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1 TITLE:

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

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23 ABSTRACT:

24 Motorcycle accidents lead to a high rate of traffic mortality and morbidity. While helmet  
25 development and mandatory wearing have reduced head injuries, little progress has been made  
26 regarding trunk protection. Wearable airbag devices represent a promising solution to prevent trunk  
27 injuries. Nevertheless, research investigations need to be performed to assess and optimise the  
28 efficiency of such devices. This work consisted in the analysis of motorcyclist trunk impact conditions

29 involved in various crash configurations to provide critical information in order to evaluate and  
30 improve the performances of airbag devices. First, an epidemiological and an accidentological  
31 analysis of data collection related to 252 real accidents, focusing on victims admitted into the shock  
32 rooms of two French trauma centres were performed. The data obtained was combined with  
33 numerical multibody parametric investigations, allowing the reproduction of 240 accident situations.  
34 An original and representative analysis of motorcyclists' impact conditions was provided, weighting  
35 the numerical study output data according to the real accident database. The impacted regions of  
36 the human body, the impact velocity and the accident chronology obtained in this work made it  
37 possible to define critical information for airbag efficiency assessment: the zones and levels of  
38 protection, the impacted surfaces as well as the airbag intervention time and the duration of  
39 maintained inflation of the airbag.

40

41 KEYWORDS:

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

43

44 1-INTRODUCTION:

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

50 All body regions suffer injuries in motorcycle accidents. Head injuries, first, have been reduced in  
51 recent decades through the development and usage of helmet technology. Both thoracic and

52 abdominal segments face risks of haemorrhagic and neurological injury, which have been clearly  
53 identified in epidemiological studies (Kraus et al., 2002; Robertson et al., 2002). Hence, the question  
54 of trunk safety is becoming a priority in PTW protection devices, as the number of injuries and their  
55 severity remain a major concern.

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

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

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

77 • The first part dealt with a dedicated epidemiological and accidentological analysis to  
78 determine the most frequent trunk injuries and to define the most relevant accident  
79 scenarios.

80 • In the second part, several configurations of PTW crashes into a passenger car were  
81 simulated through a multibody approach and the initial impact conditions of the trunk  
82 (impact location, impact obstacle, impact velocity and impact time) were examined to  
83 provide critical information for evaluating and improving the performance of airbag devices.

84

85 2-MATERIALS AND METHODS:

#### 86 **2.1- Epidemiological and accidentological database:**

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

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

101 crash into the side of another vehicle (oblique-on-side), motorcycle front crash into the front of  
102 another vehicle (Head-on), motorcycle front crash into the rear of another vehicle (head-on-rear) and  
103 other vehicle front crash into the rear of the motorcycle (rear-end).

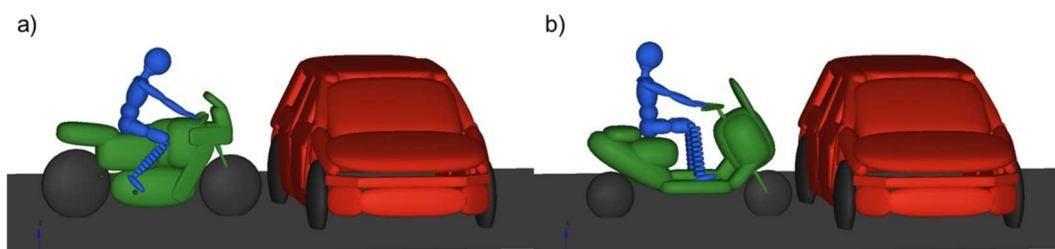
## 104 **2.2- Numerical simulations:**

105 Multibody modelling with Madymo software V7.5 was used with the purpose of providing extensive  
106 simulations of various trunk impact conditions in different accident situations. A parametric study  
107 including the type of PTW, the PTW impact speed, the accident scenario and rider morphology was  
108 performed. The definition of the accident scenarios and rider morphologies was based on the  
109 database. The range of PTW impact speeds was chosen according to those computed by (MAIDS,  
110 2009; Piantini et al., 2016) from on-scene measurements of real accident. The studied body regions  
111 were chosen as a function of epidemiological data and the areas possibly covered by airbag devices.  
112 The number of impacts and the kinematics of the rider (impact velocity and chronology) were  
113 weighted according to the epidemiological and accidentological data in order to provide a  
114 representative description and evaluation of injury risks.

### 115 2.2.1- Description of models:

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

118



119

120

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

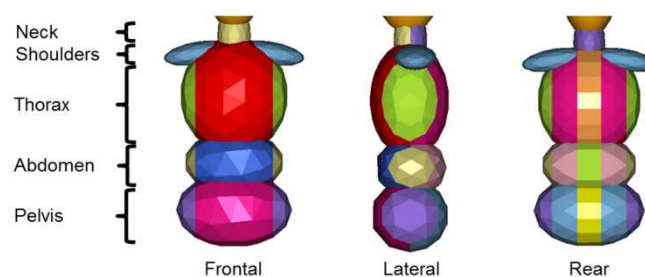
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122 The motorcyclist model is a human model derived from original models developed and validated by  
123 Yang et al. (2000). Initially used in pedestrian and cyclist accident reconstructions (Serre et al., 2007),  
124 it was later used and validated to simulate motorcyclist impacts against a light vehicle (Serre et al.,  
125 2012; Serre and Llari, 2010). A friction coefficient between the motorcyclist and the ground of 0.7  
126 (obtained from internal dedicated experiments) was used.

127 Three morphologies were defined based on the height of the 50<sup>th</sup> percentile and the weight of the  
128 5<sup>th</sup>, 50<sup>th</sup> and 95<sup>th</sup> percentile adult subjects. They coincide with a body mass index (BMI) of 19 (1m76,  
129 59 kg), 24 (1m76, 74 kg) and 32 (1m76, 99 kg), respectively. The 50<sup>th</sup> percentile male model (1m76,  
130 77kg) was adapted in order to obtain the three morphologies.

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

139



140  
141

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

142

143 Two PTW models leading to two significantly different postures of the human body were used in this  
144 work. The sport bike model is a Kawasaki Ninja 750, composed of 22 ellipsoids grouped into 12 rigid

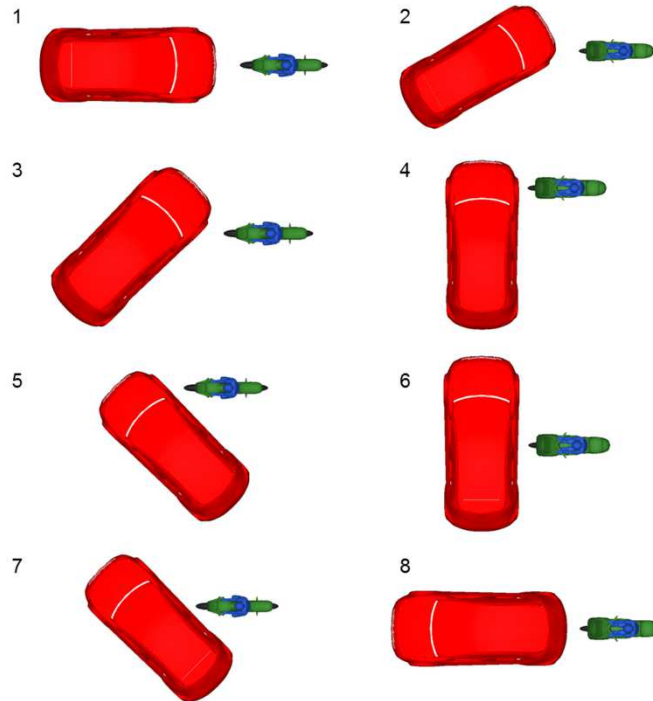
145 bodies and connected by 11 joints. The scooter model is a Sym Joryde, 125 composed of 16 ellipsoids  
146 grouped into 6 rigid bodies and connected by 6 joints. The same approaches were employed as in the  
147 work of Serre and Llari (2010) to define the geometries, masses and inertias of the PTW, as well as to  
148 model their longitudinal deformation at the time of the impact against the vehicle. The validation of  
149 the models was carried out regarding the kinematics and accelerations obtained from experimental  
150 tests (Serre and Llari, 2010).

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

#### 158 2.2.2- Parametric study:

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





164

165 **Figure 3. PTW-car collision points representing the simulated scenarios: Head-on (1), head-on 150° (2), oblique-on-side**  
 166 **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-**  
 167 **side at B-pillar level (6), oblique-on-side 45° at B-pillar level (7) and head-on-rear (8).**

168

169 2.2.3- Numerical data analysis process:

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

- 171
- 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.
- 172
- 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.
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180 • Accident chronology: the period of time between the PTW's first impact against the car and  
181 the rider trunk's first impact against the car and the ground were studied.

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

$$185 \quad \text{Weight Coefficient } (a, i) = \frac{Nd(a, i)}{Ns(a, i)} * SF \quad (1)$$

186 Where:

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

193

194 3-RESULTS:

### 195 3.1- Epidemiological and accidentological study:

196 The epidemiological analysis concerns 252 injured victims. Among them, 203 were seriously injured,  
197 i.e. sustaining at least one injury with a severity score greater than or equal to 3 (AIS3+). Table 1  
198 describes the injured body region according to the severity of the injury. Since each victim could have  
199 more than one body region affected and could sustain more than one injury to a specific injured  
200 body region, the sum of injured victims is superior to 100%. The thorax was the body region most  
201 frequently (56.7%) and seriously (54.2%) injured, followed by the lower limbs and the head.  
202 Abdominal injuries affected 31.7% of motorcyclists and 17.7% of seriously injured victims. Abdomen  
203 and pelvis were comparable in terms of serious injuries, while the latter was less subject to minor

204 injuries. Among the riders having sustained a spinal injury, thoracic (20.2%) and lumbar (15.5%) were  
 205 the most commonly affected regions, while serious spinal injuries were mainly located in the cervical  
 206 region (3.4%). Clavicle and scapula injuries were sustained by 20.2% of the riders. The neck was less  
 207 frequently injured, with 4.4% of the victims and 3.9% of the riders sustaining a serious injury. The  
 208 thorax, abdomen, thoracic and lumbar spine and shoulder injuries that could potentially be mitigated  
 209 or avoided thanks to airbag devices represent 75% and 64% of AIS1+ and AIS3+ injured victims,  
 210 respectively.

211 **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  | %           |
| <b>Head</b>            | <b>76</b>      | <b>30,2</b> | <b>53</b>      | <b>26,1</b> |
| <b>Face</b>            | <b>59</b>      | <b>23,4</b> | <b>10</b>      | <b>4,9</b>  |
| <b>Neck</b>            | <b>11</b>      | <b>4,4</b>  | <b>8</b>       | <b>3,9</b>  |
| <b>Thorax</b>          | <b>143</b>     | <b>56,7</b> | <b>110</b>     | <b>54,2</b> |
| <b>Abdomen</b>         | <b>80</b>      | <b>31,7</b> | <b>36</b>      | <b>17,7</b> |
| <b>Spine</b>           | <b>91</b>      | <b>36,1</b> | <b>15</b>      | <b>7,4</b>  |
| Cervical               | 33             | 13,1        | 7              | 3,4         |
| Thoracic               | 51             | 20,2        | 3              | 1,5         |
| Lumbar                 | 39             | 15,5        | 5              | 2,5         |
| <b>Upper extremity</b> | <b>92</b>      | <b>36,5</b> | <b>7</b>       | <b>3,4</b>  |
| Shoulders              | 51             | 20,2        | 0              | 0,0         |
| Extremity              | 51             | 20,2        | 7              | 3,4         |
| <b>Lower extremity</b> | <b>132</b>     | <b>52,4</b> | <b>86</b>      | <b>42,4</b> |
| Pelvis                 | 55             | 21,8        | 35             | 17,2        |
| Extremity              | 107            | 42,5        | 60             | 29,6        |
| <b>External</b>        | <b>11</b>      | <b>4,4</b>  | <b>1</b>       | <b>0,5</b>  |

212

213 The accidentological analysis was based on the PTW collision obstacle and on accident configuration.  
 214 Regarding the 252 AIS1+ injured victims, the most frequent collision obstacles were passenger cars  
 215 (50%), the ground (25.4%), road fixed objects (8.7%) and heavy trucks (6.4%). Table 2 shows the  
 216 percentage of injured victims for each trunk region in relation to PTW-car crash scenarios. Regarding  
 217 all injured victims, head-on-side (41.2%) was the most frequent accident configuration, followed by  
 218 head-on (20.6%) and side-on-head (18.6%) collisions. Head-on-side was the most frequent accident

219 configuration for the thorax (37.5%), the spine (30.3%), the shoulders (38.9%) and the pelvis (34.6%),  
 220 while the abdomen was most frequently injured in head-on collisions (25.8%). The distribution of  
 221 thorax and shoulder injuries was approximately the same as the collision type's share of total  
 222 accidents. The number of abdominal, spinal and pelvic injuries for riders involved in head-on-side,  
 223 side-on-head and head-on collisions was similar. With the exception of the neck, the spine (27.3%)  
 224 and pelvis (30.8%) were affected in the highest proportions of injured victims in head-on and side-  
 225 on-head configurations, respectively.

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

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

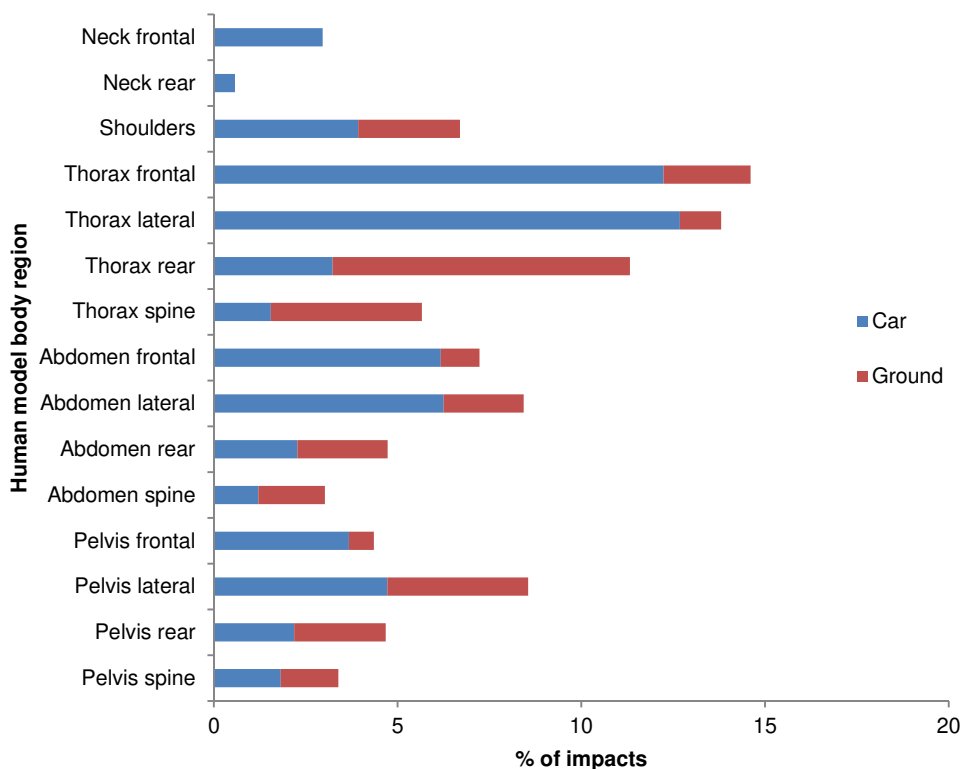
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228 **3.2- Numerical study:**

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

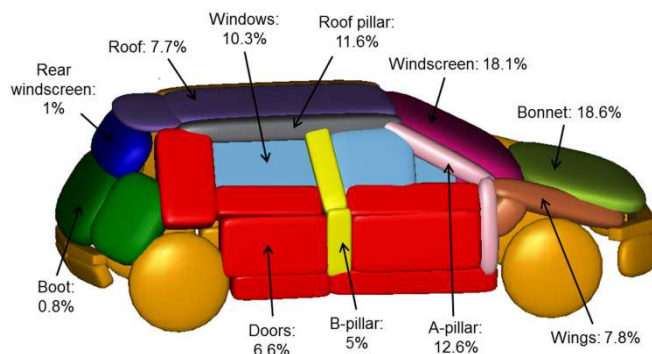
233 Regarding impacts against the car, the lateral (12.7%) and frontal (12.2%) thoracic regions are the  
 234 most strongly affected areas. The frontal and lateral abdominal zones are concerned in 12.5% of the  
 235 collisions, while the pelvis lateral area is involved in 4.7% of the impacts. The thorax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

238 The corresponding most strongly impacted parts of the car were the bonnet (18.6%), the windscreen  
 239 (18.1%), the A-pillar (12.6%), the roof pillar (11.6%) and the windows (10.3%). The rear windscreen  
 240 and the boot were rarely impacted (Figure 5).



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

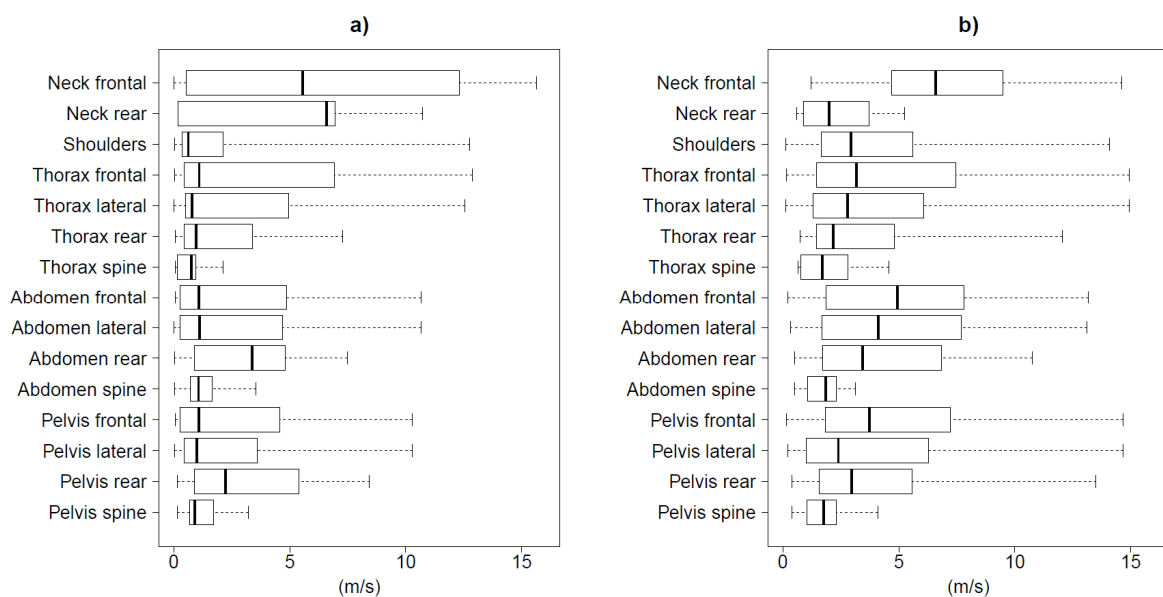


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Figure 5. Percentage of trunk impacts against the 11 parts of the vehicle.

248

249 Body impact velocity distributions for impacts against the car and the ground are reported in Figure 6  
 250 and Figure 7. The impact velocities against the car are higher than the velocities computed for  
 251 collisions with the ground. The tangential component of the impact velocities is higher than the  
 252 normal one for both impacted obstacles. Impact velocity distributions are not symmetric and  
 253 generally skewed right, i.e. there is a wider range in the velocity values above the median impact  
 254 velocities. Considering the normal components of the velocities for direct human impacts, the  
 255 highest impact velocities with the car were obtained on the frontal area of the neck, while the lowest  
 256 velocities were observed on the spine zones of the thorax, the abdomen and the pelvis. The impact  
 257 velocity gradually decreases between the upper body and the lower body. In the trunk region  
 258 specifically, the impact velocity decreases between the frontal areas and the spine. Regarding the  
 259 zones with the highest number of impacts, 75% of the frontal thoracic and abdominal impacts occur  
 260 below 6.9 m/s and 4.9 m/s, respectively. The lateral thoracic region impacts the car below 5 m/s in  
 261 75% of cases, while 75% of abdominal lateral impacts occur below 4.7 m/s. The pelvic lateral area  
 262 hits the car below 3.6 m/s in 75% of cases. The median impact velocity for these regions is around 1  
 263 m/s.

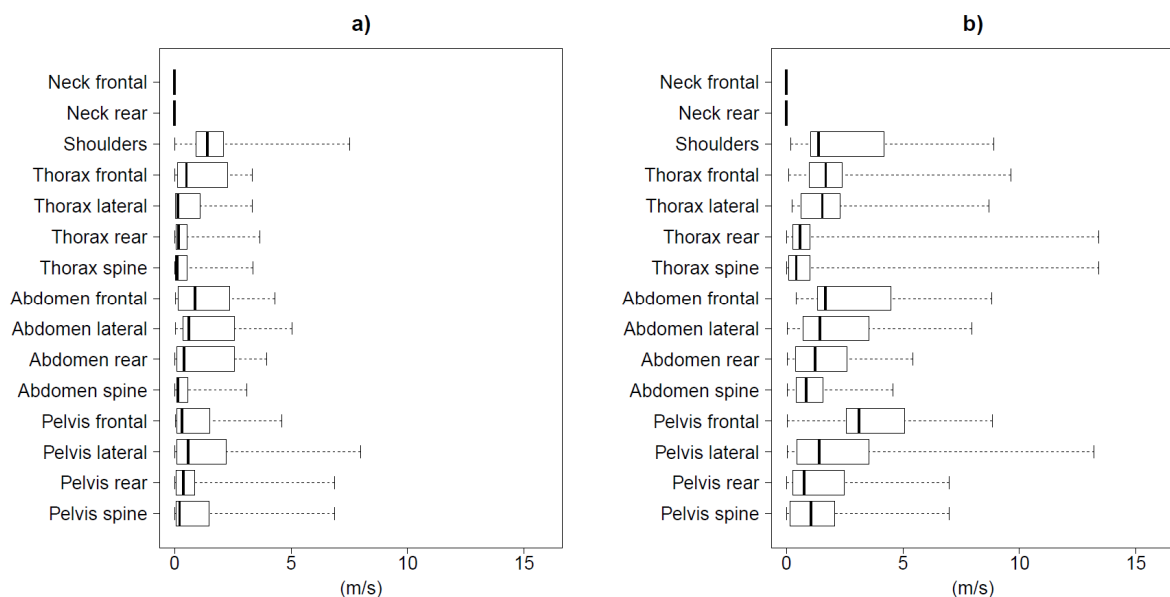


264  
 265 **Figure 6. Impact velocity distribution for each trunk region with the car. a) Normal component. b) Tangential component.**

266

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

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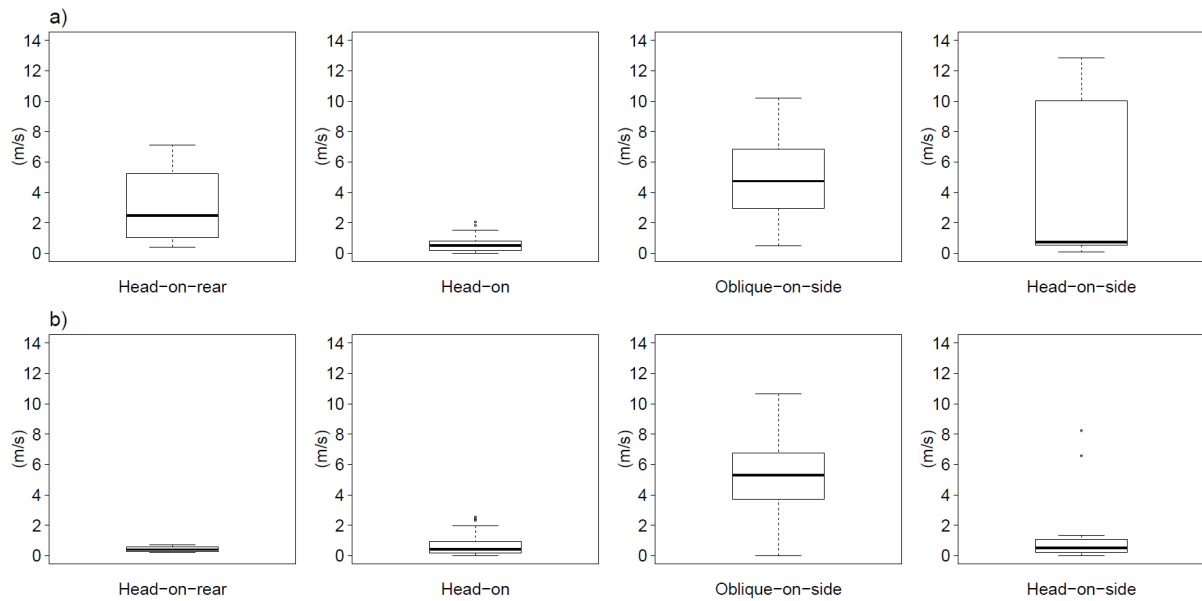


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**Figure 7. Impact velocity distribution for each trunk region with the ground. a) Normal component. b) Tangential component.**

276

277 The influence of the accident scenario on the number of impacts and on the normal impact velocity  
 278 was studied for impacts of the human body against the car. Frontal, lateral thoracic and abdominal  
 279 impact velocity distributions are shown in Figure 8. The thorax is more frequently impacted in  
 280 oblique-on-side (38.3%) and head-on (33.9%) collisions, with the highest impact velocities in head-  
 281 on-side scenarios. Head-on-side configurations make up 24.5% of collisions, with 25% above 10 m/s  
 282 as shown in Figure 8a. Abdominal impacts are more frequent in head-on (45.2%) and head-on-side  
 283 (39%) scenarios. Oblique-on-side configuration is less frequent (13.1%) but occurs at the highest  
 284 median impact velocities (5.3 m/s) as illustrated in Figure 8b.



285

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

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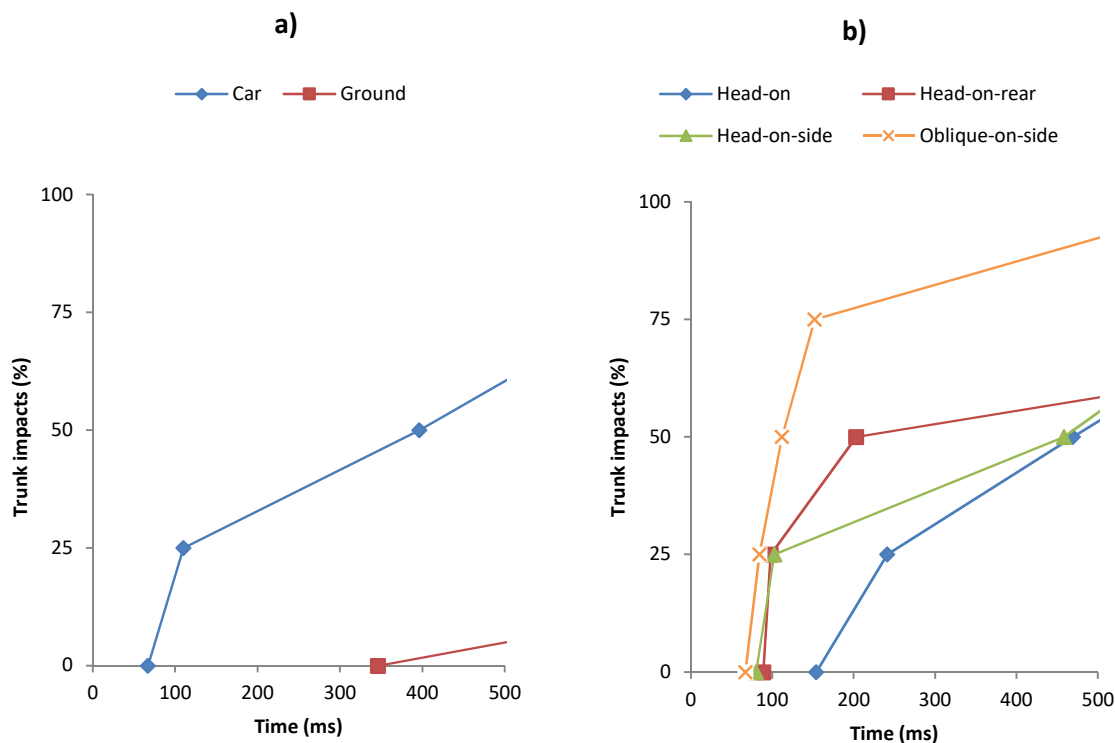
289 In addition, differences regarding riders' kinematics were observed depending on the type of PTW  
 290 and the accident scenario.

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



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

309 The analysis of the accident chronology showed that impacts against the car occurred between 67  
 310 milliseconds (ms) and 1.5 seconds (s), with 75% of collisions taking place after 110 ms. The lowest  
 311 impact time (67 ms) was found for an impact between the pelvis and the B-pillar. In this case, the  
 312 abdomen and the thorax hit the car 74 ms and 77 ms after the PTW-car contact, respectively. Impact  
 313 time against the ground ranged from 346 ms to 3 s, with 75% of impacts occurring after 1 s (Figure  
 314 9a). Concerning impacts against the car, the fastest impacts were found for oblique-on-side  
 315 collisions, with 50% of impacts under 85 ms. In head-on-rear and head-on-side configurations, 75% of  
 316 impacts occurred after around 100 ms. Head-on collisions occurred after 154 ms (Figure 9b).



317

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

320 4-DISCUSSION:

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

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

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

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

340 Regarding the distribution of injured body regions in relation to accident configuration, it was not  
341 possible to determine a unique accident situation causing the majority of the injuries. Two basic  
342 accident configurations (head-on-side/oblique-on-side and head-on) must be considered to support  
343 the design and evaluation of safety devices. Regarding collisions with the car, it was difficult to  
344 identify variations of impact angle due to the way in which the survey was completed, which was a

345 limitation of this work. In-depth accident analysis, as it was performed in the works of Fredriksson  
346 and Sui (2016) and Piantini et al. (2016), would have been useful to support the evaluation of impact  
347 speed, orientation and impacted point on the car. Nevertheless, by simulating multiple PTW-car  
348 impact conditions, the numerical investigations allowed to evaluate their sensitivity with regards to  
349 potential injury severity.

350 In the second part of this work, virtual human simulations allowed a representative original  
351 parametric study of several motorcyclists' accident situations. The evaluation of injury and severity  
352 risks for the motorcyclist was based on the number of impacts and the impact velocities, which were  
353 weighted according to the real accident data. The aim of weighting the results of the simulations is to  
354 bring them more in line with what happens in real accidents. As an example, 90 oblique-on-side  
355 scenario simulations were run (37.5% of the 240 simulations), while in the real accident dataset only  
356 8.8% of the victims were injured in this scenario (Table 2). The use of weight coefficients allows  
357 adjusting the results of the numerical study (body impact location, velocity and time distributions) to  
358 correct this kind of discrepancies. However, the sample size and the unavailable data in some cases  
359 was a limitation of this work. A larger sample size would be useful to improve the quality of the  
360 weighting method.

361 Simulations showed that impacts of the trunk against the car are more frequent and more severe  
362 than impacts against the ground. This result is consistent with the most frequent injury sources  
363 noticed by Fredriksson and Sui (2016) and Piantini et al. (2016) and should be considered as a major  
364 step forward for the design of safety devices. It makes sense to support trunk protection devices that  
365 are able to prevent injury from the first impact against the car to the collision with the ground. At the  
366 level of PTW airbag design, it has strong implications for defining the time at which to launch airbag  
367 inflation and the time during which to maintain the pressure in the airbag to be able to cover these  
368 two stages of accident situations. The results of the present work complete previous findings  
369 performed by Serre et al. (2012), confirming the required 70 ms intervention time for airbag devices

370 to prevent trunk injuries in the large majority of accident scenarios studied in this work. In the same  
371 way, the airbag inflation maintenance time of 3 s remains relevant with the 4 s duration time  
372 recommended by Serre et al. (2012). The 1 s disparity of is due to the use of two different  
373 approaches to define the proposed durations: the maximum duration of the collision, i.e. until the  
374 rider is immobilised on the ground, was considered in previous works (Serre et al., 2012; Serre and  
375 Llari, 2010), while the present work was focused on the first impact against the ground.

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

383 To assess and improve trunk safety devices in frontal and lateral impact conditions, according to the  
384 computed normal impact velocities, two levels of protection could be recommended: for the thoracic  
385 segment, a first impact level of 7 m/s on the frontal area and 5 m/s on the lateral area are proposed.  
386 The second impact level is 13 m/s for both the frontal and the lateral thoracic areas. For the  
387 abdominal segment, the two impact levels recommended on the frontal and lateral abdominal areas  
388 are 5 m/s and 11 m/s. The first impact level includes 75% of impacts, while the second level is  
389 defined to cover 100% of impacts. These impact levels represent the most severe impact conditions  
390 and cover, by far, 50% of the impacts on the thoracic and abdominal regions (normal median impact  
391 velocity below 1 m/s approximately). Further evaluations of safety devices through sub-segment  
392 testing should consider these ranks of velocities, which are strongly dependent on accident situations  
393 and subsequent human body kinematics. Nevertheless, additional investigations should be  
394 performed beforehand to check the feasibility of experimental tests as well as numerical simulations

395 at the proposed high velocity impact conditions. The impact velocities should be in agreement with  
396 the rank of velocities where human body injury tolerances were quantified and numerical models  
397 were validated to ensure the reliability of the results.

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

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

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

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

417 Secondly, the numerical study was carried out without considering the initial speed of the vehicle.  
418 Just one vehicle model was considered which was another limitation of this work. Additional

419 simulations, including parametric studies, have to be performed to investigate the effects of car  
420 speed and shape on accident kinematics. In addition to the accidentological data, the simulated  
421 scenarios were selected according to the numerical model validation, i.e. for PTW frontal impacts.  
422 Side-on-head was identified as a relevant accident scenario in the database and could not be  
423 simulated.. This accident scenario would suppose more lateral impacts for the motorcyclist (Barbani  
424 et al., 2014; Chawla et al., 2005).

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

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

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

447

#### 448 5-CONCLUSION:

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

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

459 Multibody simulations demonstrated that the impacts presenting the highest risk of injury for the  
460 motorcyclist are impacts against the car. The body regions most exposed to these impacts, and  
461 therefore the suggested protection zones for airbag devices, are the frontal and lateral thoracic and  
462 abdominal regions. The conditions of the impacts sustained by the motorcyclist, in terms of impact  
463 velocities and impacted surfaces, were also determined and could be used to define the required  
464 protection levels. Two main types of surfaces (flat and penetrant) and three impact velocities on the  
465 thorax (5, 7 and 13 m/s) and two on the abdomen (5 and 11 m/s) are recommended to evaluate and  
466 improve protection devices in order to reduce thoracic and abdominal injuries. The analysis of  
467 accident chronology allows the formulating of recommendations regarding intervention time (70 ms)

468 and maintained pressure duration (3 s) required for airbag devices. Hence, the knowledge obtained  
469 in this work allows the defining of critical information for the assessment and development of PTW  
470 safety devices and standards.

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