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Highlights

- The finite element model of E-scooter fall was developed and validated.
- E-scooter falls always cause oblique head-ground impacts, mostly on the forehead.
- High risks of severe head injuries can result from E-scooter falls.
- The bicycle helmet can greatly reduce head injury metrics in E-scooter falls.
- The bicycle helmet cannot prevent severe head injuries in E-scooter falls.

Abstract

Objective: Head injuries are common injuries in E-scooter accidents which have dramatically increased in recent years. The head impact conditions and helmet performance during E-scooter accidents are barely investigated. This study aims to characterize the head-ground impact biomechanics and evaluate bicycle helmet protection in typical E-scooter falls.

Method: The finite element (FE) model of a hybrid III dummy riding an E-scooter was developed and validated. The FE model with and without a bicycle helmet was used to reproduce twenty-seven E-scooter falls caused by the collision with a curb, in which different riding speeds (10, 20, and 30km/h), curb orientations (30, 60, and 90°), and E-scooter orientations (-15, 0, and 15°) were simulated. Head-ground impact velocities and locations were evaluated for the unhelmeted configurations while the helmet performance was evaluated with the reduction of head injury metrics.

Results: E-scooter falls always resulted in an oblique head-ground impact, with 78% on the forehead. The mean vertical and tangential head-ground impact velocities were respectively 5.7 ± 1.5 m/s and 3.7 ± 2.0 m/s. The helmet significantly ($p < 0.1$) reduced the head linear acceleration, angular velocity, HIC₃₆, and BrIC, but not the angular acceleration. However, even with the helmet, the head injury metrics were mostly above the thresholds of severe head injuries.

Conclusion: Typical E-scooter falls might cause severe head injuries. The bicycle helmet was efficient to reduce head injury metrics but not to prevent severe head injuries. Future helmet standard evaluations should involve higher impact energy and the angular acceleration assessment in oblique impacts.

Keywords: E-scooter; fall; head injury; helmet; finite element modeling

1 Introduction

Electric scooters (or E-scooters, hereafter referred to as 'ES') are a newly rising mode of transportation in recent years which aim to reduce traffic congestion and air pollution and provide people with

alternatives for short trips after traditional transportation. The ES market has rapidly expanded in France with an increase of 76% in sales value in Paris in 2018 compared to 2017 (Christoforou et al., 2021), and in the US with an increase of over 100% in ridership in 2019 compared to 2018 (Nacto, 2019). The rapid growth of ES usage has also brought rising concerns for ES safety. According to the French road safety annual report (ONISR, 2020), the number of users injured in ES accidents in 2020 was 40% more than in 2019. The annual emergency department visits due to ES accidents in the US were 27,700 in 2019, approximately 3.6 times higher than the number (7,700) in 2017 (Tark, 2020). The increasing number of ES-related injuries has placed a considerable burden on the health care system. The total economic cost of managing the ES injuries was about 0.6 million NZD for the Auckland City Hospital and 1.3 million NZD for the entire Auckland region for 7 months (Bekhit et al., 2020).

The incidence and pattern of injury in ES accidents have been examined in recent studies, and head injuries were often reported as one of the most common injuries. An epidemiologic study using the US national electronic surveillance system estimated 32,400 ES injuries during the years 2013-2017 and found the head as the most frequently (27.6%) injured body part (Aizpuru et al., 2019). A retrospective case series collected 90 medical admissions during 7 months and 58% of these admissions included head injuries (Trivedi et al., 2019). Another retrospective study recorded 175 patients with ES-related injuries and 71 patients (40.6%) sustained head injuries (Moftakhar et al., 2021). Despite a lack of data on the fatality rate, death is not uncommon in ES accidents and is often associated with head injuries. However, a low rate (less than 6%) of helmet use by ES riders was reported and considered as an important factor contributing to severe head injuries and death in ES accidents (Iroz-Elardo and Currans, 2021; Lavoie-Gagne et al., 2021). For this reason, ES riders are highly recommended to wear a helmet in many countries, even though it is not yet compulsory (Garman et al., 2020; Serra et al., 2021). The standard bicycle helmets designed for low-speed riding are commonly used by ES riders (Haworth et al., 2021; Todd et al., 2019). However, the protection performance of a standard bicycle helmet remains to verify in ES accident conditions.

The ES accident scenarios have been studied and falls were often reported as the most common (75.0%-80.2%) cause of injuries for ES riders (Cicchino et al., 2021; Kleinertz et al., 2021; Trivedi et al., 2019). ES falls initiated by hazardous surface features (e.g. potholes) and infrastructures (e.g. curbs) were found as the typical scenarios of ES falls (Cicchino et al., 2021). Typical ES falls caused by potholes were reproduced with the multi-body simulation approach in a recent study (Posirisuk et al., 2022) in which the head-ground impact force and velocity were quantified. The mean values (6.3m/s) of head-ground impact velocities were found equivalent (Posirisuk et al., 2022) to the test speed of the bicycle helmet testing standard while a high risk of skull fractures based on head impact force (Posirisuk et al., 2022) was predicted in most of the falls. However, it remains unknown whether a standard bicycle helmet would greatly reduce the head injury risks in these falls. The head-ground impact conditions also need to be further quantified in other accident conditions in which, for example, the ES motion and orientation are not perpendicular to the pothole edge or a curb.

The main objective of this study is to improve the current understanding of head injury risk in ES falls using a finite element (FE) simulation approach. More specifically, this study will address two specific goals: 1) to quantify the head-ground impact kinematics in various configurations of ES falls initiated by a curb; 2) to verify the protection performance of a standard bicycle helmet in these typical ES falls.

2 Materials and methods

2.1 The finite element models of the E-scooter and rider

The CAD model of a commercially available ES (Xiaomi Mi Folding Electric Scooter M365), which was similar in structure to the ES used in our ES-curb crash tests (hereafter referred to as 'test ES'), was obtained from a web database (CGTrader, 2020). The components (e.g. brake cables, kickstand), which would increase simulation expense but not affect the rider kinematics during falls, were removed for model simplification. The CAD model was then scaled to the dimensions (Figure 1A) of the test ES and was meshed with 3-node triangle elements with Hypermesh v.2021 (Altair Engineering Inc, USA). All the ES components except the tires were modeled with an elastoplastic material with a yield stress of 250MPa

representing the mechanical properties of typical steel. The tires were modeled as an inflated airbag with a pressure of 2.5bar which was enclosed with an elastic material with Young's modulus of 250MPa. A revolute joint was created between the tires and the ES frame to reproduce the wheels' rotation during riding. Scalar mass elements were uniformly distributed over the ES frame to have the same mass (13kg) as the test ES.

The FE model of the hybrid III 50th percentile male standing dummy (LSTC, 2020) which was developed by LSTC (Livermore Software Technology Corp., USA) was used in this study to represent a mid-sized ES rider. The same dummy was used in the experimental ES-curb crash tests reproduced for model validation (Fournier et al., 2022).

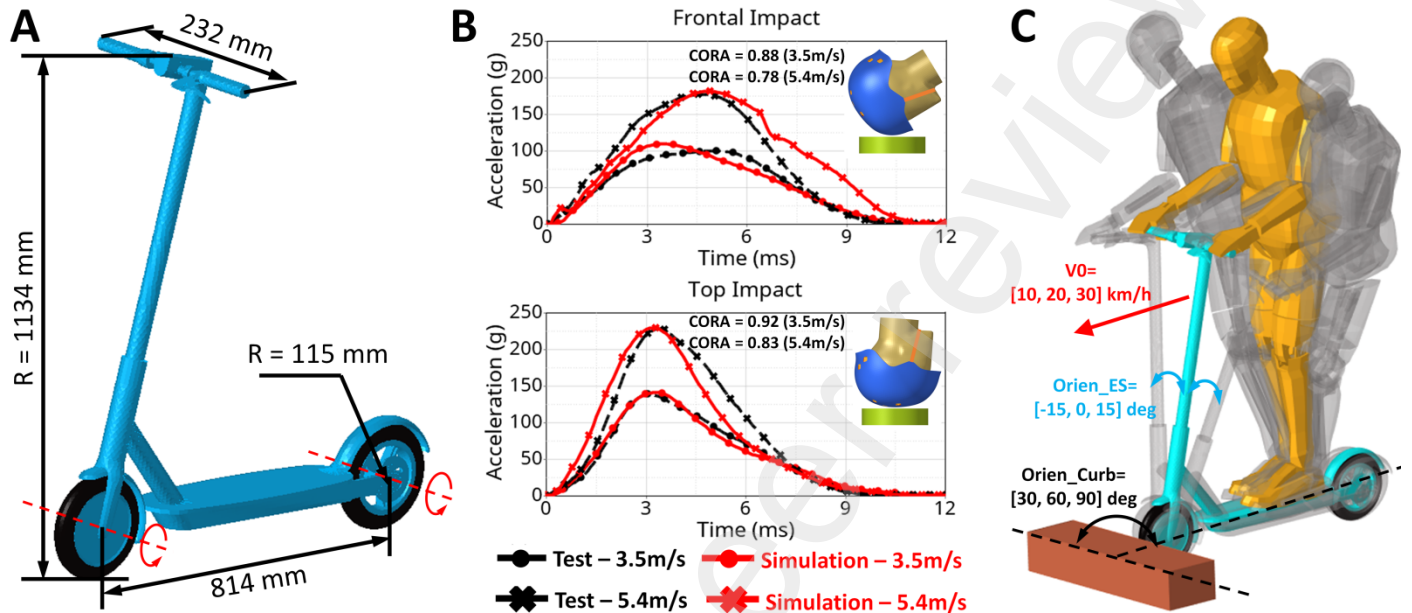


Figure. 1 FE models for E-scooter fall simulations: (A) E-scooter FE model with its key dimensions; (B) helmet FE model evaluations against experimental drop tests (CORA: correlation and analysis score); (C) model setup of E-scooter falls induced by the collision with a curb with various initial accident conditions (V0: initial velocity; Orient_ES: orientation of the E-scooter and rider; Orient_Curb: orientation of the curb).

2.2 Validation of the E-scooter fall finite element model

Typical ES falls induced by the collision of the frontal wheel with a curb were reproduced experimentally in our previous study (Fournier et al., 2022). To briefly review, the hybrid III 50th percentile male pedestrian dummy was used in the tests as the rider standing on an ES (Doc Green ESA 1919) which was propelled by a sled to hit a curb with an initial velocity of 22.0km/h (6.1m/s). The curb was placed on the ground with an angle of 90° or 50° to the ES trajectory resulting in two configurations of ES-curb impacts: perpendicular and oblique. The dummy was equipped with an airbag helmet in the oblique impact but no head protection in the perpendicular impact. The displacement and velocity of the head during falls were measured by tracking the motions of the markers on the head in high-speed videos. The head acceleration and head injury criteria (HIC₃₆) were measured by the 3-axis accelerometer at the center of gravity (CG) of the head.

The experimental tests of ES falls were reproduced with the ES and rider FE models to validate the model predictions of the head kinematics during falls and head-ground impacts (Figure 2). The rider FE model (without a helmet) was positioned to reproduce the posture of the experimental dummy. This was done with the dummy position module of LS-PrePost V4.6.15 software (Livermore Software Technology Corp., USA). The 140mm-high curb was modeled with a typical steel material with a yield stress of 250MPa while the ground was modeled with a flat rigid wall of infinite width. The curb was positioned 2cm ahead of the ES with an angle of either 90° or 50° to the traveling direction of the ES. Automatic surface-to-surface contacts were defined for the interactions among the rider, ES, and curb. In both simulations (i.e. 90° or 50° curb), an initial velocity of 22.0km/h (6.1m/s) was applied to the ES and rider. The global body kinematics as well as the displacement, velocity, and acceleration of the head CG were predicted in the simulations and compared with the corresponding experimental measurements for model validation. The

head acceleration or HIC₃₆ (Figure S1 in the Appendix) was not compared for the oblique (50° curb) impact between the simulation and test as the dummy had different head protection conditions in the test (airbag helmet) and simulation (no protection).

The global body kinematics during falls showed a high consistency between the simulations and experimental tests (Figure 2). The head displacements in the simulations were mostly within the corridors of experimental measurements (Figure 2). The head velocities in the simulations were generally consistent with the experimental measurements, despite not being completely within the corridors. The head acceleration and HIC₃₆ predicted in Simulation-1 agreed well with the magnitudes in Test-1 (90° curb) with differences below 10% (Figure 3). Based on these comparisons, the model was considered capable to predict the head kinematics and head-ground impacts during ES falls.

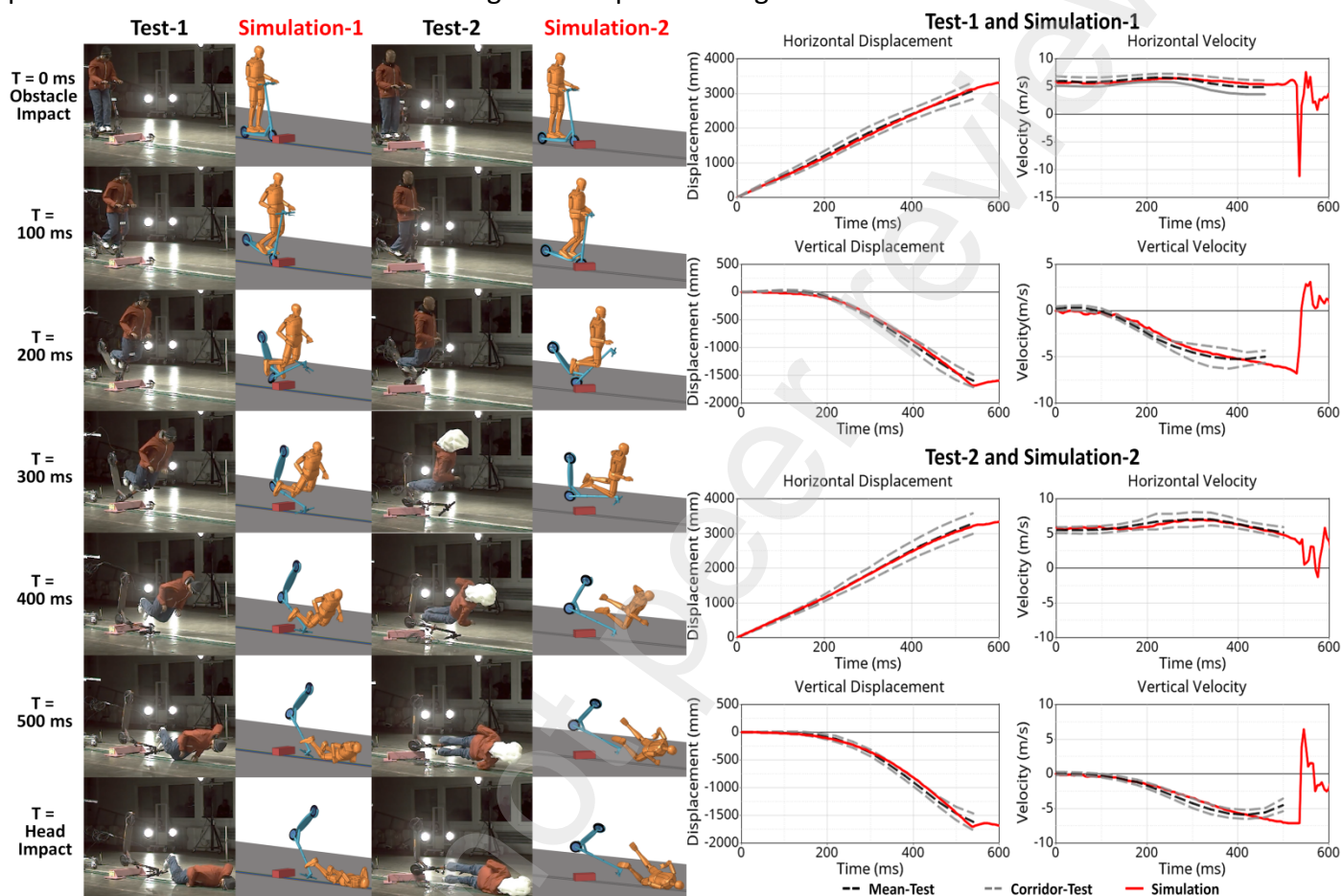


Figure. 2 Model evaluation of E-scooter fall simulations in terms of body kinematics, head displacement, and velocity during falls: Simulation-1 and Test-1 are for the E-scooter-curb perpendicular impact (90° curb); Simulation-2 and Test-2 for the E-scooter-curb oblique impact (50° curb).

Test-1 and Simulation-1 Resultant Acceleration

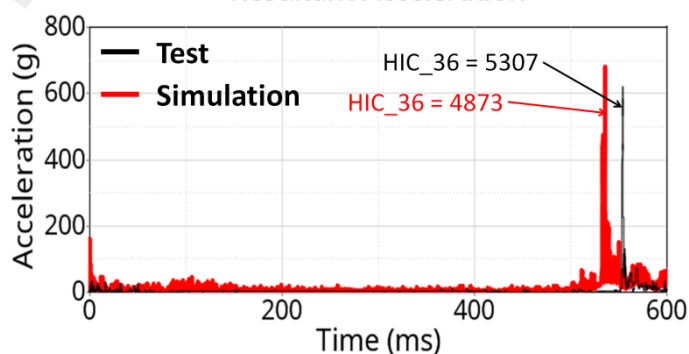


Figure. 3 Model evaluation of E-scooter fall in terms of head resultant acceleration and HIC₃₆ for Simulation-1 and Test-1 (E-scooter-curb perpendicular impact with 90° curb)

2.3 Development and validation of the helmet finite element model

A standard bicycle helmet available in the market and compliant with the EN 1078 standard (European Committee for Standardization. Technical Committee CEN/TC 158" Head Protection.", 2012) was modeled with the FE approach using the geometry data obtained from the CT scan. The outer shell and head strap were meshed with quadrilateral elements while the expanded polystyrene (EPS) liner was meshed with tetrahedral elements. Similar to other helmet FE models (Fahlstedt et al., 2016), the outer shell and head strap were modeled with an elastoplastic material (Young's modulus 1000MPa, yield stress 70MPa). The EPS liner (density 60kg/m³) was modeled with a low-density foam material, the compressive stress-strain behavior of which came from the published data in the literature (Andena et al., 2019).

The helmet FE model was validated against four experimental drop tests in which the helmeted metallic headform (5kg mass and compliant with EN960 standard (European Committee for Standardization, 2006)) was dropped on a flat rigid anvil with initial velocities of 3.5m/s and 5.4m/s. During the experimental tests, the acceleration was recorded at the head CG with a tri-axial accelerometer (10kHz) and filtered at 1kHz. In the FE simulations (Figure 1B), the headform and flat anvil were modeled as rigid bodies. A friction coefficient of 0.3 was defined for the contact between the helmet and headform, both of which were applied with initial velocities of 3.5m/s and 5.4m/s to hit the anvil. The acceleration measured at the head CG showed a good correlation between the simulations and experiments (Figure 1B) in terms of the timing and the peak value (below 5% difference). The correlation and analysis (CORA) scores (Gehre et al., 2009) of the head acceleration time-history were between 0.78 and 0.92 (Figure 1B), further indicating a high consistency in amplitude, phase, and shape between the simulated and experimental accelerations.

2.4 Head-ground impact conditions and helmet protection

The FE model of ES fall was then used to investigate the head-ground impact conditions in diverse ES fall configurations. A full factorial design of experiment (DOE) study with 27 ES falls was performed to evaluate the effect of three initial accident variables on the head impact: initial velocity (V_0 : [10, 20, 30] km/h); orientation of the ES and rider (Orien_ES: [-15,0, 15] °); orientation of the curb (Orien_Curb: [30,60, 90] °) (Figure 1C). The V_0 was chosen based on the speed limits of different countries (Everett, 2021) and the simulation setup of a previous study (Posirisuk et al., 2022). The Orien_ES of 0° represented the vertical orientation of the ES and rider while a positive (or negative) value in Orien_ES represented a farther (or closer) orientation to the curb. The Orien_Curb represented the angle between the curb and the ES traveling direction.

To verify the performance of a typical bicycle helmet in ES falls, the helmet FE model validated above (section 2.3) was worn on the ES rider for all ES fall simulations. A friction coefficient of 0.3 was defined for the contact between the helmet and the head as well as the ground. Instead of re-running the simulations from the moment of ES-curb impact, all the simulations with a helmet were continued from a moment slightly before the head hit the ground in the simulations without a helmet. To do so, a sensor was defined to monitor the vertical distance between the head and ground in the simulations without a helmet. When the head arrived 3cm (slightly higher than the helmet thickness) above the ground, a binary file containing a complete record (e.g. velocity, stress, strain, etc) of the model was written from each ES fall simulation. A full-restart of stress-initialization procedure was then implemented for the simulations with a helmet to inherit the model information from the simulation without a helmet and then to collide with the ground. The full-restart procedure was performed to save calculation expenses and, more importantly, to warrant the same head-ground impact conditions in the simulations with/without a helmet for protection evaluations.

The peak values of the linear acceleration, angular acceleration, and angular velocity predicted at the head CG as well as the HIC₃₆ and BrIC (Takhounts et al., 2013) values were evaluated for all simulations. To predict the possible head injuries during ES falls, the following injury thresholds were used in this study: 6383rad/s² head angular acceleration and 28.3rad/s head angular velocity for 50% risk of concussion (Rowson et al., 2012); 1000 HIC₃₆ for 50% risk of AIS3+ injuries (Mariotti et al., 2019); 250g head linear acceleration (Normalisation, 2011) and 1.0582 BrIC (Namiri et al., 2020) for 50% risk of AIS4+ injuries. The

paired-sample t-test was used to identify whether there was a significant difference in these head injury metrics between the simulations with and without a helmet. Pearson's correlation was performed between the head injury metrics and the head-ground vertical impact velocity during ES falls with and without a helmet. Statistical significance was defined as a two-tailed p-value < 0.10 while considering different significance levels with p-value less than 0.001, 0.01, 0.05, or 0.1. All statistical analyses were conducted with the Rstudio 1.2 software (RStudio, Inc., Boston, MA, USA). All FE simulations in this study were performed with the explicit solver in LS-DYNA 971 R11.1 (LSTC, Livermore, CA, USA).

3 Results

3.1 Head-ground impact conditions

In the 27 ES falls, the global kinematics could be divided into two phases: the ES came into contact with the curb and the rider was projected forward to fall on the floor (Figure 4A-B). The limbs always collided with the ground first, with the lower limbs in 55.6% and the upper limbs in 44.4% of the ES falls (Figure 4C). The first body-ground impact occurred at 75-678 ms while the first head-ground impact occurred at 412-815 ms during ES falls (Figure 5). The initial accident conditions showed no significant effect on the time of the first body-ground impact but the time of the first head-ground impact significantly decreased with the increasing ES initial velocity. The head impact was always oblique with a mean vertical impact velocity of 5.7 ± 1.5 m/s (range: 2.2-8.1m/s) and a mean tangential impact velocity of 3.7 ± 2.0 m/s (range: 0.7-7.6m/s). Both vertical and tangential impact velocities significantly increased with the increasing ES initial velocity (Figure 5). The vertical velocity of head-ground impact was found significantly higher in ES falls with a curb orientation of 90° than with a curb orientation of 30°.

Without wearing a helmet, the locations of impact on the head with the corresponding head-ground impact velocities are displayed in Figure 6. Among all ES falls (27 cases), the forehead hits the ground first in 21 (77.8%) ES falls with the rear head in a single (3.7%) case. The face hit the ground first in 5 (18.5%) cases.

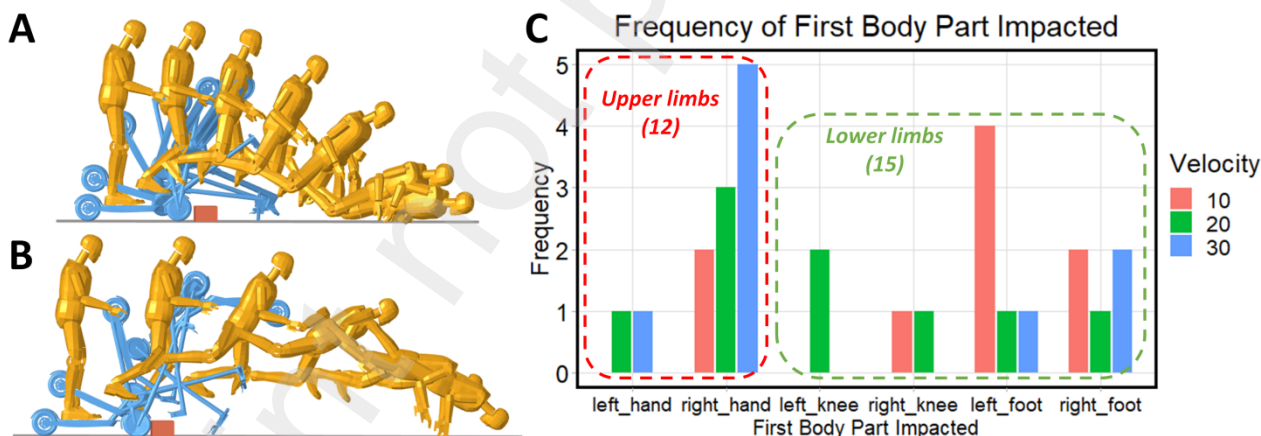


Figure. 4 E-scooter fall kinematics analysis: typical falls with upper (A) or lower (B) limbs impacting the ground first; the first body parts impacting the ground (C)

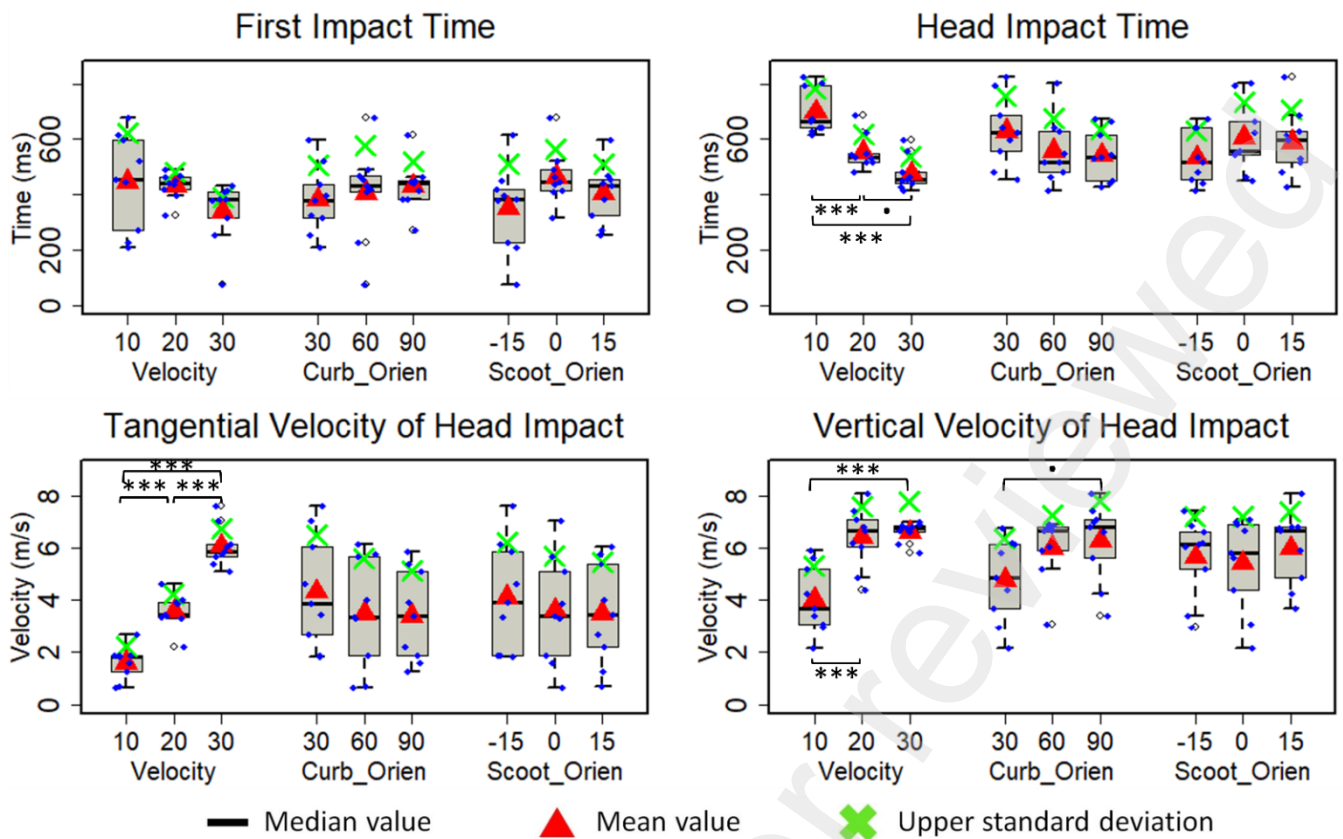


Figure. 5 The effects of initial accident conditions on the time of the first body-ground impact, the time of the first head-ground impact, the tangential and vertical velocity of head-ground impact during ES falls. P values: *** $p < 0.001$, ** $p < 0.01$, * $p < 0.05$, · $p < 0.1$

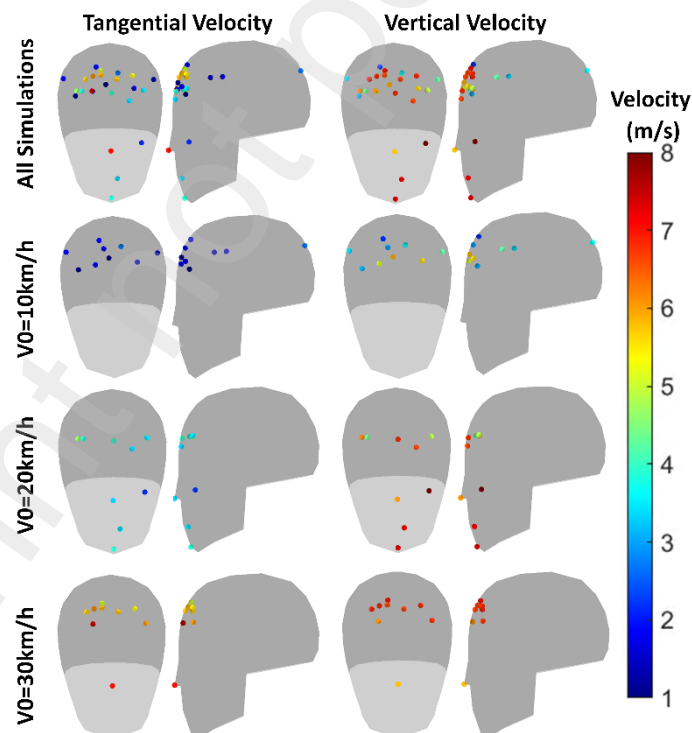


Figure. 6 The locations of impact on the head (frontal and left views), tangential and vertical velocities of head-ground impact during E-scooter falls

3.2 Helmet protection performance

In the helmeted configuration, the first impact to the head occurred on the helmet in 23 out of the 27 ES falls. In the other 4 ES falls (always with $V_0 = 20 \text{ km/h}$), the first impact to the head occurred on the face instead, and thus the helmet did not reduce the head injury metrics.

The head injury metrics were compared between the configurations with and without a helmet for all ES falls and for the falls grouped by ES initial velocities (Figure 7). Overall, the head linear acceleration and HIC₃₆ were significantly lower in the ES falls when the helmet was worn, not depending on the ES initial velocity: the head linear acceleration ($505 \pm 291g$ vs $1021 \pm 423g$) and HIC₃₆ (5503 ± 6052 vs 21301 ± 15121) were reduced on average by 51% and 70% respectively. The head angular velocity and the BrIC were also significantly lower when the helmet was worn in the ES falls with initial velocities of 10km/h and 30km/h: the head angular velocity and BrIC were both reduced on average by about 21%. However, the helmet use did not significantly reduce the head angular acceleration during ES falls. The thresholds of linear acceleration and HIC₃₆ for severe head injuries were always exceeded without the helmet and remained high with the helmet (85.2% and 92.6% of cases respectively). The number of cases with the head angular velocity and BrIC exceeding severe head injury thresholds was also reduced by 11.1% and 18.5% when the dummy wore a helmet (Figure 7 and Table 1).

All the head injury metrics during ES falls with and without a helmet were linearly correlated with the vertical velocity of head-ground impact (Figure 8): the higher the vertical impact velocity the higher the injury metrics. For the injury metrics associated with linear acceleration, the slopes of the linear regressions were less steep with helmet use, which means that with the helmet the corresponding injury metrics were more reduced at a higher impact velocity.

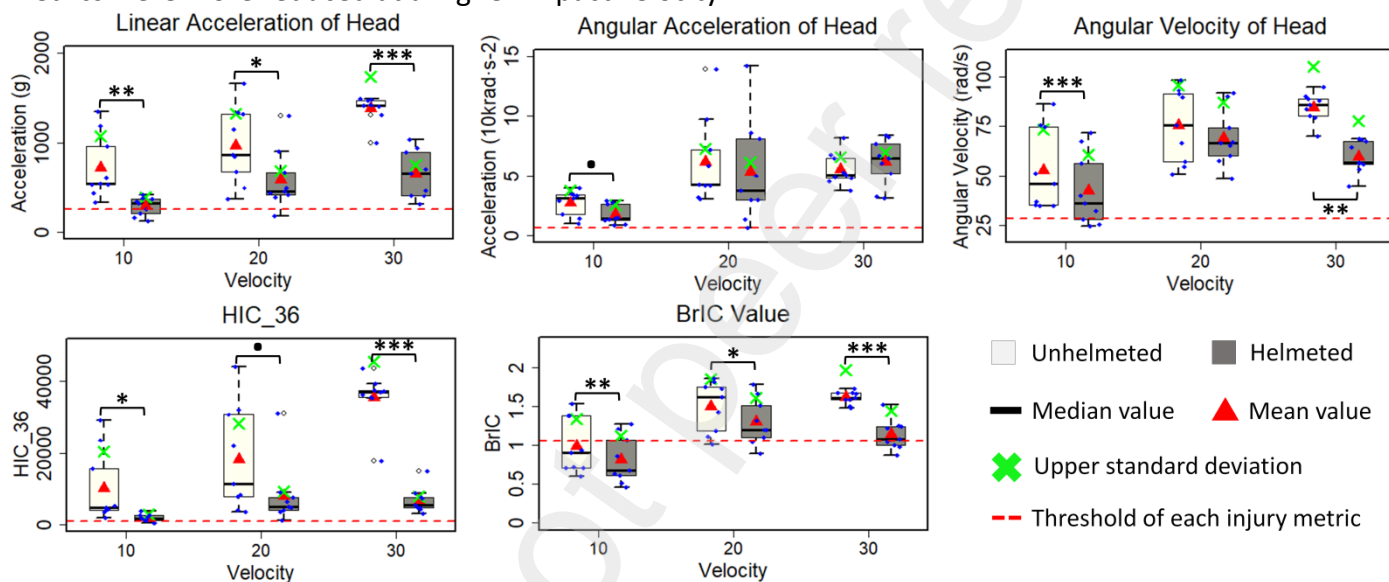


Figure. 7 Head injury metrics during E-scooter falls with and without a helmet: the linear acceleration (threshold = 250g), angular acceleration (threshold = 6383rad/s²) and velocity (threshold = 28.3rad/s) measured at the head, HIC₃₆ (threshold = 1000) and BrIC values (threshold = 1.0582). P values: *** p<0.001, ** p<0.01, * p<0.05, · p<0.1

Table 1. The number (percentage) of E-scooter falls in which the head injury metrics exceeded the injury thresholds: head linear acceleration (Head_Acc), head angular acceleration (Head_Ang_Acc), head angular velocity (Head_Ang_Vel), HIC₃₆, and BrIC values. Bold values indicate scenarios in which the number of cases with excessive head injury metrics was reduced by helmet wearing.

Initial velocity	10km/h		20km/h		30km/h		All velocity	
	No	Yes	No	Yes	No	No	Yes	No
Head_Acc	9 (100%)	6 (66.7%)	9 (100%)	8 (88.9%)	9 (100%)	9 (100%)	27 (100%)	23 (85.2%)
Head_Ang_Acc	9 (100%)	9 (100%)	9 (100%)	9 (100%)	9 (100%)	9 (100%)	27 (100%)	27 (100%)
Head_Ang_Vel	9 (100%)	6 (66.7%)	9 (100%)	9 (100%)	9 (100%)	9 (100%)	27 (100%)	24 (88.9%)
HIC ₃₆	9 (100%)	5 (77.8%)	9 (100%)	9 (100%)	9 (100%)	9 (100%)	27 (100%)	25 (92.6%)
BrIC	3 (33.3%)	3 (33.3%)	8 (88.9%)	7 (77.8%)	9 (100%)	5 (77.8%)	20 (74.1%)	15 (55.6%)

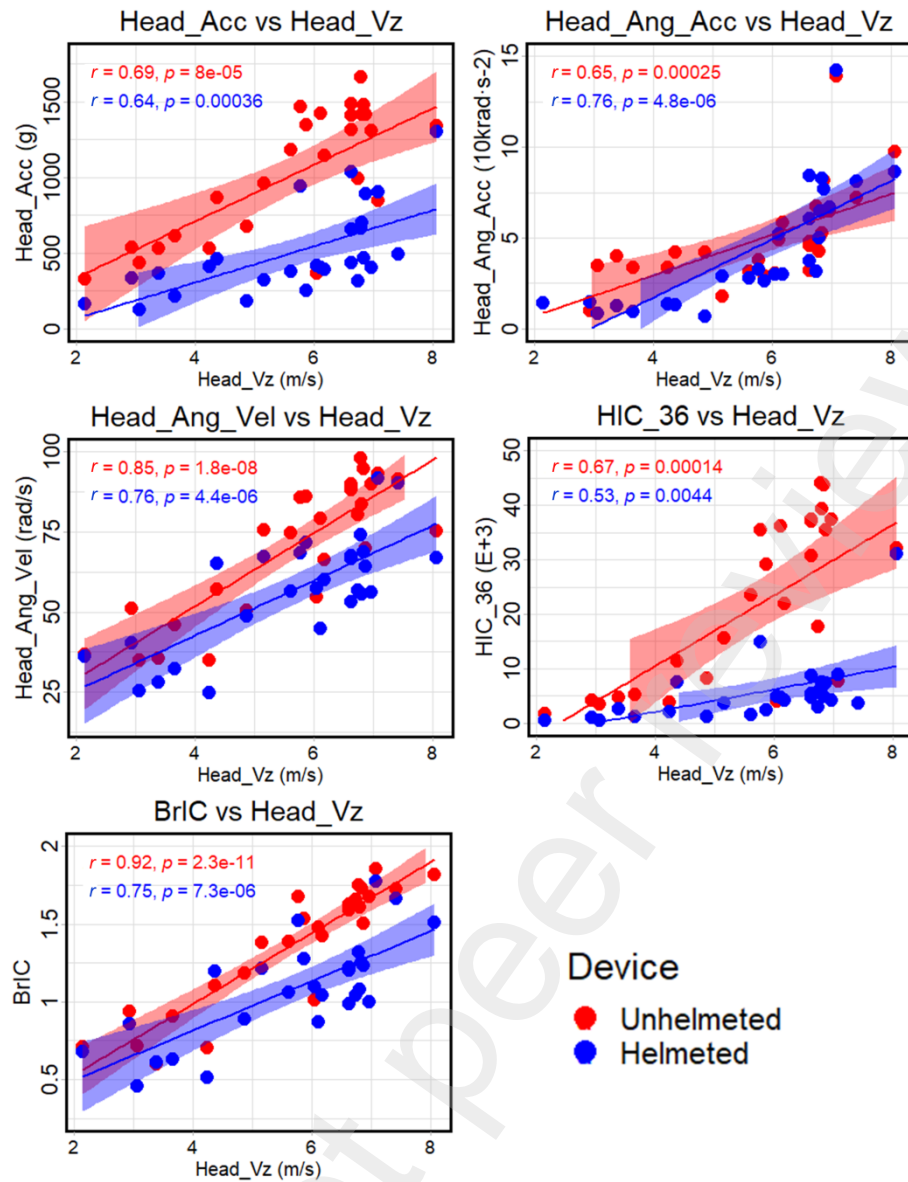


Figure. 8 Pearson's correlations (95% confidence interval) between the E-scooter rider head injury metrics and head-ground vertical impact velocity (Head_Vz). Head injury metrics: linear acceleration (Head_Acc), angular acceleration (Head_Ang_Acc), angular velocity (Head_Ang_Vel), HIC_36, and BrIC values.

4 Discussion

This study was the first to evaluate the effect of helmet use on the risk of head injuries during typical ES falls. A FE model of the hybrid III dummy riding an ES was developed, validated, and used to reproduce typical ES falls induced by the collision with a curb. It showed that this type of fall could result in a high vertical velocity of head-ground impact and therefore a high risk of severe head injuries. In all of the simulated ES falls, the helmet significantly reduced the head linear acceleration and angular velocity but had a limited effect on reducing the head angular acceleration. Despite these significant reductions in head injury metrics, the bicycle helmet modeled might not be enough to prevent the ES rider from severe head injuries, since the head injury metrics remained above the injury thresholds in most ES falls.

The ES rider in typical ES falls was found to always sustain oblique head-ground impacts with a vertical velocity of 5.7 ± 1.5 m/s and a tangential velocity of 3.7 ± 2.0 m/s. This was consistent with the findings in a recent numerical study which predicted oblique head-ground impacts with a vertical velocity of 6.3 ± 1.4 m/s and an angle of $65 \pm 10^\circ$ during ES falls induced by a pothole (Posirisuk et al., 2022). The head-ground impact velocities predicted in our study were also consistent with those predicted during bicycle fall simulations (5.2 ± 1.0 m/s and 3.7 ± 0.8 m/s for vertical and tangential impact velocities) (Bourdet et al., 2012). The similar head-ground impact velocities between bicycle and ES falls might suggest that the

helmet adequate to protect from bicycle falls should also be adequate for ES falls. Finally, the main factor influencing the head-ground vertical and tangential impact speed was the ES traveling speed before the crash, which was also reported in other crash scenarios (Bourdet et al., 2012; Posirisuk et al., 2022; Xu et al., 2016).

Without a helmet, the head angular acceleration and velocity were always above the injury thresholds, indicating a high risk of concussion. The HIC₃₆ was also always above the injury threshold with BrIC above the threshold in 74.1% of ES falls, indicating a high risk of severe (AIS3+) head injuries. Agreeing with our prediction, epidemiology studies found 54%-58% of the unhelmeted injured ES riders sustained craniofacial injuries and 14%-58% of the craniofacial injuries were severe head injuries (e.g. internal hemorrhage, skull fracture, loss of consciousness, etc) (Kleinertz et al., 2021; Trivedi et al., 2019). The head injury metrics were positively correlated with the head-ground vertical impact velocity which increased with the increasing traveling speed before the crash. Consistent with previous studies (Everett, 2021; Posirisuk et al., 2022; Santacreu et al., 2020), this might suggest that reducing the ES speed would reduce the risk of injuries for ES riders. More specifically, our results suggest that the 20km/h to 32km/h ES speed limits currently imposed by most authorities might not be enough to reduce rider head injuries in case of falls (Santacreu et al., 2020). On the contrary, the 10km/h ES speed limit newly introduced in Paris (Everett, 2021), may sufficiently reduce the head-ground impact velocities and thus head injuries in case of ES riders fall.

With the helmet, the head linear acceleration and HIC₃₆ were significantly ($p < 0.10$) reduced. The head linear acceleration was reduced on average by 500g with a helmet ($505 \pm 291g$) compared to without a helmet ($1021 \pm 423g$). Previous experimental and numerical studies also found that bicycle helmets did reduce the head linear acceleration and HIC₃₆ during head-ground impacts (Cripton et al., 2014; Wang et al., 2022). However, in our study, a high risk of severe head injuries during ES falls remained in most helmeted cases: the head linear acceleration and HIC₃₆ were above the threshold for AIS3+ head injuries in 85.2% and 92.6% of all cases respectively. This suggests that the standard evaluation of bicycle helmets cannot warrant adequate protection for the head in the simulated ES falls. This might be because the impact energy involved in the simulated ES falls was higher than that involved in the standard evaluation of bicycle helmets (European Committee for Standardization, 2012):

- the head-ground vertical impact velocity was higher than the impact speed (5.42m/s) of the bicycle helmet standard evaluation (European Committee for Standardization, 2012) in 18 (62%) ES falls;
- the equivalent mass of impact in ES falls might also be higher than the mass (5kg) used in the standard evaluation (European Committee for Standardization, 2012) since the whole body, instead of only the head, collided with the ground in real accidents.

Compared to bicycle helmets, motorcyclist helmets are tested at higher speeds (i.e. 7.5m/s for vertical impacts and 8.0m/s for oblique impacts) as required by the European testing standard (UNECE22.06, 2021). and these testing speeds are higher than the head-ground vertical impact velocities in most ES falls. It would be interesting to evaluate the performance of a motorcycle helmet in these ES falls in our future study.

During the simulated ES falls, the oblique impact of the head induced a high level of head angular acceleration (Figure 7). Angular acceleration was reported to highly contribute to the occurrence and severity of traumatic brain injury, especially diffuse brain injuries (King et al., 2003; Kleiven, 2013). Yet, the helmet simulated in this study did not significantly reduce the head angular acceleration during head-ground impacts. Although the helmet significantly reduced the head angular velocity and BrIC (Figure 7), the reductions in these injury metrics were limited. With a helmet, the head angular velocity was still above the injury threshold of concussion in 88.9% of ES falls while BrIC was above the threshold of AIS4+ head injuries in 55.6% of falls. This is not surprising as the efficiency of helmets in reducing the head rotational kinematics in oblique impacts is not evaluated in the current testing standard [18]. Several rotational management technologies (e.g. low-friction layers and fluid-filled bladders) of helmets have been developed to mitigate the head rotational kinematics during impacts (Hoshizaki et al., 2022). Test protocols involving oblique impacts have also been proposed to evaluate the helmet efficiency in reducing the head rotational kinematics (Deck et al., 2019; Hoshizaki et al., 2022). This study further demonstrated the necessity of reducing head angular kinematics in oblique impacts for ES helmets.

In this study, the unhelmeted rider was found to hit the ground mostly with the forehead (77.8%, 21 cases) and with the face in 5 (18.5%) cases. All the impacts occurring on the forehead without a helmet were found to occur on the helmet shell in the helmeted configuration. Only 1 out of the 5 impacts on the face without a helmet occurred on the helmet shell in the helmeted configuration. Moreover, no significant difference was seen in the head injury metrics during these 5 ES falls with or without a helmet. This suggested that the bicycle helmet failed to protect from impacts on the face in these ES falls. Facial injuries were often observed in the unhelmeted ES rider group (Kim et al., 2022; Yarmohammadi et al., 2020) while there is a lack of data on facial injury incidence in the helmeted group. The lower face was found particularly vulnerable to injury in bicycle crashes despite helmet use (Benjamin et al., 2019), agreeing with our observation to some extent. Unlike bicycle helmets or open-face motorcyclist helmets, full-face motorcyclist helmets may cover the facial area and thus better protection during ES falls, which remains to be verified in our future study.

Certain limitations exist in this study. The ES falls were reproduced with FE simulations, rather than multi-body simulations, to evaluate in detail the head kinematics at impact and the effect of the helmet in mitigating the risk of injuries. This choice involved a much higher computational cost than using multi-body simulations and hence limited the number of accident variables tested. For instance, even though the rider anthropometry had been shown to modify the head impact kinematics during ES falls (Posirisuk et al., 2022), only the 50th percentile rider size was considered in our study. Head injury metrics might be lower for other populations as head-ground impact velocities were previously found to be significantly higher in the mid-sized ES rider compared to the smaller- and larger-sized riders (Posirisuk et al., 2022). The hybrid III dummy rather than a detailed human body model (such as THUMS V.4 pedestrian FE model (Watanabe et al., 2012)) was used to simulate the ES rider. This choice was made to reduce computational time, increase reproducibility, and be able to validate the model against the available experimental tests. This choice made it possible to evaluate the helmet's performance in mitigating global head injury metrics. However, we were unable to predict the protection efficiency of the helmet with more refined head injury predictors such as brain stress and strain (Giudice et al., 2019). Another limitation was that our rider FE model was passive and unable to simulate the muscle reaction to the fall. In real-world falls, ES riders may have protective reflexes and use their arms to protect their head from colliding with the ground or reduce collision severities (Posirisuk et al., 2022). Thus, our simulation could represent the worst scenarios where, for some reason (e.g. drunk), the protective reflex did not occur. Only one type of bicycle helmet and only one type of typical fall scenario were investigated. Future work is thus needed to evaluate the performance of additional helmet technologies in other crash scenarios (e.g. collision with a vehicle or an obstacle, fall due to a slippery ground). Finally, the detailed head injury mechanisms in ES accidents should be further investigated by using a refined head FE model.

5 Conclusion:

This study evaluated the head-ground impact conditions and the effects of helmet use on the risk of head injuries during typical ES falls. A FE model of the hybrid III dummy riding an ES was developed, validated, and used to reproduce typical ES falls induced by the collision with a curb. These ES falls always resulted in an oblique head-ground impact, mostly at the forehead. The oblique head-ground impact contributed to a high risk of severe head injuries, especially when the ES traveling speed before the crash was 20km/h and 30km/h. During head-ground impacts, the helmet use significantly reduced the head linear acceleration but not the angular acceleration. However, the bicycle helmet was unlikely to protect against severe head injuries during the typical ES falls since the head injury metrics were mostly higher than the injury thresholds. The limited protection from the bicycle helmet might suggest the need for increasing the impact energy in the helmet evaluation standards and involving the evaluation of angular acceleration during oblique impacts. Further work is needed to verify those observations in other crash configurations.

Author statement

W. Wei, Y. Petit, P-J Arnoux, and N. Bailly conceived of the presented idea. W. Wei developed the

numerical models. W. Wei and N. Bailly designed the computational framework. W. Wei, Y. Petit, P-J Arnoux, and N. Bailly contributed to the interpretation of the results. W. Wei took the lead in writing the manuscript. All authors provided critical feedback and helped shape the research, analysis, and manuscript.

Conflict of interest

None

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Appendix

Test-2 and Simulation-2

Resultant Acceleration

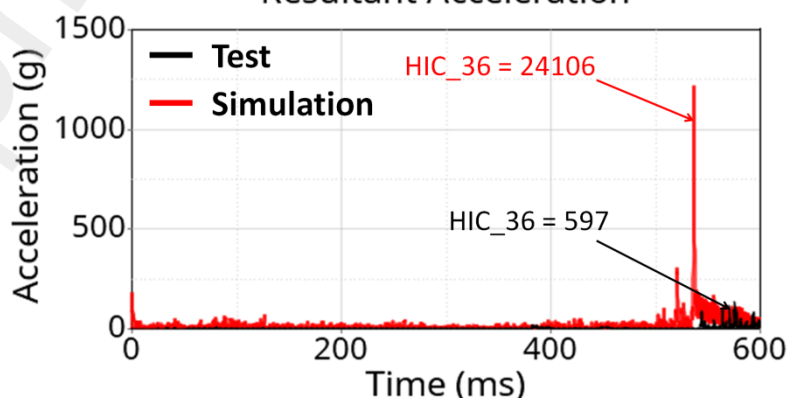


Figure. S1 Resultant acceleration of the head and the HIC₃₆ predicted in Simulation-2 and measured in Test-2 (E-scooter-curb oblique impact with 50° curb)

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