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TITLE:

Analysis of trunk impact conditions in motorcycle road accidents based on epidemiological, accidentological data and multibody simulations

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ABSTRACT:

Motorcycle accidents lead to a high rate of traffic mortality and morbidity. While helmet development and mandatory wearing have reduced head injuries, little progress has been made regarding trunk protection. Wearable airbag devices represent a promising solution to prevent trunk injuries. Nevertheless, research investigations need to be performed to assess and optimise the efficiency of such devices. This work consisted in the analysis of motorcyclist trunk impact conditions involved in various crash configurations to provide critical information in order to evaluate and improve the performances of airbag devices. First, an epidemiological and an accidentological analysis of data collection related to 252 real accidents, focusing on victims admitted into the shock rooms of two French trauma centres were performed. The data obtained was combined with numerical multibody parametric investigations, allowing the reproduction of 240 accident situations. An original and representative analysis of motorcyclists' impact conditions was provided, weighting the numerical study output data according to the real accident database. The impacted regions of the human body, the impact velocity and the accident chronology obtained in this work made it possible to define critical information for airbag efficiency assessment: the zones and levels of protection, the impacted surfaces as well as the airbag intervention time and the duration of maintained inflation of the airbag.

KEYWORDS:

Motorcyclists, accident analysis, epidemiology, multibody simulations, airbag, safety.

1-INTRODUCTION:

Accidents involving powered two-wheelers (PTW) represent 18% of fatalities within the European Union (Erso, 2017). In France, PTW users accounted for 21% of traffic fatalities and 30% of those injured and hospitalised, for a traffic share of just 1.9% (ONISR, 2017). Recent research carried out in France has shown that mortality and morbidity risks per kilometre were 20-30 times greater for PTW users than for car occupants (Blaizot et al., 2013; Bouaoun et al., 2015).

All body regions suffer injuries in motorcycle accidents. Head injuries, first, have been reduced in recent decades through the development and usage of helmet technology. Both thoracic and abdominal segments face risks of haemorrhagic and neurological injury, which have been clearly identified in epidemiological studies (Kraus et al., 2002; Robertson et al., 2002). Hence, the question of trunk safety is becoming a priority in PTW protection devices, as the number of injuries and their severity remain a major concern.

Over the last decade, airbag safety devices fitted in motorcyclists' garments have provided a promising solution, with a same device preventing thoracic, abdominal and spinal injuries. Various technologies have been reported depending on the triggering system: airbag devices with mechanical triggering systems are activated by the severance of a physical connection (a cable) between the motorcycle and the device (Helite, 2018). The other possibility is to trigger the device via electronic instruments, such as accelerometers and gyroscopes, that can be installed on the motorcycle (Bering, 2018) or on the garment (In&motion, 2018).

The evaluation and improvement of the performances of safety devices require knowledge of motorcyclists' crash conditions, such as injured body regions, injury mechanisms, accident scenarios, accident chronology, impact velocities, impacted surfaces, etc. While airbag devices were designed to prevent thoracic, abdominal and spinal injuries, few studies have analysed the impact conditions on these body regions to further promote dedicated injury criteria and standards for their evaluation. Previous work (Serre et al., 2012) has provided dedicated recommendations for intervention time (detection + activation + inflation), pressure monitoring and human body responses with regards to specific PTW-car impact situations using experimental and numerical approaches. Such data needs to be strengthened by broadening the impact conditions in order to be representative of the variability of accident situations.

The main objective of this work was to combine epidemiological, accidentological and biomechanical investigations through simulation tools to examine representative motorcyclists' trunk impact conditions in order to support airbag technology assessment and development. The work was divided into two main parts:

- The first part dealt with a dedicated epidemiological and accidentological analysis to determine the most frequent trunk injuries and to define the most relevant accident scenarios.
- In the second part, several configurations of PTW crashes into a passenger car were simulated through a multibody approach and the initial impact conditions of the trunk (impact location, impact obstacle, impact velocity and impact time) were examined to provide critical information for evaluating and improving the performance of airbag devices.

2-MATERIALS AND METHODS:

2.1- Epidemiological and accidentological database:

From 2016 to 2017, a joint dedicated survey of PTW accidents was performed between the trauma centres of Lyon and Marseille. The data collection focused on the victims admitted into the shock rooms of the hospitals' emergency department. This survey consisted in gathering detailed information about motorcyclists' trauma management in emergency services. Data on the victim (gender, height, weight, age, etc.), injury assessment and a description of the accident situation (type of PTW, safety device used, type of collision, accident scenario, accident chronology, etc.) were collected either from the victim or from witnesses of the accident. Injury assessment was coded according to the Abbreviated Injury Scale, or AIS (AAAM, 2005).

In the present work, an epidemiological study was carried out with the purpose of analysing injury patterns with regards to frequency and severity, in PTW crashes. The aim of the accidentological study was to identify the most frequent accident scenarios and to link them with the injuries sustained by the motorcyclists. Six different accident configurations for impacts of the PTW with a passenger car were considered: motorcycle front crash into the side of another vehicle (head-on-side), other vehicle front crash into the side of the motorcycle (side-on-head), motorcycle oblique crash into the side of another vehicle (oblique-on-side), motorcycle front crash into the front of another vehicle (Head-on), motorcycle front crash into the rear of another vehicle (head-on-rear) and other vehicle front crash into the rear of the motorcycle (rear-end).

2.2- Numerical simulations:

Multibody modelling with Madymo software V7.5 was used with the purpose of providing extensive simulations of various trunk impact conditions in different accident situations. A parametric study including the type of PTW, the PTW impact speed, the accident scenario and rider morphology was performed. The definition of the accident scenarios and rider morphologies was based on the database. The range of PTW impact speeds was chosen according to those computed by (MAIDS, 2009; Piantini et al., 2016) from on-scene measurements of real accident. The studied body regions were chosen as a function of epidemiological data and the areas possibly covered by airbag devices. The number of impacts and the kinematics of the rider (impact velocity and chronology) were weighted according to the epidemiological and accidentological data in order to provide a representative description and evaluation of injury risks.

2.2.1- Description of models:

The simulations carried out in this work include three main multibody systems: the motorcyclist, the PTW and the vehicle (Figure 1).

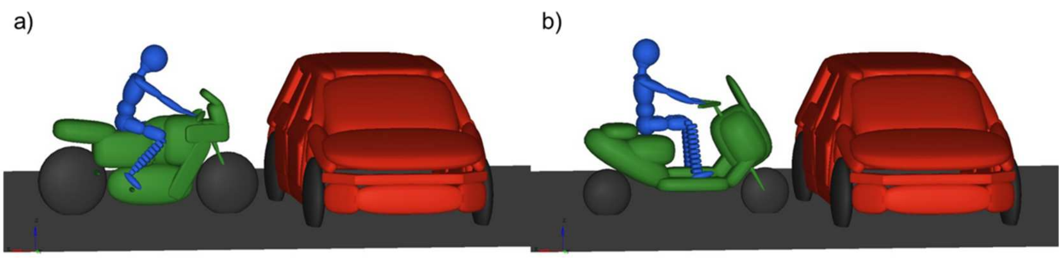

Figure 1. Multibody systems simulating PTW-car crashes. a) Sport bike. b) Scooter.

The motorcyclist model is a human model derived from original models developed and validated by Yang et al. (2000). Initially used in pedestrian and cyclist accident reconstructions (Serre et al., 2007), it was later used and validated to simulate motorcyclist impacts against a light vehicle (Serre et al., 2012; Serre and Llari, 2010). A friction coefficient between the motorcyclist and the ground of 0.7 (obtained from internal dedicated experiments) was used.

Three morphologies were defined based on the height of the 50th percentile and the weight of the 5th, 50th and 95th percentile adult subjects. They coincide with a body mass index (BMI) of 19 (1m76, 59 kg), 24 (1m76, 74 kg) and 32 (1m76, 99 kg), respectively. The 50th percentile male model (1m76, 77kg) was adapted in order to obtain the three morphologies.

The ellipsoids representing the neck, shoulders, thorax, abdomen and pelvis were meshed into 15 zones to enable the separate monitoring of body impact locations (Figure 2). The neck is composed of two zones, one anterior (neck frontal) and one posterior (neck rear). The two shoulders, right and left, make up a unique zone (shoulders). The thorax, abdomen and pelvis make up four zones each (frontal, lateral, rear and spine). In total, the trunk of the human model is composed of 4 anterior regions (neck frontal, thorax frontal, abdomen frontal, and pelvis frontal), 3 lateral regions (thorax lateral, abdomen lateral and pelvis lateral), 7 posterior regions (neck rear, thorax rear, thorax spine, abdomen rear, abdomen spine, pelvis rear and pelvis spine) and the shoulder zone.

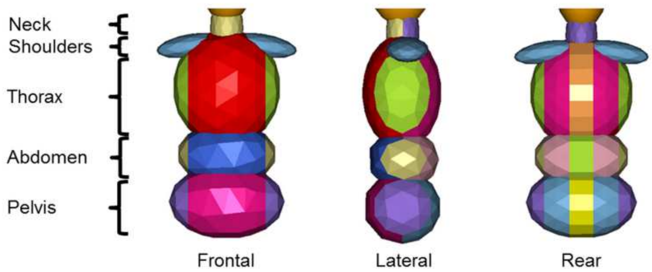

Figure 2. Division of the human model in 15 impact zones.

Two PTW models leading to two significantly different postures of the human body were used in this work. The sport bike model is a Kawasaki Ninja 750, composed of 22 ellipsoids grouped into 12 rigid bodies and connected by 11 joints. The scooter model is a Sym Joryde, 125 composed of 16 ellipsoids grouped into 6 rigid bodies and connected by 6 joints. The same approaches were employed as in the work of Serre and Llari (2010) to define the geometries, masses and inertias of the PTW, as well as to model their longitudinal deformation at the time of the impact against the vehicle. The validation of the models was carried out regarding the kinematics and accelerations obtained from experimental tests (Serre and Llari, 2010).

The vehicle model is representative of a passenger car (Renault Megane) and is derived from the car model used in previous work (Serre et al., 2012; Serre and Llari, 2010). In the present work, its geometry has been completed, leaving us with a more detailed model composed of 54 ellipsoids. For impact simulation, no initial speed was applied to the car. The possible car movement caused by the impact of the PTW was modelled by a revolute joint between the car and the ground. The stiffness of this joint was defined based on head-on-side crash test data. This joint allows car rotation around the axis perpendicular to the ground in PTW collisions against the side of the car.

2.2.2- Parametric study:

In order to provide an extensive analysis of trunk impact conditions and accident chronology, a parametric study was performed. It included type of PTW (sport bike and scooter), PTW impact speed (30, 40, 50, 60 and 70 km/h), impact configuration between the PTW and the car (2 head-on, 1 head-on-rear, 3 oblique-on-side and 2 head-on-side collisions (Figure 3)) and 3 rider morphologies (BMI 19, BMI 24 and BMI 32).

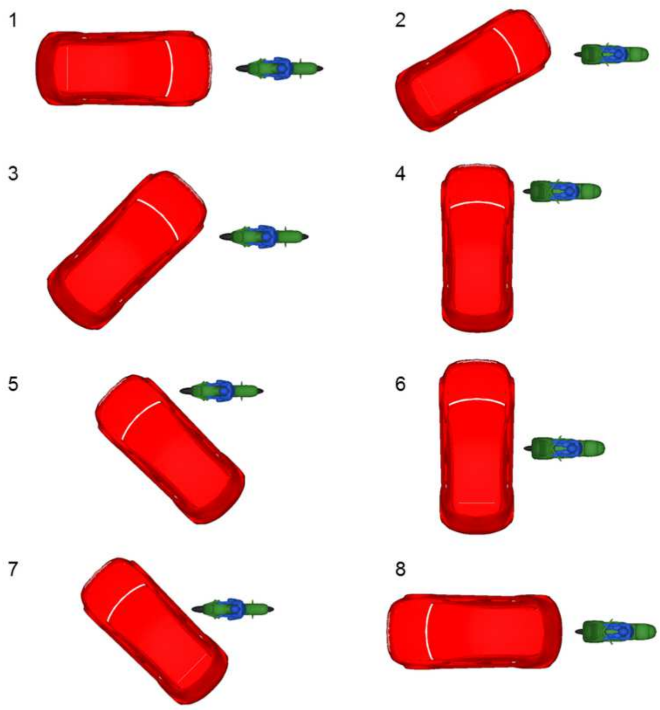

Figure 3. PTW-car collision points representing the simulated scenarios: Head-on (1), head-on 150° (2), oblique-on-side 135° at front wheel level (3), head-on-side at front wheel level (4), oblique-on-side 45° at front wheel level (5), head-on-side at B-pillar level (6), oblique-on-side 45° at B-pillar level (7) and head-on-rear (8).

2.2.3- Numerical data analysis process:

Based on the simulation output data, an analysis was carried out on the following parameters:

- Number of impacts: the number of impacts sustained by the 15 human body zones against the vehicle and the ground were examined. Considering impacts with the car, the number of trunk impacts against the 11 parts of the vehicle was also analysed. The number of impacts was assumed as a potential indicator of injury risk for the motorcyclist.
- Impact velocity: the normal and tangential velocities of the body region just before impact were measured. The normal and tangential velocities are relative to the impacted surface and were computed from the output velocities of each body of the human model. A hypothesis was made considering the impact velocity as a factor representing the severity of the motorcyclist's impact.

- Accident chronology: the period of time between the PTW's first impact against the car and the rider trunk's first impact against the car and the ground were studied.

The results were weighted according to the number of simulations and the number of cases of PTW-car accidents included in the database to highlight the representativeness of the launched simulations (Equation 1).

$$Weight\ Coefficient\ (a,i) = \frac{Nd\ (a,i)}{Ns\ (a,i)} * SF \qquad (1)$$

Where:

- a: accident configuration code (head-on, head-on-rear, oblique-on-side and head-on-side)
- i: injured body region code (neck, thorax, abdomen, spine, shoulders and pelvis)
- Nd: number of accidents in the database per accident configuration and injured body region (Table 2)
- Ns: number of simulations per accident configuration
- SF: scale factor (set to 100) to improve coefficient readability

3-RESULTS:

3.1- Epidemiological and accidentological study:

The epidemiological analysis concerns 252 injured victims. Among them, 203 were seriously injured, i.e. sustaining at least one injury with a severity score greater than or equal to 3 (AIS3+). Table 1 describes the injured body region according to the severity of the injury. Since each victim could have more than one body region affected and could sustain more than one injury to a specific injured body region, the sum of injured victims is superior to 100%. The thorax was the body region most frequently (56.7%) and seriously (54.2%) injured, followed by the lower limbs and the head. Abdominal injuries affected 31.7% of motorcyclists and 17.7% of seriously injured victims. Abdomen and pelvis were comparable in terms of serious injuries, while the latter was less subject to minor injuries. Among the riders having sustained a spinal injury, thoracic (20.2%) and lumbar (15.5%) were the most commonly affected regions, while serious spinal injuries were mainly located in the cervical region (3.4%). Clavicle and scapula injuries were sustained by 20.2% of the riders. The neck was less frequently injured, with 4.4% of the victims and 3.9% of the riders sustaining a serious injury. The thorax, abdomen, thoracic and lumbar spine and shoulder injuries that could potentially be mitigated or avoided thanks to airbag devices represent 75% and 64% of AIS1+ and AIS3+ injured victims, respectively.

Table 1. Body region injured and AIS score group among the 252 injured PTW users.

	AIS 1+ (n=252)		AIS 3+ (n=203)	
	No. of riders	%	No. of riders	%
Head	**76**	**30,2**	**53**	**26,1**
Face	**59**	**23,4**	**10**	**4,9**
Neck	**11**	**4,4**	**8**	**3,9**
Thorax	**143**	**56,7**	**110**	**54,2**
Abdomen	**80**	**31,7**	**36**	**17,7**
Spine	**91**	**36,1**	**15**	**7,4**
Cervical	33	13,1	7	3,4
Thoracic	51	20,2	3	1,5
Lumbar	39	15,5	5	2,5
Upper extremity	**92**	**36,5**	**7**	**3,4**
Shoulders	51	20,2	0	0,0
Extremity	51	20,2	7	3,4
Lower extremity	**132**	**52,4**	**86**	**42,4**
Pelvis	55	21,8	35	17,2
Extremity	107	42,5	60	29,6
External	**11**	**4,4**	**1**	**0,5**

The accidentological analysis was based on the PTW collision obstacle and on accident configuration. Regarding the 252 AIS1+ injured victims, the most frequent collision obstacles were passenger cars (50%), the ground (25.4%), road fixed objects (8.7%) and heavy trucks (6.4%). Table 2 shows the percentage of injured victims for each trunk region in relation to PTW-car crash scenarios. Regarding all injured victims, head-on-side (41.2%) was the most frequent accident configuration, followed by head-on (20.6%) and side-on-head (18.6%) collisions. Head-on-side was the most frequent accident configuration for the thorax (37.5%), the spine (30.3%), the shoulders (38.9%) and the pelvis (34.6%), while the abdomen was most frequently injured in head-on collisions (25.8%). The distribution of thorax and shoulder injuries was approximately the same as the collision type's share of total accidents. The number of abdominal, spinal and pelvic injuries for riders involved in head-on-side, side-on-head and head-on collisions was similar. With the exception of the neck, the spine (27.3%) and pelvis (30.8%) where affected in the highest proportions of injured victims in head-on and side-on-head configurations, respectively.

Table 2. Injured body region according to the PTW-car collision type reported in the real accident database.

	Total (n=102)	Neck (n=4)	Thorax (n=56)	Abdomen (n=31)	Spine (n=33)	Shoulders (n=18)	Pelvis (n=26)
	%	%	%	%	%	%	%
Head-on-side	41.2	0	37.5	22.6	30.3	38.9	34.6
Side-on-head	18.6	50	21.4	22.6	24.2	16.7	30.8
Oblique-on-side	8.8	0	10.7	16.1	12.1	5.6	11.5
Head-on	20.6	50	17.9	25.8	27.3	22.2	19.2
Head-on-rear	7.8	0	7.1	9.7	6.1	11.1	3.8
Rear-end	2.9	0	5.4	3.2	0	5.6	0

3.2- Numerical study:

A total of 240 simulations were run: 60 head-on, 30 head-on-rear, 90 oblique-on-side and 60 head-on-side scenarios. The number of impacts sustained by each body region according to the impacted surface (the car or the ground) is reported in Figure 4. More impacts are observed against the car than against the ground.

Regarding impacts against the car, the lateral (12.7%) and frontal (12.2%) thoracic regions are the most strongly affected areas. The frontal and lateral abdominal zones are concerned in 12.5% of the collisions, while the pelvis lateral area is involved in 4.7% of the impacts. The thorax rear (8.1%), thorax spine (4.1%) and pelvis lateral (3.8%) regions of the human model are the most strongly impacted zones against the ground.

The corresponding most strongly impacted parts of the car were the bonnet (18.6%), the windscreen (18.1%), the A-pillar (12.6%), the roof pillar (11.6%) and the windows (10.3%). The rear windscreen and the boot were rarely impacted (Figure 5).

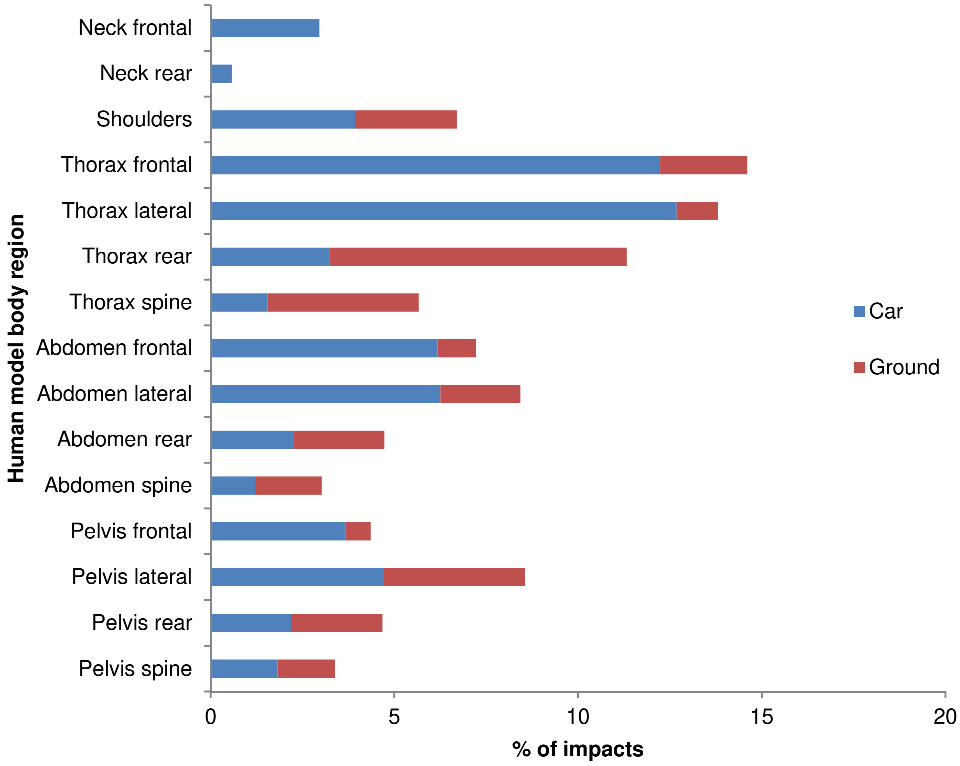

Figure 4. Percentage of impacts against the car and against the ground.

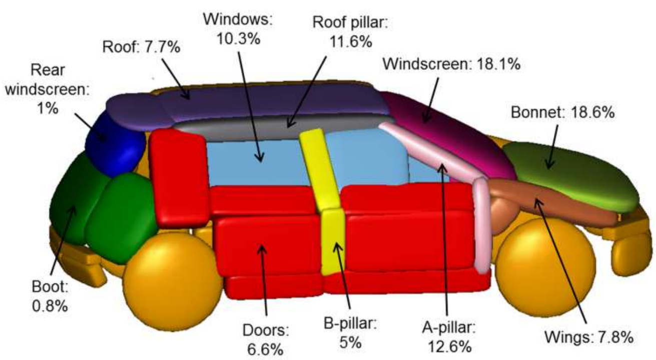

Figure 5. Percentage of trunk impacts against the 11 parts of the vehicle.

Body impact velocity distributions for impacts against the car and the ground are reported in Figure 6 and Figure 7. The impact velocities against the car are higher than the velocities computed for collisions with the ground. The tangential component of the impact velocities is higher than the normal one for both impacted obstacles. Impact velocity distributions are not symmetric and generally skewed right, i.e. there is a wider range in the velocity values above the median impact velocities. Considering the normal components of the velocities for direct human impacts, the highest impact velocities with the car were obtained on the frontal area of the neck, while the lowest velocities were observed on the spine zones of the thorax, the abdomen and the pelvis. The impact velocity gradually decreases between the upper body and the lower body. In the trunk region specifically, the impact velocity decreases between the frontal areas and the spine. Regarding the zones with the highest number of impacts, 75% of the frontal thoracic and abdominal impacts occur below 6.9 m/s and 4.9 m/s, respectively. The lateral thoracic region impacts the car below 5 m/s in 75% of cases, while 75% of abdominal lateral impacts occur below 4.7 m/s. The pelvic lateral area hits the car below 3.6 m/s in 75% of cases. The median impact velocity for these regions is around 1 m/s.

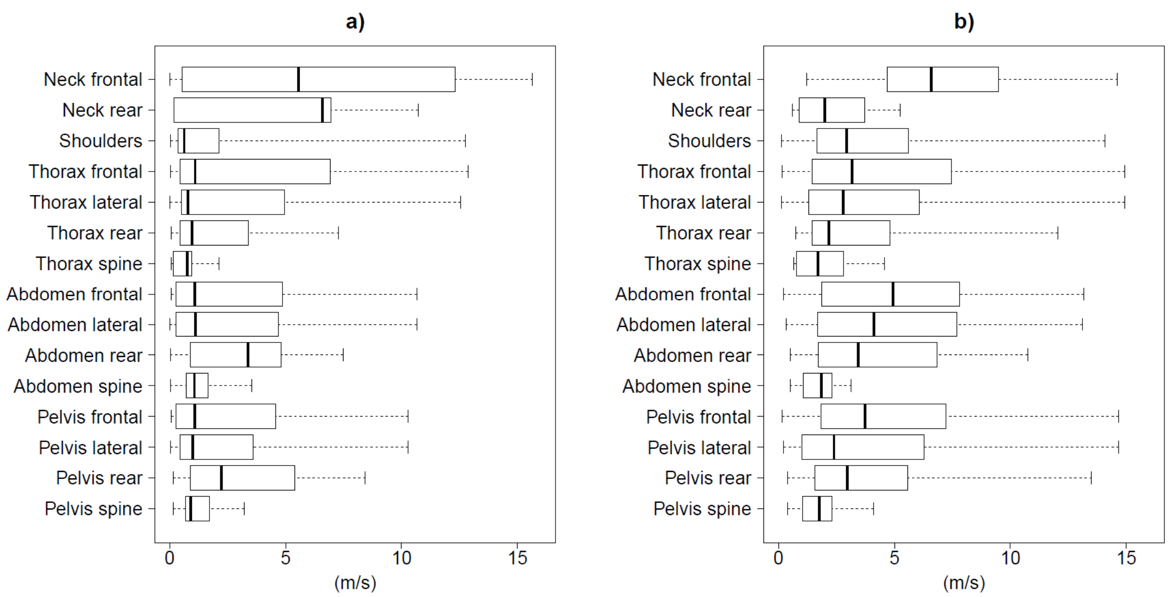

Figure 6. Impact velocity distribution for each trunk region with the car. a) Normal component. b) Tangential component.

Regarding collisions against the ground, the highest normal impact velocities were observed on the shoulders and pelvic areas. Contrary to the car, the speed tends to decrease progressing up the trunk. In relation to the most affected zones, thorax rear and thorax spine collisions occur at a maximum velocity of 3.7 m/s and 3.4 m/s, respectively. Pelvic lateral impacts occur at a maximum velocity of 8 m/s.

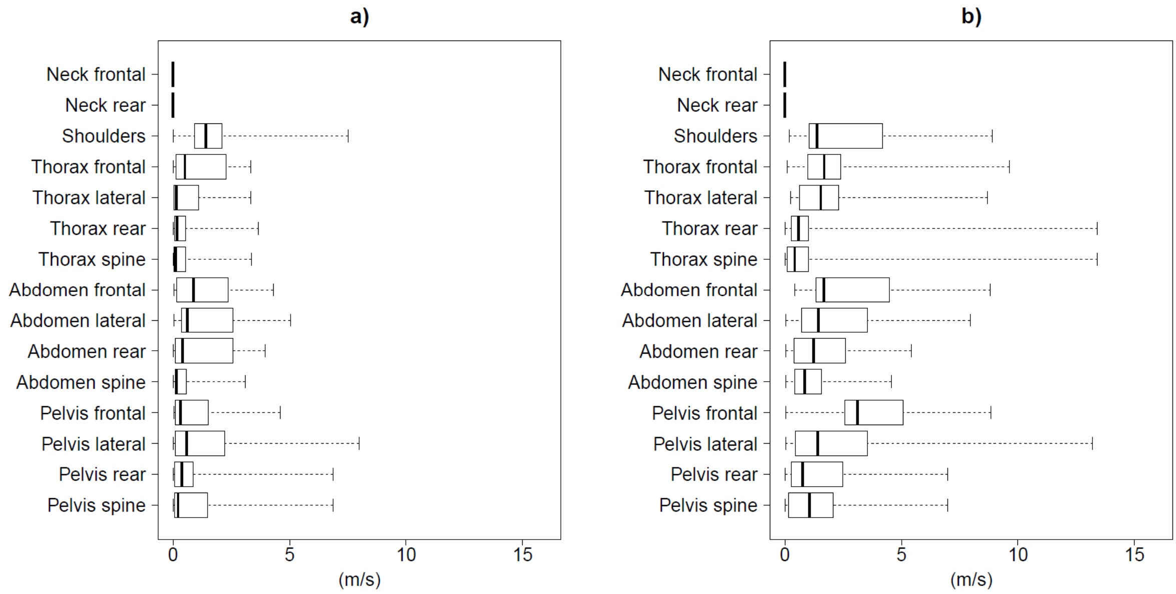

Figure 7. Impact velocity distribution for each trunk region with the ground. a) Normal component. b) Tangential component.

The influence of the accident scenario on the number of impacts and on the normal impact velocity was studied for impacts of the human body against the car. Frontal, lateral thoracic and abdominal impact velocity distributions are shown in Figure 8. The thorax is more frequently impacted in oblique-on-side (38.3%) and head-on (33.9%) collisions, with the highest impact velocities in head-on-side scenarios. Head-on-side configurations make up 24.5% of collisions, with 25% above 10 m/s as shown in Figure 8a. Abdominal impacts are more frequent in head-on (45.2%) and head-on-side (39%) scenarios. Oblique-on-side configuration is less frequent (13.1%) but occurs at the highest median impact velocities (5.3 m/s) as illustrated in Figure 8b.

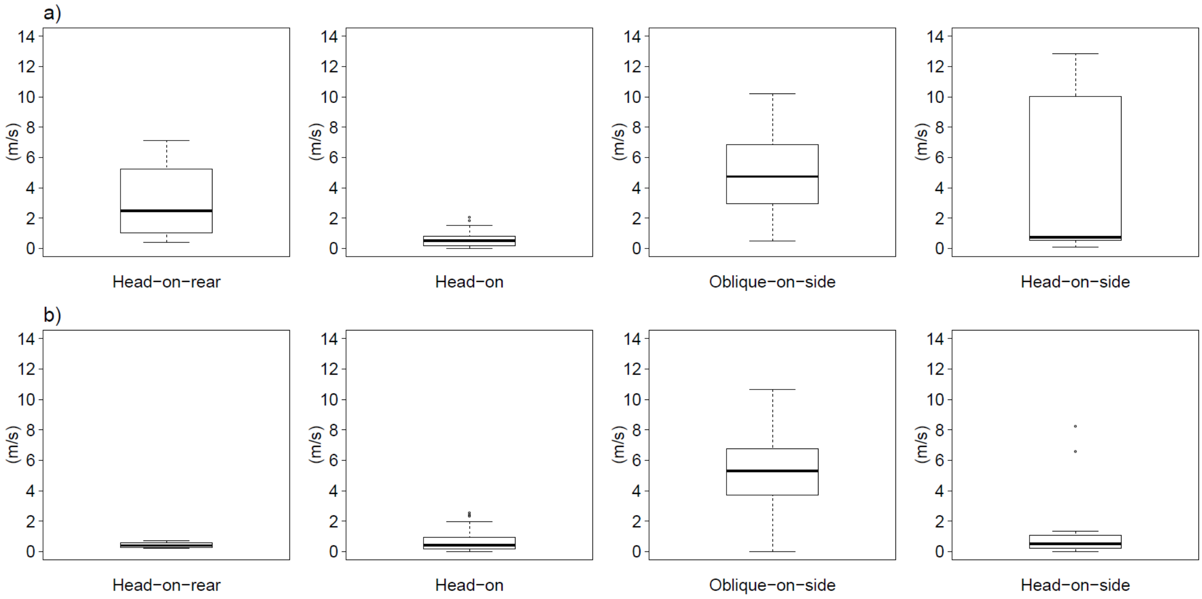

Figure 8. Normal impact velocity distribution according to the accident scenario. a) Frontal and lateral thoracic regions. b) Frontal and lateral abdominal regions.

In addition, differences regarding riders' kinematics were observed depending on the type of PTW and the accident scenario.

Pure frontal collisions (90°) involve a strong deceleration of the PTW and its rotation on a horizontal axis. The rider is decelerated by the PTW front part and is ejected upwards and continues to advance towards the car with their head forwards. The scooter rider is decelerated firstly by the impact of their lower limbs against the front glove compartment and secondly by the impact of their thorax against the handlebars and their pelvis and abdomen against the front glove compartment. For the sport bike rider, deceleration occurs during contact between the pelvis and the tank. The ejection of the rider towards the car with their head forwards supposes more violent impacts of the head and upper trunk regions with the car (Figure 6a). Consequently, there are very different distributions of thoracic and abdominal impact velocities in head-on-side and head-on-rear collisions (Figure 8). In head-on-side collisions, the median is around 0.6 m/s in both cases, but there is substantially more variation in the case of thoracic impacts, ranging from 0.1 to 12.9 m/s. In head-on-rear collisions, the median velocity is higher for thoracic impacts (2.5 m/s) than for abdominal impacts (0.4 m/s) and there is more variation in the case of thoracic impacts, ranging from 0.4 to 7.1 m/s.

In oblique collisions (45°), the rider is not decelerated by any forceful contact against the PTW. This scenario implies a PTW rotation on a vertical axis and a straight trajectory of the rider towards the car. Due to the straight trajectory of the rider, thoracic and abdominal impact velocity distribution is comparable in oblique-on-side collisions (Figure 8). In both cases, the median is around 5 m/s and the distribution ranges approximately from 0.3 to 10.5 m/s.

The analysis of the accident chronology showed that impacts against the car occurred between 67 milliseconds (ms) and 1.5 seconds (s), with 75% of collisions taking place after 110 ms. The lowest impact time (67 ms) was found for an impact between the pelvis and the B-pillar. In this case, the abdomen and the thorax hit the car 74 ms and 77 ms after the PTW-car contact, respectively. Impact time against the ground ranged from 346 ms to 3 s, with 75% of impacts occurring after 1 s (Figure 9a). Concerning impacts against the car, the fastest impacts were found for oblique-on-side collisions, with 50% of impacts under 85 ms. In head-on-rear and head-on-side configurations, 75% of impacts occurred after around 100 ms. Head-on collisions occurred after 154 ms (Figure 9b).

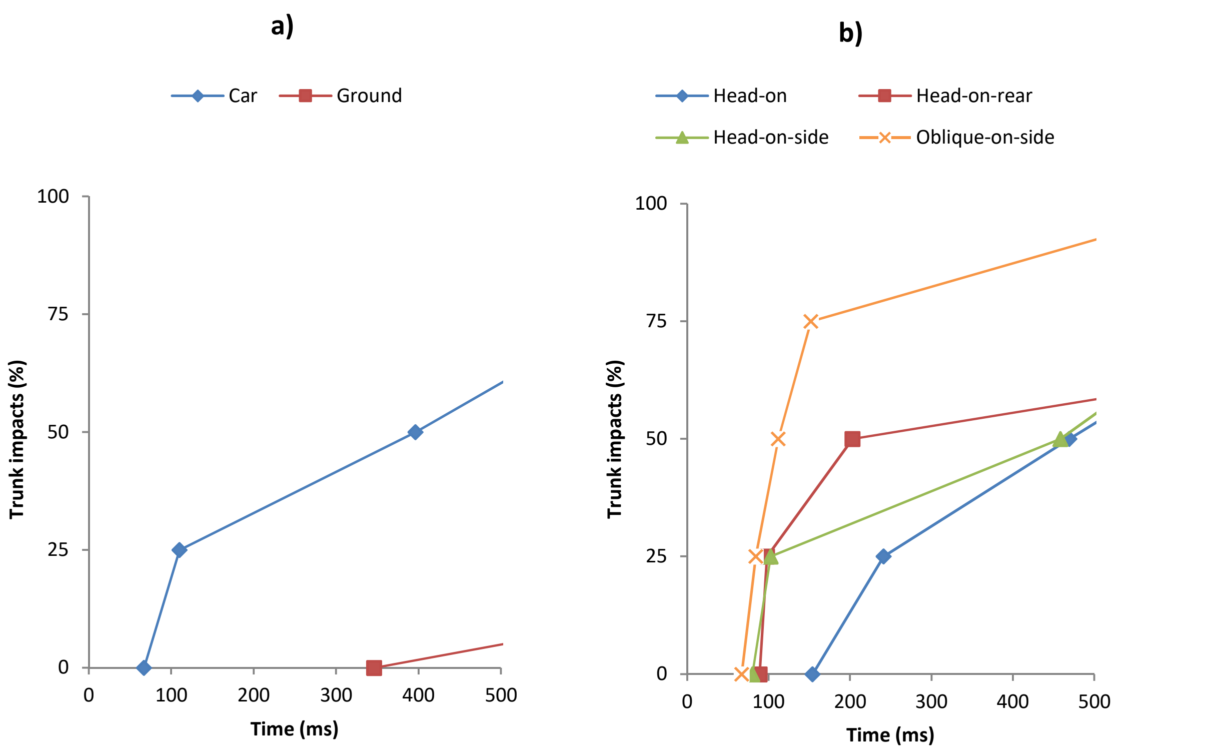

Figure 9. Trunk impact time cumulative percentage. a) Impacts with the car and the ground. b) Impacts with the car according to the accident scenario.

4-DISCUSSION:

Based on real accident and clinical data, numerical investigations were performed to provide an analysis of trunk injury conditions in the context of motorcyclists' accidents.

In the first stage of this work, a dedicated survey including a questionnaire (for patients and medical staff) was put together at the hospital, combining accident data (to identify PTW impact conditions) and clinical information (to assess injury severity with AIS classification).

Focusing on seriously injured victims (AIS3+), the thorax was the most frequently injured body region and the abdomen also sustained an important number of injuries. These results were in agreement with the work of Moskal et al. (2007), which focused on severely injured victims (AIS4+), and the MAIDS project (MAIDS, 2009). The multiple injuries reported at the trunk level have important implications as far as supporting the implementation of safety devices is concerned. Based on their frequency, severity and locations, airbag technology, by offering extended protective areas, appears as a promising alternative to prevent PTW trunk injuries.

The accidentological analysis performed through this survey enabled us to identify PTW collisions with passenger cars as the most frequently recorded collision type. These results are relevant with previous findings (Liers, 2013; MAIDS, 2009; Moskal et al., 2007). Head-on-side collisions between PTWs and cars were the leading crash configuration registered in the dataset used in this work. Depending on the samples, head-on-side (Piantini et al., 2016), head-on (Moskal et al., 2007; Zulkipli et al., 2012) and oblique-on-side (COST 327, 2001; ISO 13232, 2005) collisions were identified as the most frequent accident scenarios.

Regarding the distribution of injured body regions in relation to accident configuration, it was not possible to determine a unique accident situation causing the majority of the injuries. Two basic accident configurations (head-on-side/oblique-on-side and head-on) must be considered to support the design and evaluation of safety devices. Regarding collisions with the car, it was difficult to identify variations of impact angle due to the way in which the survey was completed, which was a limitation of this work. In-depth accident analysis, as it was performed in the works of Fredriksson and Sui (2016) and Piantini et al. (2016), would have been useful to support the evaluation of impact speed, orientation and impacted point on the car. Nevertheless, by simulating multiple PTW-car impact conditions, the numerical investigations allowed to evaluate their sensitivity with regards to potential injury severity.

In the second part of this work, virtual human simulations allowed a representative original parametric study of several motorcyclists' accident situations. The evaluation of injury and severity risks for the motorcyclist was based on the number of impacts and the impact velocities, which were weighted according to the real accident data. The aim of weighting the results of the simulations is to bring them more in line with what happens in real accidents. As an example, 90 oblique-on-side scenario simulations were run (37.5% of the 240 simulations), while in the real accident dataset only 8.8% of the victims were injured in this scenario (Table 2). The use of weight coefficients allows adjusting the results of the numerical study (body impact location, velocity and time distributions) to correct this kind of discrepancies. However, the sample size and the unavailable data in some cases was a limitation of this work. A larger sample size would be useful to improve the quality of the weighting method.

Simulations showed that impacts of the trunk against the car are more frequent and more severe than impacts against the ground. This result is consistent with the most frequent injury sources noticed by Fredriksson and Sui (2016) and Piantini et al. (2016) and should be considered as a major step forward for the design of safety devices. It makes sense to support trunk protection devices that are able to prevent injury from the first impact against the car to the collision with the ground. At the level of PTW airbag design, it has strong implications for defining the time at which to launch airbag inflation and the time during which to maintain the pressure in the airbag to be able to cover these two stages of accident situations. The results of the present work complete previous findings performed by Serre et al. (2012), confirming the required 70 ms intervention time for airbag devices to prevent trunk injuries in the large majority of accident scenarios studied in this work. In the same way, the airbag inflation maintenance time of 3 s remains relevant with the 4 s duration time recommended by Serre et al. (2012). The 1 s disparity of is due to the use of two different approaches to define the proposed durations: the maximum duration of the collision, i.e. until the rider is immobilised on the ground, was considered in previous works (Serre et al., 2012; Serre and Llari, 2010), while the present work was focused on the first impact against the ground.

Frontal, lateral thoracic and abdominal regions were the most frequently impacted regions of the human body against the car. Similar impact locations on the thorax were observed in the MOSAFIM project (MOSAFIM, 2013), where direct frontal/lateral impacts on the ribs and direct frontal impacts on the sternum were identified as the main injury mechanisms. The highest injury severity risk was observed on the frontal and lateral trunk regions, due to the highest impact velocities computed with weighted accident simulations. They suggest that safety devices should cover both the frontal and the lateral areas of the thorax and the abdomen.

To assess and improve trunk safety devices in frontal and lateral impact conditions, according to the computed normal impact velocities, two levels of protection could be recommended: for the thoracic segment, a first impact level of 7 m/s on the frontal area and 5 m/s on the lateral area are proposed. The second impact level is 13 m/s for both the frontal and the lateral thoracic areas. For the abdominal segment, the two impact levels recommended on the frontal and lateral abdominal areas are 5 m/s and 11 m/s. The first impact level includes 75% of impacts, while the second level is defined to cover 100% of impacts. These impact levels represent the most severe impact conditions and cover, by far, 50% of the impacts on the thoracic and abdominal regions (normal median impact velocity below 1 m/s approximately). Further evaluations of safety devices through sub-segment testing should consider these ranks of velocities, which are strongly dependent on accident situations and subsequent human body kinematics. Nevertheless, additional investigations should be performed beforehand to check the feasibility of experimental tests as well as numerical simulations at the proposed high velocity impact conditions. The impact velocities should be in agreement with the rank of velocities where human body injury tolerances were quantified and numerical models were validated to ensure the reliability of the results.

Considering impact location on the vehicle, the trunk impacts both flat surfaces (such as the bonnet and the windscreen) and penetrant surfaces (such as the A-pillar and the roof pillar). For further evaluation of safety devices, test methods should consider flat and penetrant impact conditions.

The posterior thoracic areas (thorax rear and thorax spine) were the most frequently impacted anatomical regions with regards to collisions with the ground. Considering spinal injuries, indirect impacts (leading to spine unit compression, bending, etc.) are the most frequent injury mechanisms, followed by direct impacts (MOSAFIM, 2013). Therefore, covering the back of the motorcyclist with protection devices such as airbags or back protectors does not seem to provide protection from all the spinal injury mechanisms as pointed out in the work of Otte (1998).

The model strength was supported by previous works (Serre et al., 2012; Serre and Llari, 2010) and inspires confidence regarding its ability to investigate such accident situations. However, modelling choices as well as model definition lead to some limitations in this work, suggesting the need for further improvements.

Firstly, the simplified definition of the multibody models in terms of geometry and contact accuracy could modify the global kinematics as well as the local impact conditions of the human body analysed in this work. For example, a more detailed whole spine representation on the human model or a more precise geometry of the PTW parts playing an important role in the motorcyclists’ deceleration (tank of the sport bike or front glove compartment of the scooter) could provide more realistic results.

Secondly, the numerical study was carried out without considering the initial speed of the vehicle. Just one vehicle model was considered which was another limitation of this work. Additional simulations, including parametric studies, have to be performed to investigate the effects of car speed and shape on accident kinematics. In addition to the accidentological data, the simulated scenarios were selected according to the numerical model validation, i.e. for PTW frontal impacts. Side-on-head was identified as a relevant accident scenario in the database and could not be simulated.. This accident scenario would suppose more lateral impacts for the motorcyclist (Barbani et al., 2014; Chawla et al., 2005).

Thirdly, a hypothesis was made, defining the number of impacts and the impact velocity as factors of injury and severity risk. Despite the impossibility of knowing the cause of injury, these magnitudes allowed for the analysis of impact frequency and severity. The use of velocity as an indicator of impact severity is in line with the work of Neal-Sturgess et al. (2001), where relationships between AIS and velocity were quantified for restrained and unrestrained vehicle occupants. Forces, deflections and accelerations, which are used as injury criteria in the automobile field, were not analysed in the present work because of their dependence on model contact laws, and their relevance to PTW safety is not established.

Currently, the effectiveness of PTW airbag devices is unclear in terms of the protection levels offered and the accident scenarios covered. Many questions remain: which injuries and injury mechanisms should be prevented? Which accident situations should be considered? Which impact conditions should be mitigated? The set of impact conditions defined in this work could be used as input data for a more detailed FE study in order to simulate local impacts on trunk body segments to study injury mechanisms. For example, the benefits of airbag wearing in reducing skeletal thoracic injuries were quantified by Thollon et al. (2010). Some content related to protection zone, impactor shape, impact velocity, intervention time and duration time could be defined more accurately and could be useful for the development of evaluation tests and standards. In Europe, there is a standard that includes the requirements and test methods for mechanically activated inflatable protectors for motorcycle riders (EN 1621-4, 2013). In addition, the French organization SRA (Sécurité et Réparation

Automobiles, 2013) has developed a classification of airbag devices that includes mechanical and electronic activation systems. However, no standard is recognised throughout the European Union and the methodology used to evaluate the performances of airbag devices is unclear.

5-CONCLUSION:

A data collection of 252 PTW victims was used to analyse trunk injury typologies and to identify the most frequent accident scenarios. A parametric study involving multibody models was carried out in order to reproduce 240 accident situations and to analyse motorcyclists' impact conditions and the related accident chronology. The originality of this work resided in the application of weight coefficients to match the simulations with reality.

The epidemiological analysis showed that the most vulnerable anatomical regions of the trunk (in this work neck, shoulders, thorax, abdomen, spine and pelvis) are the thorax and the abdomen. Accidents involving a passenger car, in particular on the side (head-on-side and oblique-on-side) and the front (head-on) of the vehicle were identified as the main crash configurations resulting from the accidentological study.

Multibody simulations demonstrated that the impacts presenting the highest risk of injury for the motorcyclist are impacts against the car. The body regions most exposed to these impacts, and therefore the suggested protection zones for airbag devices, are the frontal and lateral thoracic and abdominal regions. The conditions of the impacts sustained by the motorcyclist, in terms of impact velocities and impacted surfaces, were also determined and could be used to define the required protection levels. Two main types of surfaces (flat and penetrant) and three impact velocities on the thorax (5, 7 and 13 m/s) and two on the abdomen (5 and 11 m/s) are recommended to evaluate and improve protection devices in order to reduce thoracic and abdominal injuries. The analysis of accident chronology allows the formulating of recommendations regarding intervention time (70 ms) and maintained pressure duration (3 s) required for airbag devices. Hence, the knowledge obtained in this work allows the defining of critical information for the assessment and development of PTW safety devices and standards.

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