the analysis. Moreover, one

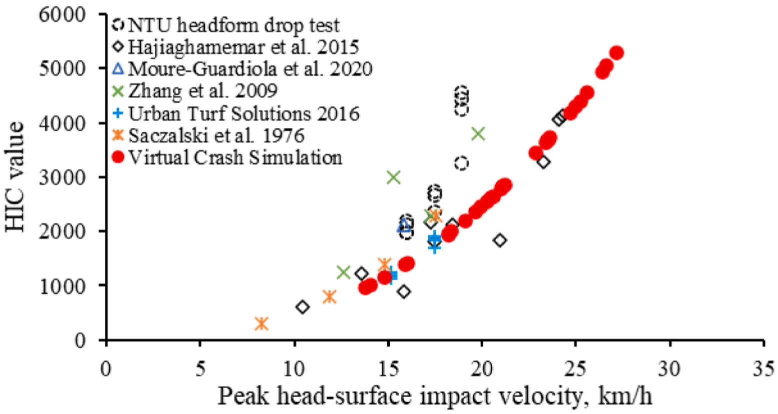


Fig. 6. Comparison of HIC value estimated using Virtual Crash data and published experimental data.

Fig. 7. Comparison of pedestrian's fall mechanism between (a) laboratory experiment using human dummy (GuideDogs, 2021), and (b) Virtual crash simulation.

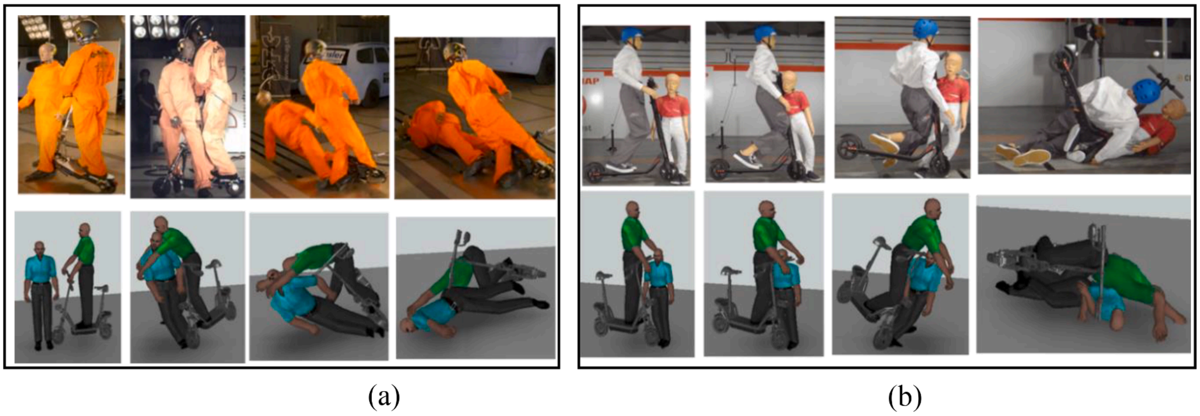


Fig. 8. Comparison of experiments using human dummies and Virtual Crash simulations for 90-degrees collision between e-scooter and (a) adult pedestrian (b) child pedestrian.

way Analysis of Variance (ANOVA) tool has been used to assess if any variable has a significant effect on the collision metrics.

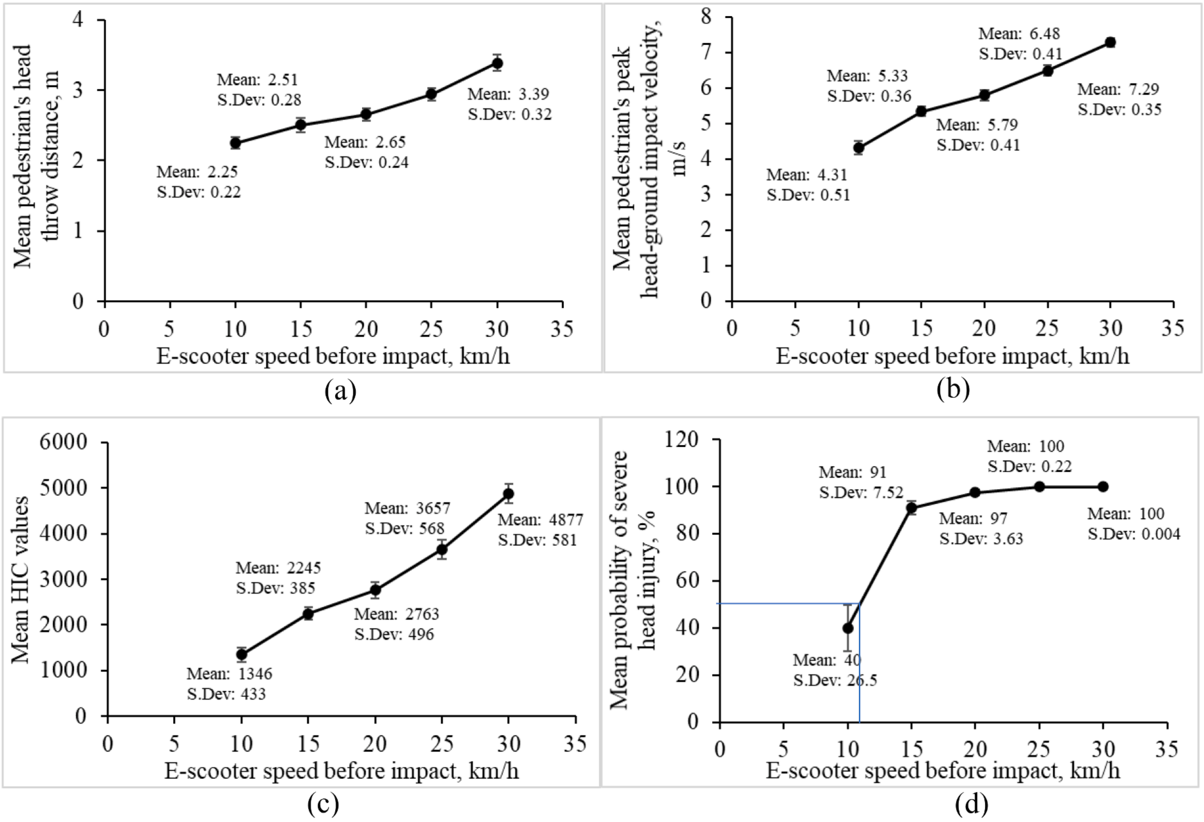
Effect of speed

Speed has been known to be the most crucial factor in a collision as it relates to the momentum and kinetic energy of the rider-vehicle system (Organization). Fig. 9 shows the overall effect of e-scooter speed on a pedestrian's throw distance, peak head impact velocity, HIC, and probability of severe head injury. It should be noted that the results presented in Fig. 9 are mean values considering two levels of pedestrian, four levels of e-scooter mass, and four levels of impact directions. Therefore, there are 32 simulations for each speed.

The results have shown a 75 % increase in the mean head throw distance of the pedestrians from 2.25 m at 10 km/h collision speed to 3.39 m at 30 km/h. Similarly, mean peak head-ground impact velocity, HIC, and probability of severe head injury have shown an increase of 69 %, 260 %, and 150 %, respectively, when speed is increased from 10 km/h to 30 km/h. The results were analyzed using a single factor ANOVA. Collision speed showed a significant effect on mean head throw distance ($F(df1, df2) = 14.25$, $p = 0.000$), mean peak head-ground impact velocity ($F(df1, df2) = 104.62$, $p = 0.000$), mean HIC value ($F(df1, df2) = 82.33$, $p = 0.000$), and mean probability of severe head injury ($F(df1, df2) = 77.55$, $p = 0.000$).

The results can be attributed to the increase in momentum and the kinetic energy of the e-scooter and rider system for higher speeds. The HIC values increased approximately by 900 for every 5 km/h increase in the collision speed. However, there is a steep increase in the probability of severe head injury when the collision speed is increased from 10 to 15 km/h. This sharp increase in the probability of severe head injury can be explained by the "S" shaped curve of HIC vs. AIS probability graph, as illustrated in Fig. 5. There is a significant increase in the probability of severe head injury when the HIC value increased from 1200 to 1800. At 10 km/h, the mean HIC value is around 1346 ± 158, corresponding to the probability of severe head injury is 40 % ± 9.7 %. Considering the error bar based on a 95 % confidence interval, the probability of severe head injury ranges from nearly 30 % to 50 %. However, when the speed is increased to 15 km/h, the HIC value is more than 2000, which significantly increases the probability of severe head injury to 91 %. The results clearly signify that the probability of severe head injury to the pedestrian could increase drastically even with a small increment in collision speed.

A recent article by Paudel et al. (Paudel et al., 2022) has also suggested that the speed range of 10–15 km/h is crucial for a pedestrian head injury in a bicycle-pedestrian collision. Fig. 10 compares the HIC and probability of severe head injury to pedestrian in e-scooter-pedestrian collisions and bicycle-pedestrian collisions. It is interesting to note that e-scooter-pedestrian collisions are more likely to result in severe head injury at higher speed. The HIC value and the probability of severe head injury to pedestrians at 10 km/h collision speed are similar in both bicycle-pedestrian (HIC: 1349, AIS 4: 42 %) and e-scooter-pedestrian



(a) (b)

(c) (d)

Fig. 9. Effect of speed on collision metrics (a) mean pedestrian's head throw distance, (b) mean pedestrian's peak head-ground impact velocity, (c) mean HIC value and (d) mean probability of severe head injury (32 simulations per speed).

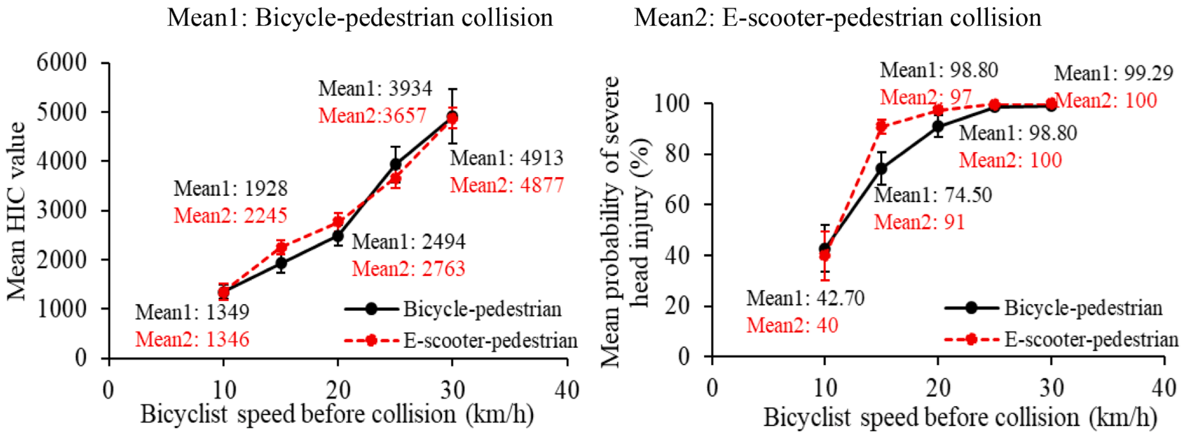


Fig. 10. Comparison between bicycle-pedestrian and e-scooter-pedestrian collisions.

collisions (HIC: 1346, AIS 4: 40 %,). However, the values rapidly increase to HIC: 2245 and AIS 4: 91 % for e-scooter-pedestrian collision in comparison to HIC: 1928 and AIS 4: 74 % for bicycle-pedestrian collision at the collision speed of 15 km/h. The results have shown that the probability of severe head injury to the pedestrian is greater in an e-scooter-pedestrian collision than a bicycle-pedestrian collision at the same speed.

Limiting the speed of e-scooters in crowded places like footpaths and shared paths will reduce the risk of severe head injury to pedestrians in the event of a collision. Fig. 9 shows that speed below 11 km/h has a probability of severe head injury of less than 50 %. Based on the results and because this study investigates the worst-case scenarios where pedestrians are likely to endure maximum possible head injury severity, the authorities could adopt a speed limit of not more than 11 km/h, especially in the shared space where there is a higher risk of pedestrian and e-scooter conflicts. Some cities have already imposed lower speed limit for e-scooters in areas with high pedestrian density. For example, the speed limit for e-scooters is 10 km/h on footpaths in Singapore (LTA, 2021), 10 km/h in most areas in Paris (Euronews, 2022), 8 mph (12.9 km/h) in 'go slow' areas in London (UKAuthority, 2021), and 6 km/h in pedestrian areas without cars in Rome (Euronews, 2022). Whilst a lower speed limit might reduce the risk of injury to pedestrians, this must be balanced against the rideability and utility of the e-scooter when the speed is set too low.

Effect of height and mass

This section discusses the effect of pedestrian profiles on collision metrics. In this study, two pedestrian profiles are modeled based on the mean height and mass of a Singaporean adult and child. Although the pedestrian profiles account for the anthropomorphic data, it does not include the age-related biomechanical factors like skin properties and differences in injury susceptibility of adult and child. The main aim of this study is to see the effect of mass and height on the impact outcomes.

Fig. 11 shows the combined effect of pedestrian profiles having different heights and masses. It should be noted that Fig. 11 represents the combined effect of 5-speed levels, four vehicle mass levels, and four impact direction levels. The pedestrian's profile has a more distinct effect on head throw distance, peak head-ground impact velocity, and HIC value. Pedestrian's profile that resembles an adult has 13 %, 6 %, and 16 % higher values for mean head throw distance, head-ground impact velocity, and HIC values, respectively, compared to the pedestrian profile resembling a child with lesser mass and a shorter height. A single factor ANOVA analysis also showed a significant effect of pedestrian's profile on mean head throw distance (F(df1, df2) = 25.77, p = 0.000), mean peak head-ground impact velocity F(df1, df2) = 3.99, p = 0.047), and mean HIC values F(df1, df2) = 4.39, p = 0.037). However, the results did not show a significant effect of pedestrian profile on the probability of severe head injury F(df1, df2) = 2.26, p = 0.13).

To have further insight into the combined effect of height and mass, the results were plotted against the impact speed, as shown in Fig. 12. The difference in head throw distance between two pedestrians' profiles is distinctly visible. A similar effect can be seen for peak head-ground impact velocity and HIC values except for 15 km/h collision speed. Nonetheless, the results have suggested that collisions with e-scooters are most likely to cause significant injuries to both child and adult pedestrians. Moreover, both profiles are likely to sustain similar severity of the injuries with the increasing collision speed. Therefore, limiting the riding speed could help reduce both the probability of collisions and the severity of the injury to both riders and pedestrians (Posirisuk et al., 2022).

Effect of impact direction

In this study, four possible directions of impact have been considered, as shown in Fig. 4. All four directions of impact represent direct head-on impacts where the centerline of the pedestrian body and the e-scooter are inline. The results on the effect of impact directions on collision metrics are shown in Fig. 13. It should be noted that Fig. 13 represents mean results for 5 levels of speed, 4 levels of e-scooter mass, and 2 levels of pedestrian profile. A single factor ANOVA has suggested no significant effect of impact directions on the overall mean head throw distance (F(df1, df2) = 0.89, p = 0.44), head impact velocity (F(df1, df2) = 0.57, p = 0.64), HIC values (F(df1, df2) = 0.61, p = 0.61), and probability of severe head injury (F(df1, df2) = 0.34, p = 0.79).

The analysis was further extended by plotting the collision metrics against the collision speed. Although no significant effect of impact directions was found on mean values of collision metrics, Fig. 14 suggests that a 90-degrees impact has a slightly longer head throw distance followed by 270-degrees. Moreover, the 180-degrees impact has the lowest head throw distance. On the other hand, 180-degrees impact has a slightly higher head-ground impact velocity, HIC, and probability of severe head injury. The insignificant effect of impact direction can be attributed to all collisions being direct centerline collisions. Further analysis can be carried out to investigate oblique and off-center collisions, such as collisions between e-scooter handlebars and pedestrians.

Effect of e-scooter mass

The mass of an E-scooter may range from 12 kg to more than 30 kg depending on the drive types, motor ratings, and battery capacity. Some E-scooters have a dual-drive system with two hub motors. The motor

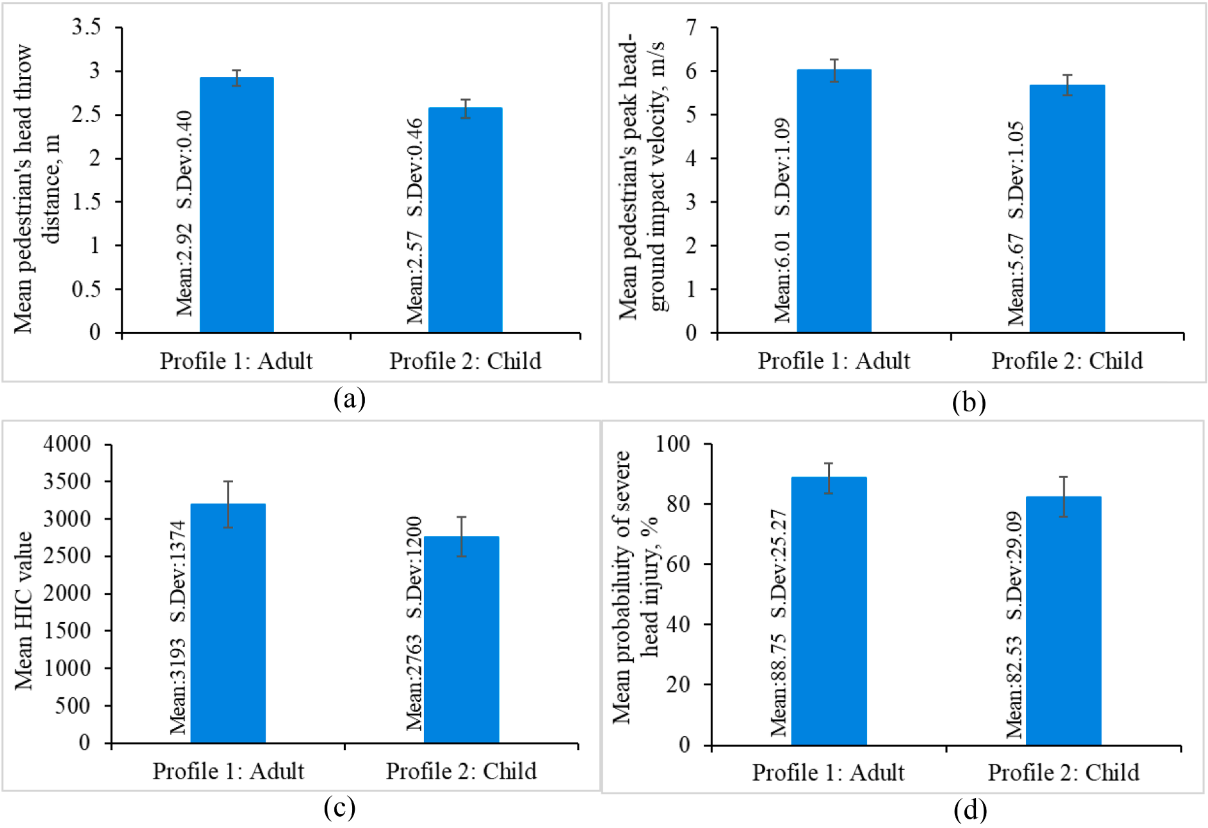


Fig. 11. Overall effect of pedestrian profile on collision metrics (a) mean pedestrian's head throw distance, (b) mean pedestrian's peak head-ground impact velocity, (c) mean HIC value and (d) mean probability of severe head injury (80 simulations profile).

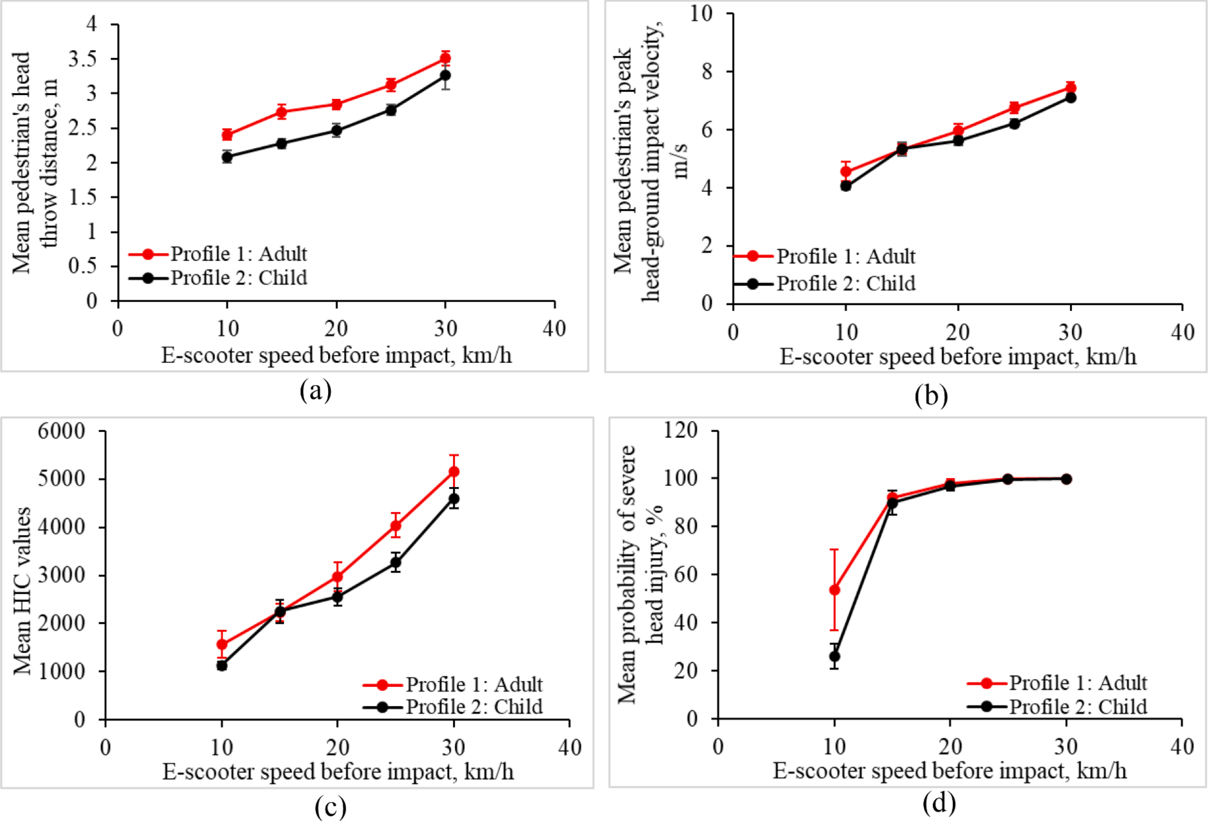


Fig. 12. Effect of age profile on collision metrics for different collision speed: (a) mean throw distance (b) mean peak head-ground impact velocity (c) mean HIC value and (d) mean probability of severe head injury.

rating itself may range from 250 W to 800 W or more (Winchcomb, 2022) Dual hub motors with higher power ratings and battery capacity significantly increase the weight of the e-scooter (Paudel & Fah Yap, 2021). Fig. 15 shows the influence of e-scooter mass on the collision metrics. Again, it should be noted that the results presented in Fig. 15 are based on 5 levels of speed, 2 levels of pedestrian profiles, and 4 levels of impact direction.

No significant difference in collision metrics can be observed in Fig. 15. A single factor ANOVA also confirmed that e-scooter mass does not have significant effect on mean head throw distance (F(df1, df2) = 0.14, p = 0.93), peak head-ground impact velocity (F(df1, df2) = 0.18, p = 0.91), HIC values (F(df1, df2) = 0.16, p = 0.92), and probability of severe head injuries (F(df1, df2) = 0.22, p = 0.87). The total energy of the e-scooter and rider system only increased by 21 %, even though the mass of the e-scooter is increased by more than twice. Moreover, there are few contact points between the e-scooter and the pedestrian, which could limit the transfer of momentum to the pedestrian.

We also analyzed collision metrics at each collision speed for different E-scooter mass. However, not much difference in collision metrics was observed when increasing the mass of the E-scooter. The results are shown in Fig. 16.

Although the results have suggested no significant effect of e-scooter mass on collision metrics, we should not neglect the other effect associated with the increased mass of the e-scooter. Usually, e-scooters become heavier due to the use of a heavier and more powerful motor that provides fast acceleration. Research has shown that the e-scooter could lose its self-stability property when being accelerated heavily (Paudel & Fah Yap, 2021). Limiting the weight of the e-scooter will help the respective authority restrict the maximum power rating of the motor and battery capacity.

Further research based on single-track vehicle dynamics has found that the current designs of e-scooters are indeed less stable, difficult to ride, wobbly, and twitchy compared to standard big-wheel bicycles (Paudel & Yap, 2020; Paudel et al., 2018; Paudel et al., 2020). Moreover, the regulation regarding the user's age, use of helmet, places permitted to the rider, motor power for e-scooter, and other micro-mobility devices are not consistent across the world. Austria has 12 years as the minimum age to allow e-scooter riding compared to a minimum age limit of 16 in Singapore and the Netherlands. Countries such as Portugal, Spain, and Finland have maximum motor ratings as high as 1000 W, enabling riders to accelerate much faster than riding a normal bicycle. On the other hand, the ergonomic design of e-scooters, including the type of brakes (disc brakes, electronic brakes), location of brakes (left or right), and brake-lever to wheel coupling should also be carefully considered. Therefore, to create a safer environment for pedestrians and riders, e-scooter design and legislation should complement each other. Manufacturers need to revisit the design of the e-scooters, considering the existing infrastructure to make them more rideable and safer. At the same time, safety measures such as limiting e-scooter speed, weight, and motor power ratings could be adopted.

Pedestrian's fall mechanism

In order to interpret the outcome of the e-scooter and pedestrian collisions, we studied the simulation videos and tried to correlate them with the results presented in Section 3.2. The main aim of studying the simulation videos is to identify a general trend and key differences in fall mechanisms between different profiles and impact locations.

The overall fall mechanism is divided into four sections: (i) vehicle–pedestrian contact, (ii) rider-pedestrian contact, (iii) falling, and (iv) pedestrian-ground contact as shown in Fig. 17. The analysis suggests that the pedestrian's head velocity increases rapidly after a collision with the rider and achieves maximum value just before the pedestrian's body impacts the ground. The results clearly show that the pedestrian's

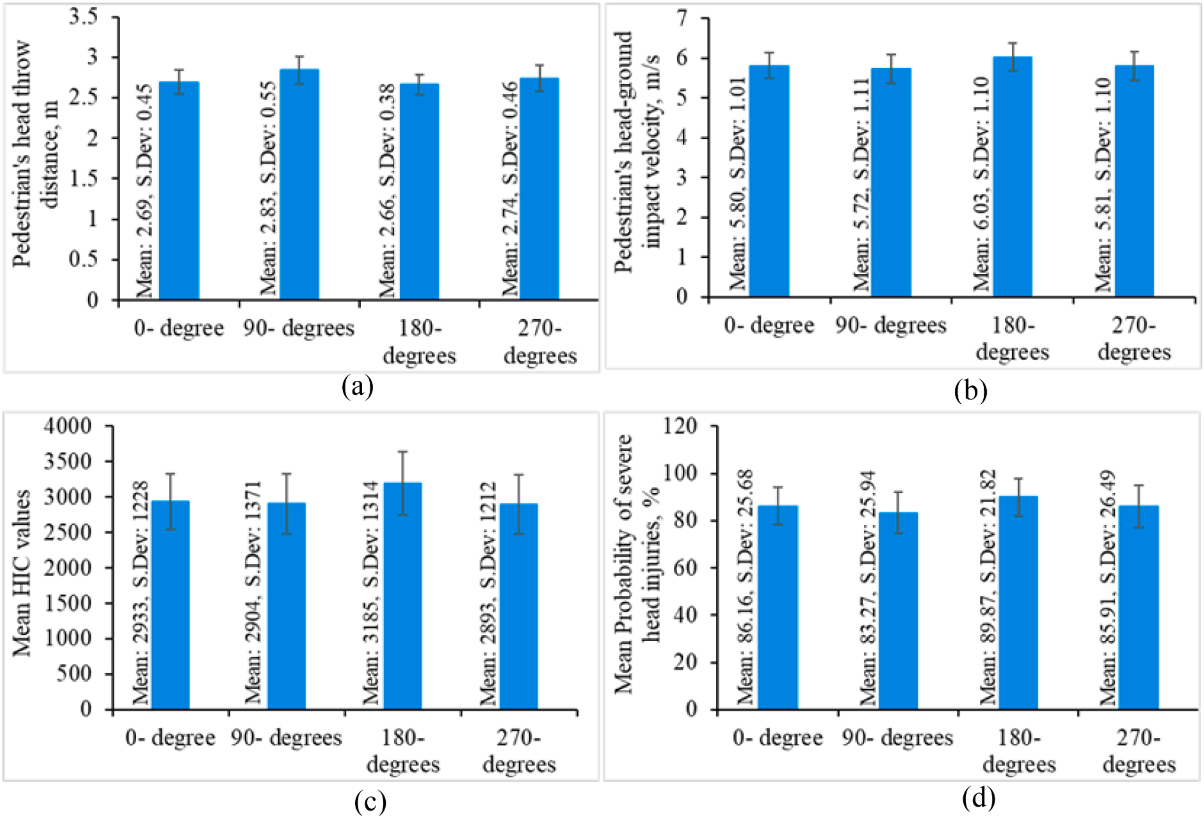


Fig. 13. Overall effect of impact directions on collision metrics (a) mean pedestrian's head throw distance, (b) mean pedestrian's peak head-ground impact velocity, (c) mean HIC value and (d) mean probability of severe head injury (40 simulations profile).

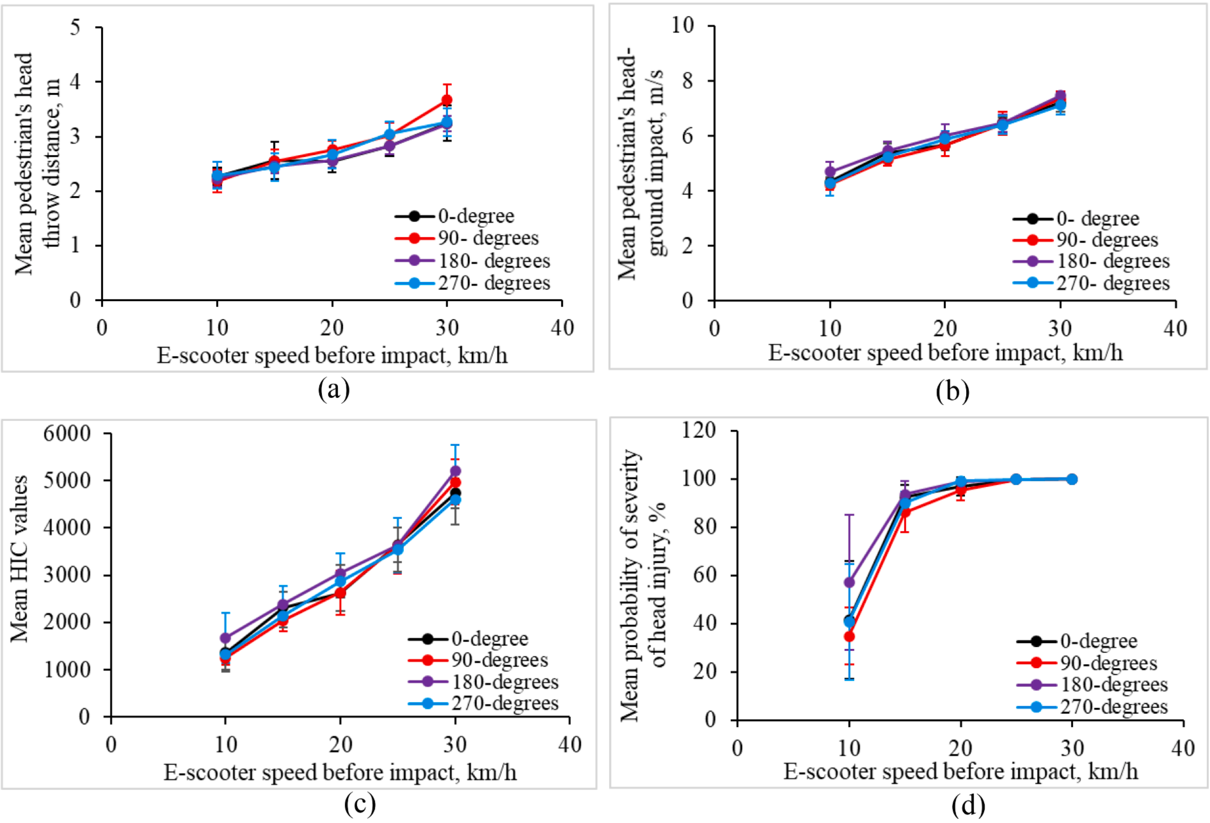


Fig. 14. Effect of age profile on collision metrics for different collision speed: (a) mean throw distance (b) mean peak head-ground impact velocity (c) mean HIC value and (d) mean probability of severe head injury.

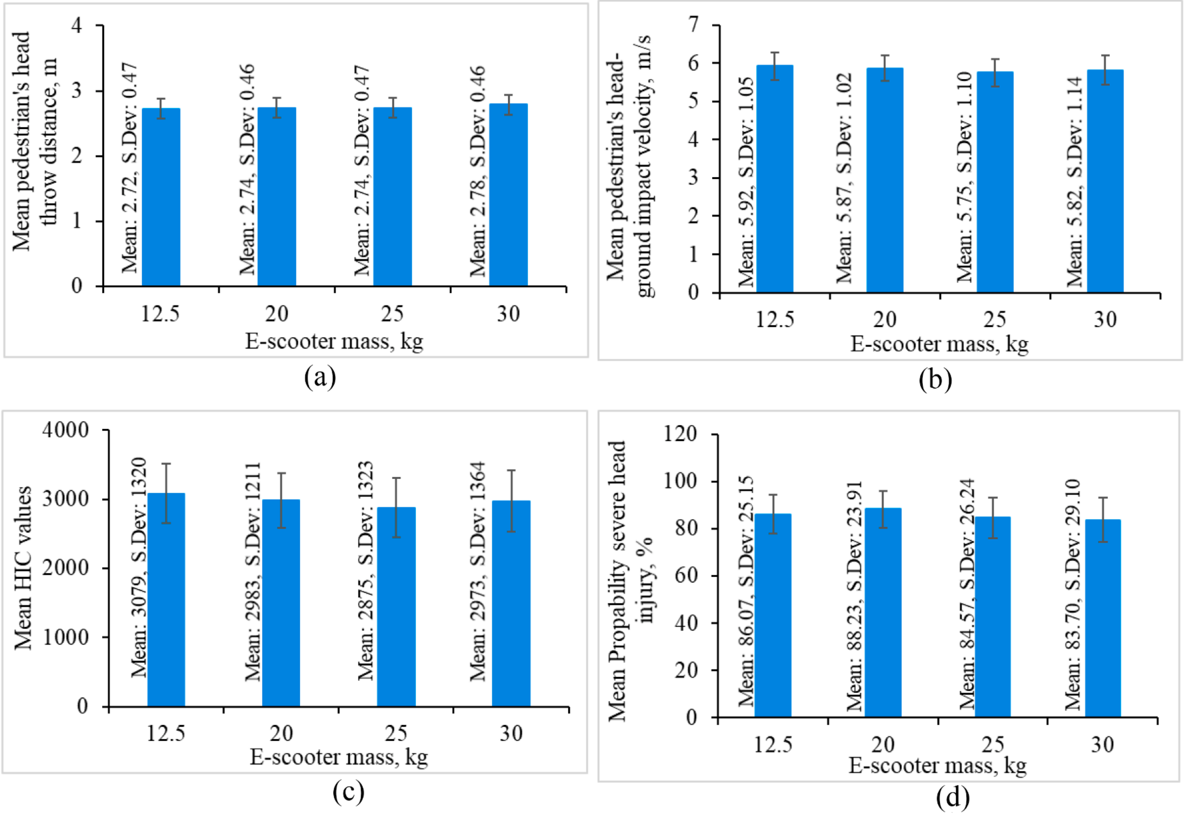


Fig. 15. Overall effect of e-scooter mass on collision metrics (a) mean pedestrian's head throw distance, (b) mean pedestrian's peak head-ground impact velocity, (c) mean HIC value, and (d) mean probability of severe head injury (40 simulations profile).

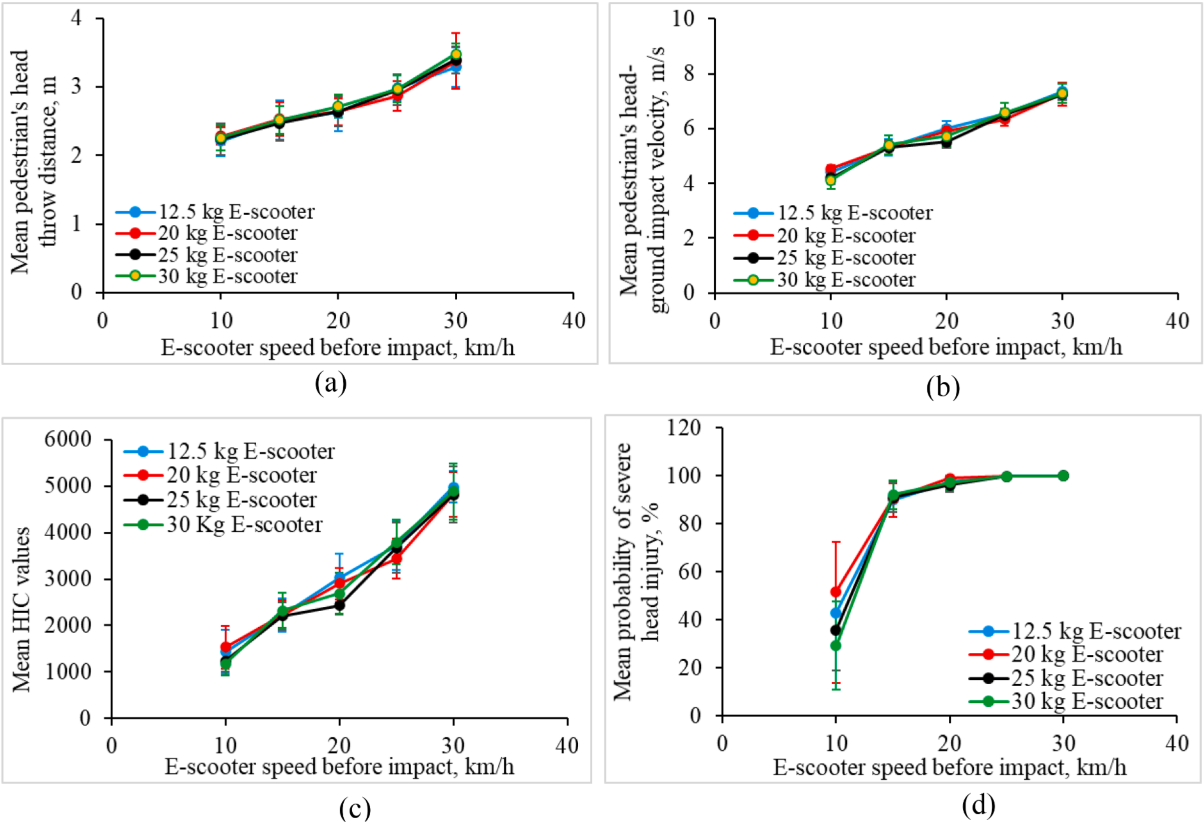


Fig. 16. Effect of age profile on collision metrics for different collision speed: (a) mean throw distance (b) mean peak head-ground impact velocity (c) mean HIC value and (d) mean probability of severe head injury.

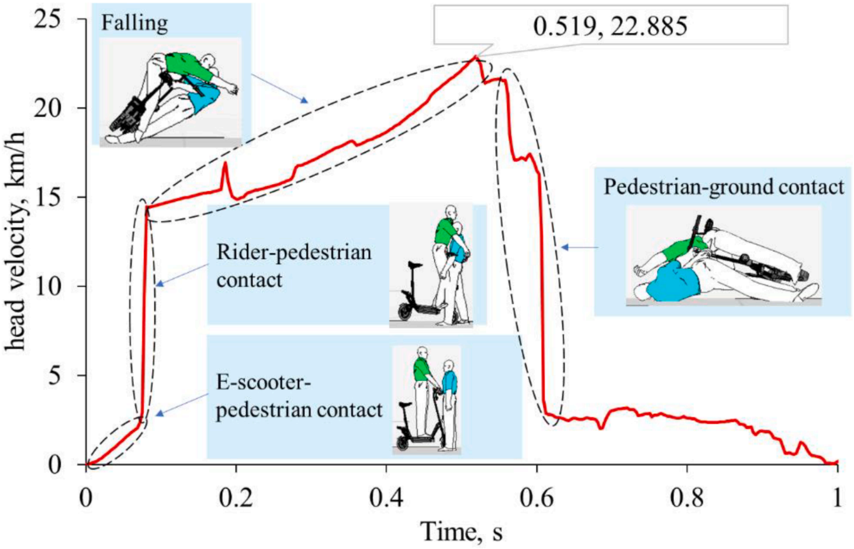


Fig. 17. Key events in e-scooter and pedestrian collision and corresponding head velocity profile.

head velocity did not increase significantly in a primary contact between an e-scooter and a pedestrian. This observation also provides an insight into the finding that increasing the e-scooter mass did not have a significant influence on collision metrics. At the same time, the finding also highlights the risk associated with the standing posture of the rider on e-scooters. Furthermore, different aspects of the collision such as the location of first contact from the e-scooter to the pedestrian, rider-pedestrian interaction during the collision, bending of the pedestrian body parts, pedestrian's body parts that make first contact with the ground, direction of head impact on the ground were also analyzed.

The study of the simulation videos has suggested that the direction of the pedestrian's head impact on the ground depends on the orientations of the pedestrian. In a 0-degree collision, the pedestrian falls backward such that the back of the head impacts the ground. Similarly, in a 180-degree collision, the front of the head impacts the ground and for 90- and 270-degree collisions, the right and left sides of the head impact the ground, respectively. This is also evident from the crash tests experiments (GuideDogs, 2021; Hess, 2020) presented in Figs. 6 and 7.

For 90 and 270-degree collisions, the first impact came from the wheel at the lower leg of the pedestrians. Since the wheel transferred the momentum to the lower leg, pedestrians leaned toward the riders, as shown in Fig. 18. This effect was observed on child pedestrians even at low collision speeds. However, this collision effect was more pronounced for adult pedestrians at higher speeds. Thereafter, the pedestrian collided with either the rider or the e-scooter handlebar, which made the pedestrian's head snap sideways. In contrast, for 0 and 180-

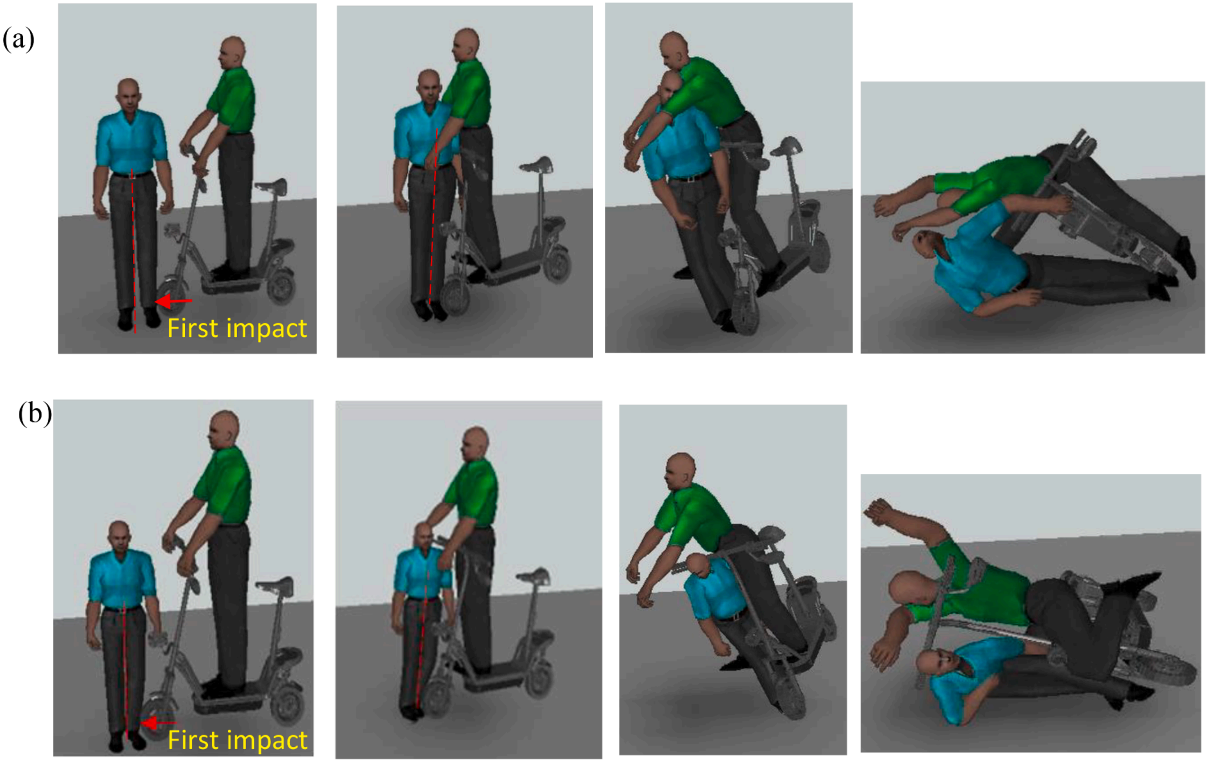


Fig. 18. Pedestrians motion just after colliding with an e-scooter (90 degrees collision) (a) adult pedestrian profile and (b) child pedestrian profile.

degree collisions, the initial impact on the pedestrian came from the handlebar and rider. No leaning motion towards the rider was observed for 0 and 180-degree collisions.

Simulation videos also showed that both adult and child pedestrians fall directly to the ground immediately after the collision. The handlebar height is considerably higher than the center of mass location for a child pedestrian profile. Therefore, any impact from the handlebar would make child pedestrians with lower center of gravity fall forward directly to the ground (FIELD, 2001). This is also evident in Fig. 8 (b) and Fig. 18 (b). However, with the center of mass location for an adult pedestrian at a similar height to the e-scooter's handlebar, it was counterintuitive to observe the falling mechanism of an adult pedestrian similar to a child pedestrian. In fact, when the impact is close to the center of mass location, it is reasonable to expect that the pedestrian would be longitudinally thrown initially before falling to the ground (Paudel et al., 2022). However, closer observation revealed that immediately after the e-scooter handlebar impacts the adult pedestrians around the waistline, the rider's and pedestrian's upper bodies collide. As a result, the rider's momentum is transferred to the upper body of the adult pedestrians. Because of the additional momentum transfer to the upper body, the adult pedestrian starts to fall directly towards the ground. However, such rider-pedestrian upper body impact was not observed for child pedestrians, as shown in Fig. 8 (b) and 18. Moreover, the slightly higher impact velocity for the adult pedestrian in Fig. 11 (b) could also be explained considering the extra momentum transferred from the adult rider and the fact that the adult pedestrian's head falls from a greater height than a child pedestrian.

As the pedestrian falls towards the ground after the collision, the head throw distance depends on the height of the pedestrians' profiles. This observation supports the results presented in Fig. 11 (a) and 12 (a) that adult pedestrian profiles have longer throw distances than child pedestrian profiles. However, it should be noted that the child pedestrian profiles are based on population height of 7–12 years old. Further research is needed to understand the collision mechanism and outcome for children below 7 years with shorter height and lesser mass.

We found that head-ground impact is largely influenced by the e-scooter impact direction on the pedestrian. For example, for 0-degree head on collision, the forehead has the tendency to hit the ground. Whereas, for 180-degree collision, pedestrian's back of the head has tendency to hit the ground. We also observed bending of body parts such as neck, hip, and leg while falling towards the ground. As the knee joints cannot bend backward, it bends forward while falling towards the ground. For 90 and 270-degree collisions, the pedestrian's waist hits the ground first, followed by the shoulder and the head. Whereas, at 0-degree collision, the hip contacts the ground first, followed by the head. In all impact directions except 180-degree collisions, body parts such as the waist, hip, or shoulder contact the ground before the head impacts the ground. However, for 180-degree impacts, there is a maximum possibility of the head directly impacting the ground without any significant break of fall. This is illustrated in Fig. 19. This observation also supports the results in Fig. 13, where 180-degree collisions have a slightly higher impact velocity compared to the other collision direction. Moreover, a 180-degree collision makes the pedestrian's head snap backward, which may cause neck and head injury. In fact, head and neck injuries have been reported to constitute nearly 28 % of the total e-scooter related injuries (Kappagantu et al., 2021).

The simulations were able to show how different body parts could be impacted while during a collision. Reports have also indicated that almost half of the patients in e-scooter related collisions suffer from multiple injuries in more than one body part (Bloom et al., 2021; English et al., 2020).

Limitations.

This paper is based on the collision simulations that involve human subjects. A simulation study using human subjects is challenging and always involves some limitations. In this section, the authors would like to acknowledge the major limitations of this study. Therefore, the results should be considered together with the limitations.

One of the important limitations in this study is the lack of laboratory crash data in published literature. The collisions involving vehicles and human subjects (riders or pedestrians) are usually studied using ATB models in a controlled laboratory set-up. Such crash tests are generally performed for heavy motor vehicles, and adequate reference data is available to validate simulations between motor vehicles and cyclists or pedestrians0020collisions. As e-scooters are a relatively new mode of transportation and have become popular recently, data from laboratory crash tests are limited for model validation. As a result, we could only validate our simulations with very limited experimental data. However, our simulations were comparable, qualitatively and quantitatively, and

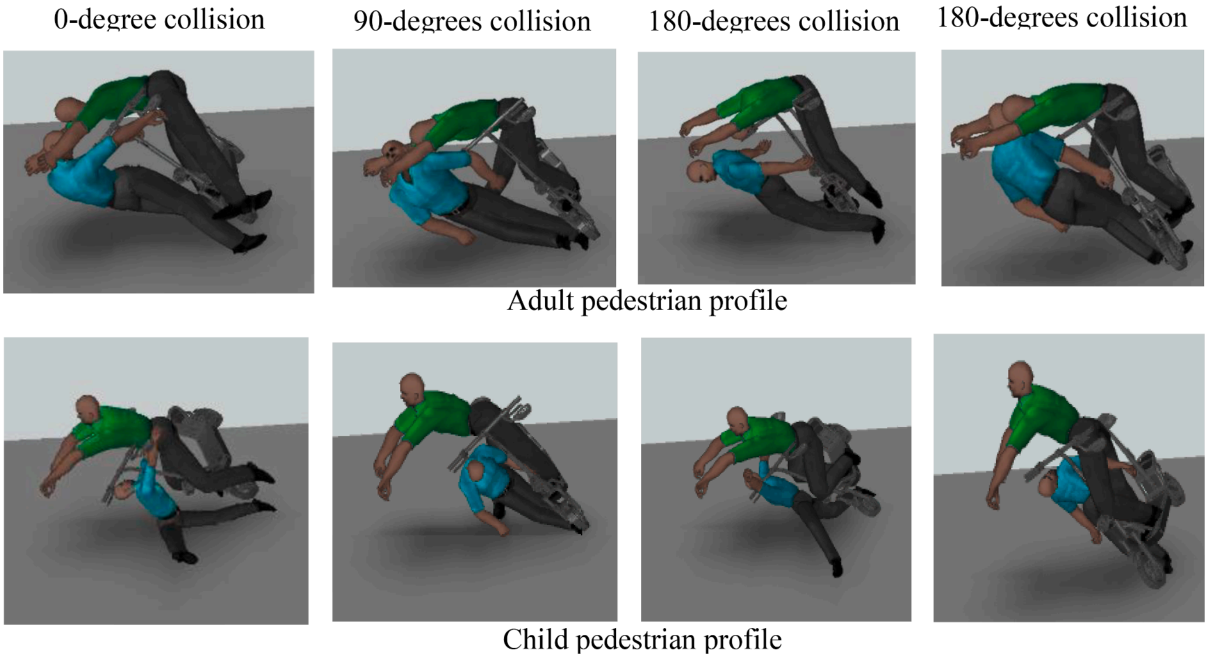


Fig. 19. Falling mechanism for different collision directions and pedestrian profile just before pedestrian's body impacts the ground.

able to replicate similar pedestrian falling motions compared to laboratory crash tests.

The second limitation of the study is the human models. We have used two pedestrian profiles that differ in height and mass to represent an adult and a child pedestrian. We have not included the female pedestrian profile due to the lack of experimental data to validate the collision data and mechanism. Moreover, we have not considered the difference in biomechanical properties of skin, tissues, or bones in an adult and a child. Moreover, the study also does not consider the difference in injury susceptibility between a child and an adult. Nonetheless, the study preserves the anthropomorphic details of an adult and child. Despite the limitation, a human model based on multiple ellipsoids connected with ragdoll joints is useful for predicting the throw distance and impact kinematics. In addition to this, the human model used in the simulation does not react to the impact and can be considered a passive human model. In real-life scenarios, human models react to falling by extending their arms to break the fall. However, both riders and pedestrians collapse in the simulations, resulting in a maximum possible head impact velocity before colliding into the ground. Therefore, the results, such as an estimate of HIC value and probability of severe head injury in this study, represent the worst-case scenarios.

The third limitation of the study is the rider's posture. Our study has considered a posture where the rider stands on the e-scooter's deck with the leg at the same location. However, we understand that some riders prefer to ride the e-scooter with one foot behind another, and some e-scooters allow riders to sit on a saddle. Moreover, the rider does not hold on to the handlebar when colliding with the pedestrians in the current simulations. Further study has to be done to confirm if the rider's posture significantly affects the pedestrian's injury mechanism and collision metrics.

The fourth limitation of this study is the contact characteristics used in simulations. Since there was no dedicated study on contact parameters such as coefficient of friction for e-scooter wheels and chassis with the ground surface and coefficient of adhesion for e-scooters wheels, we selected these parameters based on published literature on bicycles and motor vehicles like cars and motorcycles. With more information about the contact characteristics of e-scooters and human subjects, the accuracy of the simulation could be improved in the future.

Conclusion

This paper has investigated the collision between e-scooters and pedestrians. The analysis considered 5 collision speeds ranging from 10 km/h to 30 km/h, 4 e-scooter masses ranging from 12.5 kg to 30 kg, four direct collision directions (0, 90,180,270 degrees), and 2 pedestrian profiles that differ in height and mass. A total of 160 simulations were performed to study the injury kinematics of pedestrians when colliding with e-scooters. The results were analyzed using four collision evaluation metrics, throw distance, peak head impact velocity, HIC value, and probability of severe head injury. The overall scenario of the simulation is modeled in such a way that it represents the worst-case scenarios where a pedestrian is more likely to be thrown away with maximum possible head impact velocity and injury severity.

The results have shown that collision speed is a significant factor in determining the outcome of a collision between an e-scooter and a pedestrian. A higher collision speed means a higher momentum and kinetic energy transfer to the pedestrian. The analysis has shown that even a 5 km/h increment in collision speed from 10 km/h to 15 km/h could drastically increase the probability of severe head injury. A slightly higher risk of head injury was observed for 180-degrees collisions. Closer observation revealed that the pedestrian's head has the maximum possibility of impacting the ground with no proper break of fall from other body parts such as the waist, shoulder, or hip for 180-degree collisions. However, single-factor ANOVA suggested no significant effect of collision direction on collision metrics.

An adult pedestrian was observed to collide with the scooterist's upper body immediately after the e-scooters collided with the pedestrian. However, no such body-to-body impact was observed for e-scooterist and child pedestrians. Nonetheless, both pedestrian profiles fall toward the ground because of the body-to-body impact in adult pedestrians and handlebar-to-head impact in child pedestrians. A single factor ANOVA suggested a significant effect on pedestrian profile on head throw distance, peak head-ground impact velocity, and HIC value. However, no significant difference was observed in the probability of severe head injury. This suggested that both child and adult are equally vulnerable to e-scooter collisions.

The analysis also considered four different e-scooter masses ranging from 12.5 kg to 30 kg. No significant effect of e-scooter mass on collision metrics was observed.

Moreover, snapping of the head and neck was observed in the simulation, which could result in neck injury.

Finally, the result suggested that a riding speed below 11 km/h has an overall probability of severe head injury of less than 50 %. Considering the fact that these results represent the worst-case scenario, the concerned authorities are recommended to implement a speed limit of not more than 11 km/h for e-scooterist on narrow and crowded shared paths. The study could be further extended to include more pedestrian profiles, including females and elderly, with the availability of more experimental data.

CRediT authorship contribution statement

Milan Paudel: Conceptualization, Validation, Formal analysis, Writing – original draft. **Yap Fook Fah:** Conceptualization, Methodology, Funding acquisition, Writing – review & editing, Supervision. **Tantyana Binte Mohamed Rosli:** Software, Formal analysis, Data curation. **Kai Hou Tan:** Software, Formal analysis, Data curation. **Hong Xu:** Conceptualization, Funding acquisition, Writing – review & editing, Supervision.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

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