MÁSTER EN INGENIERIA PARA LA MOVILIDAD Y SEGURIDAD (M2S)

TRABAJO FIN DE MÁSTER

Analysis of standing electric scooter accidents with vehicles using different human body models and the influence of using a helmet on them

Autor: Diego Guzmán Terrón

Directores: Manuel Valdano

Francisco José López Valdés

Madrid

31 de agosto de 2022

Declaro, bajo mi responsabilidad, que el Proyecto presentado con el título

Analysis of standing electric scooter accidents with vehicles using different human body models and the influence of using a helmet on them

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Autorizada la entrega del proyecto

EL DIRECTOR DEL PROYECTO

Fdo.: Manuel Valdano Fecha: 31/ 08/ 2022......

Fdo.: Francisco J. López Valdés Fecha: 31/ 08/ 2022

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Anexo M2S
Conocimientos aplicados

La realización de este trabajo ha requerido la aplicación de conocimientos que he estado aprendiendo a lo largo del Máster de Ingeniería para la Movilidad y Seguridad.

La mayoría de los conceptos han surgido de las siguientes asignaturas:

- ***Simulación multifísica***: a pesar de que los conceptos de esta asignatura están enfocados al uso del programa de simulación ANSYS, es importante saber los conceptos claves del funcionamiento de este tipo de programas de elementos finitos. Gracias a esto, se pudo entender mejor como obtener las simulaciones de la manera más correcta, llegando a tener un punto de vista crítico de los resultados obtenidos.
- ***Biomecánica del daño***: la gran mayoría del trabajo se basa en el concepto de cómo funcionan los criterios de lesión, como se obtienen y ser muy crítico a la hora de realizar una lectura sobre diferentes artículos científicos, llegando a ver las virtudes o defectos de estos. Se ha aplicado principalmente conceptos de valor de HIC (*Head Injury Criteria*) y BrIC (*Brain Injury Criteria*).
- ***Estructuras ligeras***: poder entender correctamente las partes que comprenden el chasis de un automóvil, para poder entender los materiales usados y las partes más rígidas de un vehículo, llegando a poder ser determinante a la hora de realizar este tipo de simulaciones.
- ***Logística y transporte global***: esta asignatura me ha podido permitir ser muy crítico en cómo tratar los datos que existen de diversas fuentes y como ser capaz de distinguir una fuente fiable de otras. Además, también fue útil a la hora de poder ver como la implementación de ciertas regulaciones no tienen por qué ser las correctas para solucionar un problema en concreto.
- ***Sistemas de retención y seguridad integrados***: gracias a esta asignatura, pude aprender a utilizar programas de elementos finitos no lineales muy complejos, como es el caso de *PRIMER*, que utiliza un solver *LS-Dyna* para resolver esta interacción entre modelos muy complejos, para poder mejorar la seguridad de los ocupantes de los vehículos.
- ***Movilidad sostenible***: para poder entender como está cambiando el comportamiento, tanto de la movilidad tradicional (vehículos propulsados por gasolina o diésel como método de propulsión) y como la introducción de nuevos modos de transporte, como la micro-movilidad) están cambiando el paradigma, generando un problema de infraestructuras en muchas de las grandes ciudades.

Analysis of standing electric scooter accidents with vehicles using different human body models and the influence of using a helmet on them

Diego Guzman
Universidad Pontificia Comillas, Madrid, Spain

Abstract

Due to the growth of urban mobility due to various factors, there has been an increase in the use of standing electric scooters to move around large cities. However, due to the low level of information on the risks of using this type of vehicle, there has been an increase in accidents and, therefore, in the number of injuries caused by these. For this purpose, several simulations of collisions against the rear side door of a stationary vehicle will be performed with two types of human body models: Dummy Hybrid III 50th and THUMS AM50 V4.02, as well as the influence of helmet use on these models. All this, together with a scooter model obtained by reverse engineering, will allow us to use LS-Dyna finite element simulation software to obtain the necessary data to perform an analysis and compare them. The kinematics, resulting accelerations and maximum angular velocities will be observed to perform the analysis. There is a significant difference between the kinematics of both human body models. In the Dummy Hybrid III model, impact and rebound occurred in an upright position, whereas with the THUMS model, impact occurred in an upright position while in the rebound stage, the coronal plane rotated on an axis parallel to the longitudinal axis of the vehicle. Since no reference to studies with real tests has been found, it is very difficult to verify the data obtained. Data obtained from accelerations give an indication that it represents a low risk related to head injuries. The results are very similar between the two human body models, and the use of the helmet in the simulations has been able to reduce these values. The data obtained related to angular velocities are different depending on the human body model used. In the Dummy Hybrid III, the risk of brain injury is around 15% AIS3+, while in the THUMS model, this value increases to 50% AIS3+. The use of helmets has also been able to reduce these values. Helmet use has been able to increase occupant safety while using a standing electric scooter. However, the lower facial area is still very unprotected in this type of collision. the use of full-face helmets is recommended, despite the discomfort it represents for the user. With the findings obtained from this study new means can be obtained to assess correctly head and brain injuries, using the human body model that most closely resembles reality, together with an awareness campaign of the use of full-face helmets in standing electric scooters to reduce the risks of head and brain injury.

Keywords

- Standing electric scooter
- Head injury
- Dummy Hybrid III 50th
- THUMS AM50
- Vehicle
- LS-Dyna

Introduction

Urban mobility has experienced a considerable increase due to population growth in large cities and, due to the latest policies being implemented in large cities around the world, the aim has been to reduce vehicle mobility of traditional combustion fuels (gasoline and diesel) in delimited areas in city centers to reduce environmental and noise pollution, which has been on the rise in recent years. But these policies have caused the population to look for various alternatives to reach their final destination: use of public transport, replacing their current vehicle with one that consumes fuels with lower pollutant emissions (CNG, LPG, hydrogen, electric), or switching to micro-mobility.

Since 2017, there has been an increase in the use of SES (*"Standing Electric Scooters"*) as a means of transport in urban areas of large cities, both in Europe and in America and Asia (*Thaddeus et al., 2020*). The reason for the boom of this vehicle is due to its versatility in the city, availability of the service in the cities, comfort of use of these, in addition to the advertising campaigns carried out through social networks (*Allem et al., 2018*).

In 2018, a study of standing electric scooters and "bike-share" usage was conducted in the city of Washington D.C. (United States). Upon completion, an average usage time of 5 minutes was recorded to travel a distance of approximately 650m, making 7050 trips with 287 scooters in a day (*McKenzie, 2019*). Other studies went so far as to show a 100% increase in standing electric scooters users in the United States from 2018 to 2019 (*Nitesh et al., 2021*).

Due to this increase in the use of electric scooters in cities, there has also been an increase in the number of accidents involving SES. The problem with this type of accident is that most people who use this means of transport are not fully aware of the dangers associated with using SES on public roads, which may or may not be equipped for this type of mobility. According to the U.S. Consumer Product Safety Commission, the number of occupants that have been injured during a SES involved accident between 2017 and 2019 has been estimated to be 132,800 (*Tark, 2020*).

Because of this problem, the number of citizens with injuries related with SES accidents have been also on the rise. Several studies have been obtaining medical emergencies records from various urban ares around the world. A study conducted on 2 emergencies departments in Southern California, 249 patients were presented (mean age, 33.7 years; 58.2% males) with injuries related with SES (80.2% falling, 11% collided with an static object and 8.8% collided with a moving object or vehicle) with almost no one using a helmet (4.4% were registered), and the most common injuries characteristics from patients were fractures (31.7%), head injuries (40.2%) and contusions, sprains and lacerations (27.7%) (*Trivedi et al., 2019*). Findings from another study carried out in the two largest level 1 trauma centers Frankfurt (Germany) showed that over a 9-month period, a total of 76 patients were presented (mean age 34.28 years; 69.7% males), from which, 92,1% suffered an accident without any external influence, 32.9% admitted it was their first time using this type of vehicles and only one patient was using a helmet while using a SES. The most affected areas from patients injuries where the upper extremities (47.4%), head and face (38.2%), lower extremities (36.8%) and chest (9.2%) (*Störmann et al., 2020*). Another study conducted in an emergency room from the Hospital Asepeyo Sant Cugat over a three years period in Barcelona (Spain) in which 167 patients were included for the study (mean age 37.4 years; 55% males). 62.8% of the patients were presented with fractures, 21.5% with multiple contusions, 9.5% head injuries, 7.18% ligament and/or tendon injuries and 2.4% required suture (*Bascones et al., 2022*). In other study, gathered data from an emergency department during a 7 month period in downtown Dallas, Texas (U.S.A.) and showed that out of 90 patients (mean age, 31.8 years; 62.2% males), none of the were reported using any sort of helmet. The injuries presented from all patients were located in head and face (81.1%), extremities (64.4%), intracranial (6.7%), abdomen (3.3%) and chest (2.2%) (*Bhavin et al., 2019*). In a trauma center located in Cologne (Germany), it was carried out a study over with a duration of one year where 59 patients (mean age, 30.03; 40.68% males) were presented with injuries associated with SES accidents. None of the patients were wearing a helmet during the accident, presenting some injury located in the following areas: head and face (62.7%), upper extremity (50.84%), lower extremity (47.45%) and spine (6.77%) (*Andreas et al., 2021*). After reviewing three trauma centers in the U.S.A. during a time spam of 14 months, this study presented 103 patients (mean age, 37.1years; 65% males) whom presented extremity fractures (42%; 8% were AIS3+), facial fractures (26%; 1% were AIS3+), intracranial hemorrhage (18%) and head-AIS3+ (15%). From this study, 98% of all patients were not wearing a helmet (*Leslie et al., 2019*).

From the review of the previous studies, we can identify that one of the most important aspects to supervise is the head injuries produced in this type of accidents with SES, taking into account that almost none of the SES users were using a helmet during the accident. So it is important to understand the biomechanics involved of SES users.

In this study, we want to assess the damage that occurs to the head during an impact with a vehicle through simulations to be able to predict the injury risk associated with. Not only this, but also because of how the previous studies that were similar have carried out their research (*Passines et al., 2022*)(*Van Rooij et al., 2003*), we also want to assess the difference between two HBM, and with or without the use of helmet. Because of the difference in the geometry, mass distribution and the materials used for each model, different kinematics and dynamics will be observed, showing if the use of more complex HBM is really necessary for this type of modelizations and how is the influence of the helmet in this type of accidents.

Methods

We have used LS-Dyna software for our simulations. LS-Dyna is a general-purpose FEM (Finite Element Method) program that is capable of simulating real and complex problems. It has been used in the automotive industry for analyzing passive safety (*Marklund et al., 2001*)(*Borovinšek et al., 2007*).

Standing electric scooter model

The standing electric scooter model was based on the Ninebot Kickscooter E22E from Segway (Figure 1a). The CAD model has been built by reverse engineering, obtaining the dimensions and masses of several of the main components, separating it into 3 different parts and assigning a node to each of them with the values of the corresponding masses, separating it into 3 different parts and assigning a node to each of them with the values of the corresponding masses, center of masses and inertias, showed in Table 1. These parts interact with each other by declaring JOINT_REVOLUTION to allow the base to rotate

	Mass [kg]	Center of mass (X,Y,Z) [mm]	Mass moments of Inertia (Ixx, Ixy, Ixz, Iyy, Iyz, Izz) [kg·mm^2(·10^3)]
Base	3.15	(-701.5, -20, 101.4)	(19.082, -0.942, 0, 207.311, 0, 200.051)
Motor wheel	3.22	(-81.5, -20, 101.4)	(14.705, -0.036, 0, 161, 0, 8.72)
Steering column & battery	5.18	(-181.5, -20, 580.3)	(527.266, -191.540, 0, 514.320, 0, 14.705)

Table 1: Masses and inertial properties from scooter model

(a) Ninebot Kickscooter E22E from Segway

(b) Scooter model

Figure 1: Scooter used and model

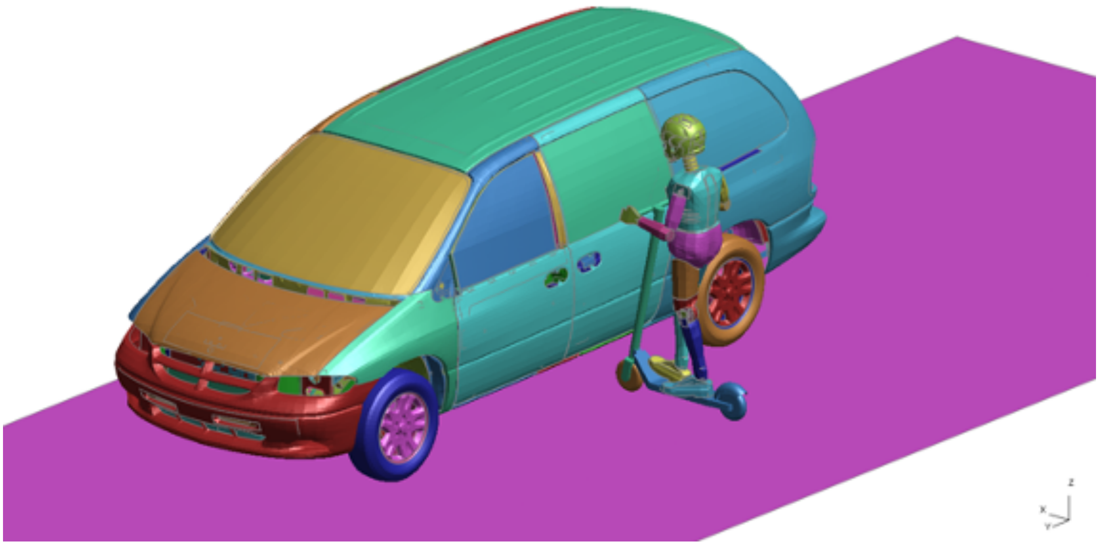


Figure 2: Positioning of simulation models

within the handlebar & battery Z local axis, while the motor wheel can rotate on its principal axis of revolution (Y axis). Finally, all parts of the scooter are declared under a rigid material, with aluminum properties.

Human body models

For this simulations, we have used two types of HBM: *Dummy Hybrid III 50th* and *THUMS AM50 V4.02*. The Dummy Hybrid III 50$^{\text{th}}$ has been created by the Livermore Software Technology Company (LSTC) using over 7468 nodes with a total mass of 78.06 kg and a height of 1682mm, while THUMS AM50 V4.02 has been developed by TOYOTA using over 760000 nodes with a total mass of 77.6kg and 1786mm. The Dummy Hybrid III 50$^{\text{th}}$ has been widely used for real Crash-Test and the simulation model has been verified through a series of tests calibrations (*Noureddine et al., 2000*). Meanwhile, the THUMS AM50 V4.02 aims to simulate human body kinematics and injury responses in car crashes as being the most detailed HBM from the all and has been also verified through a number of test that have been corroborated through some studies (*Hardy et al., 2001*)(*Kroell et al., 1974*).Both these models do not have any muscle activation, for example with the neck tension through impact.

It is very important to position correctly the HBM on the scooter model in order to obtain the most realistic kinematics and dynamics as possible. For this purpose, we have positioned the HBM in the most upwards position, with the right foot at the front, parallel to the scooter base, and the left foot at the back, with the foot protruding with a slightly angle from the base. Because of the complexity of the THUMS model, the hands are grabbing the handlebar meanwhile the dummy, because of the constrained degrees of freedom from some articulations, the hands are on the sides of the handlebar.

Vehicle model

The vehicle is a finite element model from the 1997 Dodge Grand Caravan modelled by George Washington University. The model is conditioned primarily for frontal collisions, but, due to the nature of the test, this will not greatly affect the results. The vehicle has over 344000 nodes with a mass of 2043 kg. The validation of this model has been done through a series of simulations and contrasting the results with those obtained by NCAP Crash-Tests (*Jesus et al., 2000*). All the impacts will occur in the center of the left side door. We chosen this type of vehicle because there are studies that also used them (*Ptak et al., 2022*)(*Peng et al., 2012*).

Helmet model

Because we want to determine the influence of helmets for SES occupants, we have used a KTH Riddell Revolution Speed Classic helmet. This type of helmet are used to protect American football players from head-to-head collision between them to reduce their head injury risk (*Mazdak et al., 2017*). We have chosen this helmet because it was the only one available for us at the moment, being really similar to an open face helmet. Because of this, it has been modified to remove the front grill that covers the mouth area.

Contacts

Because of the nature of this modelizations, this models are going to have a high computational cost. In order to reduce this, because of validation from the models with tests can implies that the materials have been define with great accuracy, making us relay on AUTOMATIC_SURFACE_TO_SURFACE contacts to minimize the computational cost. This type of contact are recommended for crash simulations since the orientation of parts relative to each other cannot always be anticipated, checking for penetrations on shell elements automatically. In all contacts, the friction coefficient has been declared as 0.3.

Boundary conditions

The boundary conditions applied in all simulations for this study are as follows:

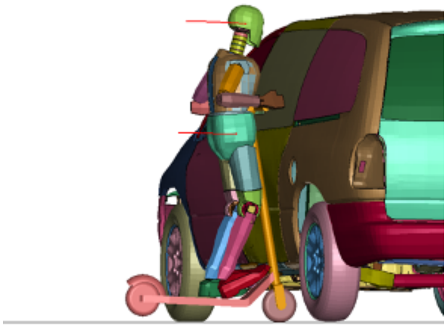
- The speed of the scooter, human body model and helmet will be 25 km/h. This is because it is the maximum speed limit allowed in most European and North American cities (*Ishmael et al., 2020*).
- In all simulations, the scooter, human body model, helmet and vehicle will be under the action of gravity.
- Since the vehicle is modeled for frontal impacts, 2 longitudinal members with the identifications 90000099 and 90000100 have been fixed to block the movement of the vehicle and to allow the corresponding deformations of the side door.

In total, 4 simulations with different human body model and using or not using helmet will be performed in a cluster with the characteristics shown in Table 2.

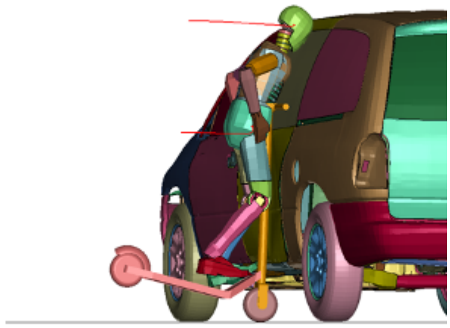
The number of CPUs used for each simulation has varied according to the availability of these resources, since they have been used for other simulations in other departments or research areas.

Cluster characteristics	
Platform type	Open MPI 2.1.3. Xeon64
Operating system	Linux CentOS 6.10 uom
Nº CPUs	64 CPUs

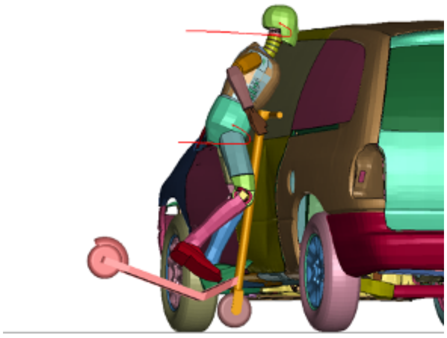
Table 2: Cluster characteristics



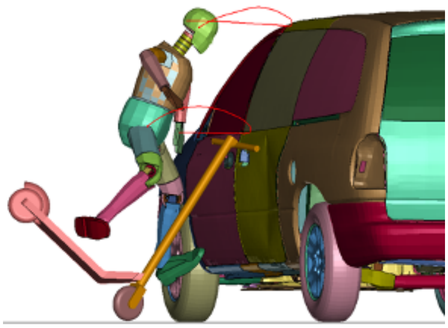
(a)



(b)

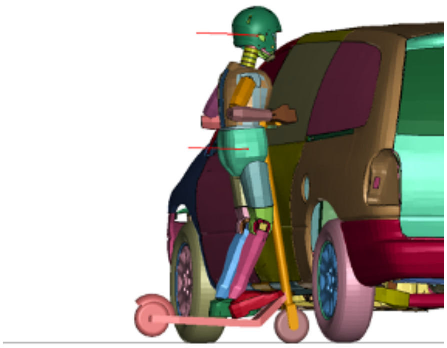


(c)

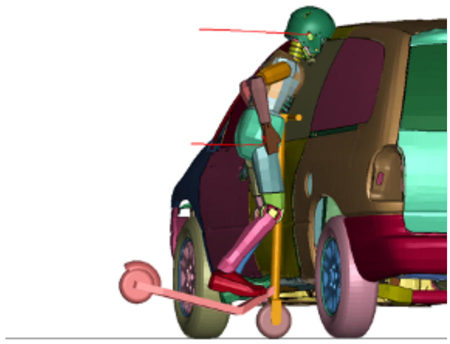


(d)

Figure 3: Kinematics with Dummy Hybrid III 50th without helmet



(a)



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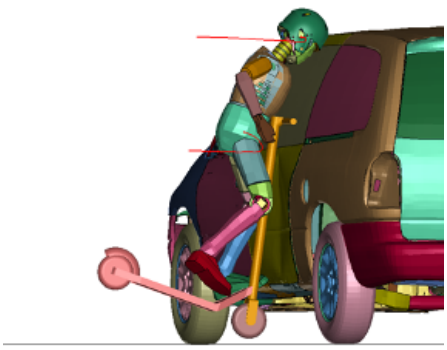
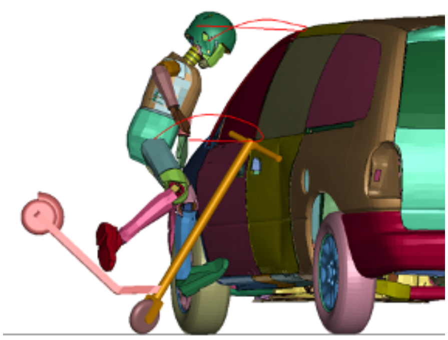
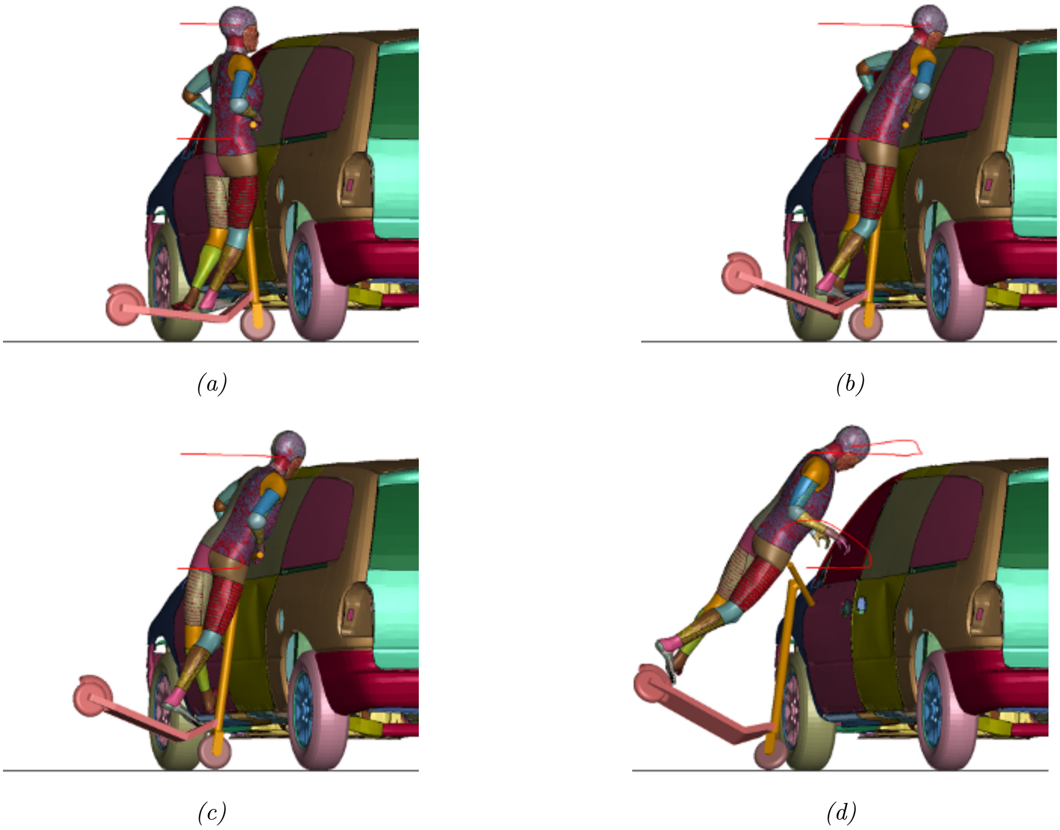


(c)



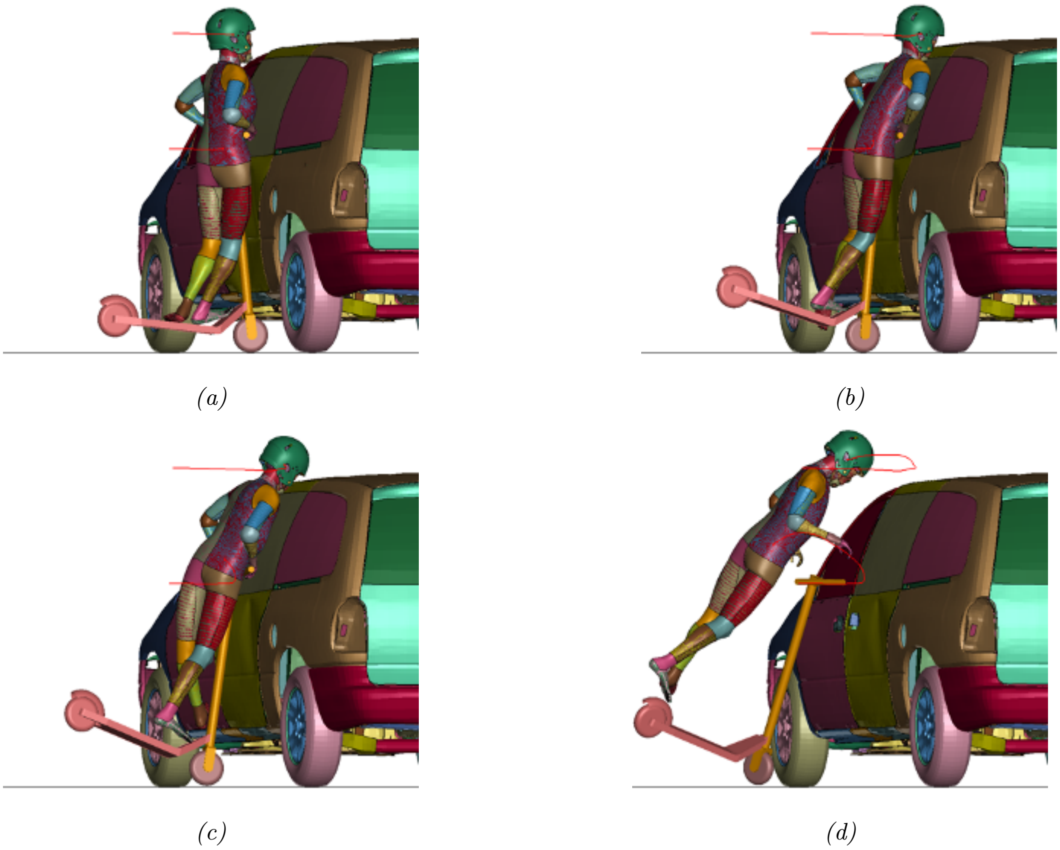
(d)

Figure 4: Kinematics with Dummy Hybrid III 50th with helmet



(a) (b) (c) (d)

Figure 5: Kinematics with THUMS AM50 without helmet



(a) (b) (c) (d)

Figure 6: Kinematics with THUMS AM50 with helmet

Outcome measurements for predicting injury risks

It is important to review the occupant injury zones after the accident. Using the same studies that have been discussed in the previous section, we will look at how to correctly contrast the probability of head injury risk through the use of damage criteria that are accepted by the medical and scientific community (*NHTSA, 1999*)(*Takhounts et al., 2013*). For this purpose, two injury criteria will be used: HIC15 and BrIC.

Results

Because we are focused in the injuries that can be produced over the head, we have tracked the head's center of mass and human body model's center of gravity. Both of these will be highlighted in a red curve (Figure 3, Figure 4, Figure 5 and Figure 6). We have four simulation cases.

- Dummy Hybrid III 50th without helmet
- Dummy Hybrid III 50th with helmet
- THUMS AM50 V4.02 without helmet
- THUMS AM50 V4.02 with helmet

Kinematics

After analyzing the kinematics obtained from all simulations, we can divide them into two stages: impact stage and the rebound stage. The impact stage contains the duration between the initial position and the instant after there is no longer contact between some human body model part and the vehicle. Meanwhile, the rebound stage contains the duration between there is no longer contact between some human body model part and the vehicle and separates completely from the scooter contact.

During the impact stage, both dummy and THUMS models impact occurs in the same manner: the steering column is the first part to impact the side door, and the next parts are in the following order: the legs, abdomen, hands, chest and head. During the rebound stage, begins to differ the kinematics, depending the type of human body model used. With the dummy model, the first part that ceases to be in contact is the chest, being thrown the body back in an upright position, with a small inclination forwards of the coronal plane with respect of the vehicle longitudinal plane. On the THUMS model, the legs are the first parts that are no longer in contact with the vehicle and the rest is thrown out from the vehicle impact with a greater distance and in a bigger inclined coronal plane than the dummy simulation.

As shown in Figure 4 and Figure 6, the use of the helmet on both human body models do not affect to the kinematics at all. And, because of the type of helmet that has been used for this modelizations, the face of both human body models impact the upper side door even though the helmet also impacts in the dummy simulation.

Head acceleration data

All the acceleration data has been collected through accelerometer that have been situated in the center of mass of both heads, using a filter CFC1000, as stipulated in the SAE J211 standard (*SAE J211-1, 1995*).

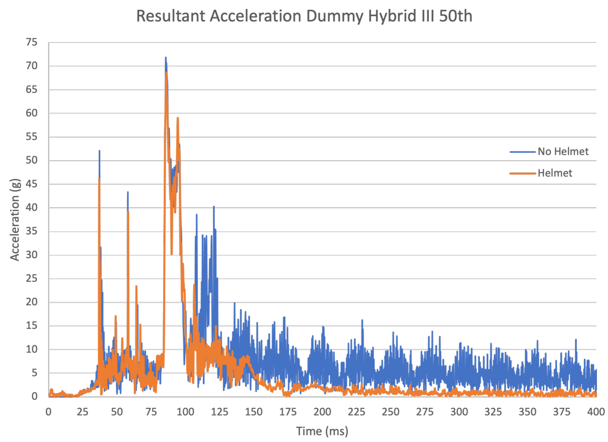


Figure 7: Resultant acceleration from Dummy Hybrid III simulations

From the analysis from the resultant acceleration data (Figure 7 and Figure 8), it can be observed that impacts occurs almost in the same instant for both human body models (83.6ms for Dummy Hybrid III and 76.9ms for THUMS AM50). The peak acceleration value are similar without the use of helmet (blue graph's in Figure 7 and Figure 8) in both human body models and there is a slight difference between the models using the helmet (orange graph's in Figure 7 and Figure 8), having a higher head acceleration value in the case of the dummy model. It can be seen that the graph's form is similar also in both

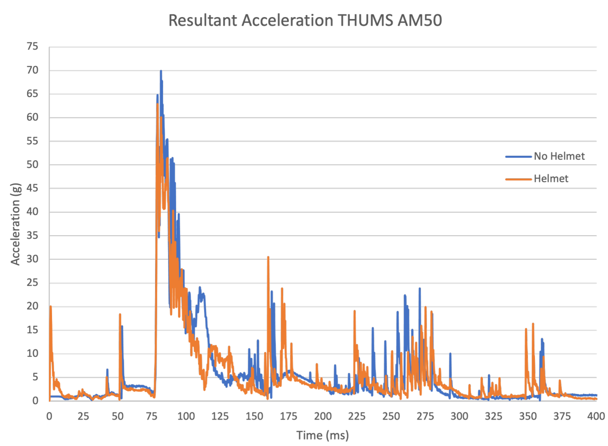


Figure 8: Resultant acceleration from THUMS simulations

cases, even though their kinematics are not the same, observing a high disturbance in the dummy impact without a helmet.

According to the IIHS, the maximum value allowed during a crash-test is 700, indicating a 5% of a head-AIS4+. Also, it is important the peak acceleration value and how was obtain in order to establish correctly the injury sustained by the occupant (*IIHS, 2014*). In terms of HIC15 values, regardless of the simulation performed, the values obtained has been calculated over similar time periods within the simulation (between the interval comprehended by 75ms and 100ms). The values obtained during these simulations are shown in Table 3.

	HIC15	BrIC
Hyb. III without helmet	225.8	0.552
Hyb. III with helmet	195.6	0.522
THUMS without helmet	215.1	0.949
THUMS with helmet	149.2	0.831

Table 3: HIC15 and BrIC values obtained from simulations

BrIC values

To be able to corroborate the data obtained from the acceleration data, we also obtained the angular velocities from the three principal directions from the human body models to obtain the BrIC value. According to the study carried out for the

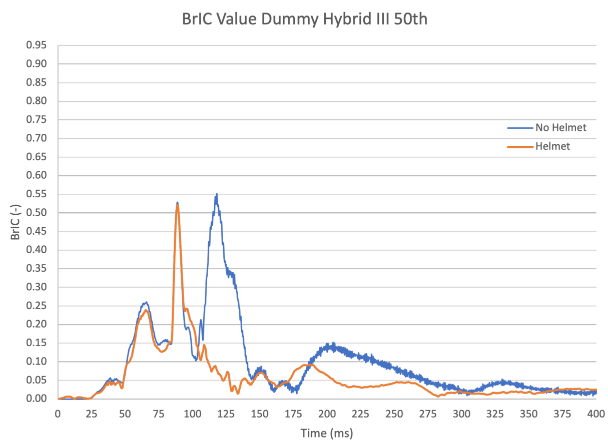


Figure 9: BrIC graph from Dummy Hybrid III simulations

Stapp Car Crash Journal (*Takhounts et al., 2013*), this value will enable to assess brain injury risk depending on the maximum angular velocities. The critical values of BrIC depends on the human body model used in each simulation. In case of the Dummy Hybrid III 50th the limit would be 1.03, meanwhile in the THUMS AM50 is 0.8 (based on the maximum principal strain critical (MPS) value). It can be appreciated the differences in the results obtained in

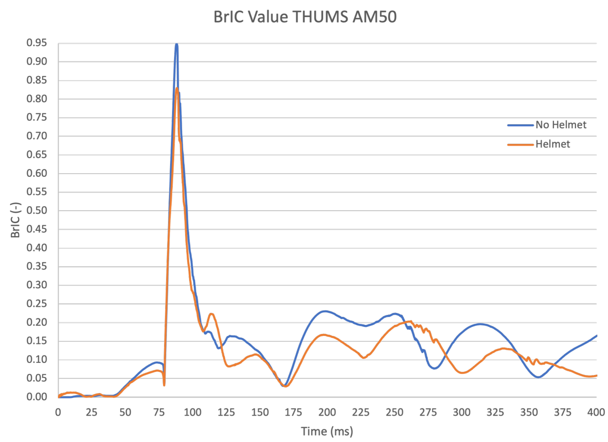


Figure 10: BrIC graph from THUMS simulations

both human body models. With the Dummy Hybrid III (Figure 9), the BrIC peak value is obtained in different instants depending, whether it is using the helmet or not. Ether way, both peak values (Table 3 are below the critical values for the Dummy Hybrid III 50th by almost half its value.

By contrast, in the case of the THUMS simulations (Figure 10), both peak values (Table 3) occurs in the same instant. While using the THUMS model, the peak values are higher than the critical values for humans. This equivalent to a 50% of suffering a brain-AIS3+. With the use of a helmet, the THUMS madel was able to reduce its peak value a 12.4%.

Validation of simulation

No studies with real experimentation have been found to be able to validate the data. According to one study (*Ptak et al., 2022*), the acceleration values and graph shape obtained is similar to the one obtained by this study. The difference in values obtained is a result of the fact that they performed the impact on the B-pillar of the vehicle, which is one of the most rigid areas of the vehicle in terms of safety and the vehicle model is different t the one we used, affecting the kinematics.

Discussion

After the completion of this study, we can proof that there are evidences enough to verify that there are differences between using a Dummy Hybrid III 50th and THUMS AM50 model.

After using a commercial standing electric scooter in a multi-body dynamics program simulation, using two human body models with or without the use of a helmet to be able to assess the head and brain injuries also. The computational cost of all simulations are presented in Table 4.

Our results are able to show that depending the type of HBM used, the kinematics of the SES occu-

	Duration	CPU's
Hyb. III without helmet	14h 15min	16
Hyb. III with helmet	71h 8min	16
THUMS without helmet	113h 34min	32
THUMS with helmet	138h 24min	32

Table 4: Computational cost of simulations

pant will differ, being more dangerous in the THUMS case (this being more representative of the human body). Because of the model differences in heights (1682mm for Dummy Hybrid III and 1786mm for THUMS AM50) and the modelization of different parts of the human body model, we are able to observe theses differences. In both cases, the only methods of energy dissipation occur because of the plastic deformation that have withstand, damping from the suspension shock absorbers and coils and the foam from the helmet. The damping is very small from the suspension and the tyres friction with the floor because of the restrictions imposed to the longitudinal members of the vehicle, the movement is more limited than it would be in a real situation, therefore, increasing the acceleration and angular velocity values obtained. Also, the scooter model, because the model is based on and being declared as a rigid material, it would not absorb also part of the energy from the collision. In the case of folding standing electric scooters, it is possible that the hinge between the base and the steering column could act as a fuse to dissipate some energy.

All the HIC15 values are below the critical value, indicating that there is a very low risk of having a head injury. But this results may not be a correct indication of the facial injuries it may be subject to. In all simulations, the face is the part of the head that suffers the main impact. Because of the kinematics produced, the scooter handlebar acts as a pivot point, possibly being responsible of a higher head acceleration peak. While using a helmet, only the Dummy Hybrid III benefited from suffering the same facial impact as without it because of the model dimensions. Meanwhile the THUMS model face impacts the upper part of the side door in both cases, even though it has obtained a lower HIC15. This might be produce by the helmet materials that are in contact during the simulation, obtaining an acceleration signal with less disturbances and therefore, a lower HIC15 value. There is a study determine the importance of craniofacial injuries that are being produced from accidents with standing electric scooters involvement (*Bhavin et al., 2019*). The results obtained from were facial injuries from all spectrums, demonstrating the correlation between facial injuries and the use of standing electric scooters.

And for the BrIC values, because of the kinematic differences between both models, the values are considerably different. The Dummy Hybrid III simulations had a significant outcome differences in their graph shape. This can be produce because of the introduction of the helmet, being the one element that it is capable of absorbing part of the heads kinetic energy during the impact, generating a more controlled angular velocity at the beginning of the rebound stage giving a peak BrIC value at the instant the handlebar acts like a pivoting point for the upper body before the impact occurs. Meanwhile the BrIC peak value in the simulation without using the helmet occurs moments after the impact during the rebound stage. With the THUMS model simulations, the values are obtained in the same instant, with or without using the helmet. This occurs due that in both impacts, the helmet does not protect the standing electric scooter face, producing almost a same response.

As has been shown in this study, the most affected area from the impact is the facial area. Because of the helmet model that has been used, only the Dummy Hybrid III was benefited from using it because of the models dimensions but still suffered the impact on its face. This is quite alarming because most regulations that oblige the standing electric scooter occupant to wear a helmet during use on the street, do not specify what type of helmet should be used. A study has shown that using helmets can significantly reduce risk of serious facial injury to the upper and middle face regions but not for the entire face (*Thompson et al., 2000*). As it has been demonstrated in this study, the lower part of the face is the most vulnerable zone during the impact, as the study from Dallas has already indicated (*Bhavin et al., 2019*). After this study, we recommend the use of full-face helmets for reducing full facial injuries.

After seen the results that have been obtained, and taking into account the computational cost of all simulations (Table 4), we have reached the following conclusions:

- There is a significant difference between the kinematics of both human body models. In the Dummy Hybrid III model, impact and rebound occurred in an upright position, whereas with the THUMS model, impact occurred in an upright position while in the rebound stage, the coronal plane rotated on an axis parallel to the longitudinal axis of the vehicle. Since no reference to studies with real tests has been found, it is very difficult to verify the data obtained.
- Data obtained from accelerations give an indication that, in collisions with a static vehicle in the side door area, it represents a low risk related to head injuries. The results are very similar between the two human body models, and the use of the helmet in the simulations has been able to reduce these values and therefore increase occu-

pant safety.

- The data obtained related to angular velocities are different depending on the human body model used. In the Dummy Hybrid III, the risk of brain injury is around 15% AIS3+, while in the THUMS model, this value increases to 50% AIS3+. The use of helmets has also been able to reduce these values, although to a lesser extent than accelerations, as these are not usually designed for this type of parameter.
- Helmet use has been able to increase occupant safety while using a standing electric scooter. However, due to the type of helmet used in the simulations, the lower facial area is still very unprotected in this type of collision. This is why the use of full-face helmets is recommended, despite the discomfort it represents for the user.

We hope that with the findings obtained from this study, together with future real experimentation, new means can be obtained to assess correctly head and brain injuries, in this and other types of situations, eventually using the human body model that most closely resembles reality. All this, together with an awareness campaign of the use of full-face helmets in standing electric scooters in order to reduce the risks of head and brain injury.

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