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Design of an after-market lower limb protector for scooters: preliminary estimation of effectiveness

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Abstract

The number of vehicles on the roads is constantly increasing. Considering the circulating park in Italy, recent data show that Powered Two-Wheelers (PTWs) have increased by about 20% just in ten years (2006-2016). PTW crashes are not decreasing at the desired pace and thus rider safety is still a concern. Previous studies showed that lower limbs are the region of the body with the highest probability of injury in a road crash. The aim of this paper is to perform a preliminary assessment of the effectiveness for a new concept of leg protector. The device is conceived for after-market installation on scooters and it is designed to mitigate leg injuries reported by the riders in side impacts at low speeds. To assess the effectiveness of the protector, five crash tests configurations of the scooter equipped with the protector were reproduced in a virtual environment. A Hybrid III model was selected as the best dummy compromise for the analysis to calculate the safety performance. Being the dummy not validated for side impacts, the evaluation was performed through a comparative analysis with and without the protector. Two different series of simulations were performed: moving-stationary (with stationary motorcycle) and moving-moving. The results of the first set of analyses (moving-stationary) show that the protector has provided a protection to the lower limbs in each configuration. In addition, the injuries to the upper body (head and chest) are equivalent or show a slight decrease. Analyzing the kinematic of the impact, the protector has a restraining effect on the rider. In the moving-moving analyses, the protector does not provide a significant improvement in leg protection, and the injury parameters worsen compared to the reference configuration. The study contributes to solve the problem of motorcyclists lower limbs protection in road crashes, studied on several occasions in the past without a concrete solution.

Keywords: Side impact; leg protector; leg injuries; FE analises.

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1. Introduction

The number of vehicles on the roads is constantly increasing. In ten years (2005-2014) the Powered Two-Wheeler (PTW) circulating park in Europe increased by about 12% (ACEM (2014)). Despite the PTW crashes reduction by about 37% (European Commission (2016)) in the same decade, rider safety is still a concern since it is the mode of transport for which the number of fatalities decreased the least (European Commission (2016)). Previous studies showed that lower limbs are the body region with the highest probability of injury in a road crash (Sporner et al. (1990)), (Chinn et al. (2004)); this probability is approximately equal to 60%.

In order to reduce the incidence of lower limbs injuries in PTW users, innovative solutions are studied over the years. Among these are leg protectors, devices designed for avoiding or reducing the impact agaist the lower extremities (Sporner et al. (1990)). Early research in the late 1960s investigated leg protectors composed of a rigid protective structure in order to prevent direct contact between the legs and the impacting vehicle or the ground. Results (Rogers et al. (1998)), (Bothwell et al. (1971)), (Uto (1975)) showed a possible reduction in lower legs injuries, but a change from bending fractures to twisting ones for the upper legs occurred. In addiction, chest and head accelerations were generally greater indicating an overall increase in injuries. In the 1980s energy absorbing leg protectors were developed with the aim of absorbing part of the energy transferred during the collision. The studies carried out in those years included the solutions proposed by Chinn et al. (2004) and Tadokoro et al. (1985). Their results underlined a marked reduction in the energy transferred to the lower legs, but the injuries were shifted to the upper leg changing from bending to twisting fractures.

The aim of this study is to perform a preliminary assessment of the effectiveness of a new concept of leg protector, designed to mitigate leg injuries reported by riders in side impacts at low speeds. Side impacts represent 26.1% of impact conditions (ACEM (2009)), and they have not been sufficiently studied over the past years. The proposed device is conceived for after-market installation on scooters (the most common vehicle typology involved in a road accident (67.5% Piantini et al. (2016), 38.4% ACEM (2008))). The study contributes to solve the problem of riders lower limb protection in road crashes, already studied in the past without a viable solution.

2. Methods

To assess the effectiveness of the protector, five crash test configurations with a car impacting against a scooter with the rider were reproduced in a virtual environment. Altair Hypermesh was used as finite element pre-processor, while LSTC (Livermore Software Technology Corporation) LS-DYNA was used as solver.

The reference scooter chosen was Piaggio MP3, whose finite element model (Fig. 1) was provided by Piaggio & C. SpA and it was updated by MOVING group (Barbani et al. (2012), Barbani et al. (2014)). The selected car model, Ford Taurus (Fig. 1), was developed and distribuited by the Nation Crash Analysis Center (NCAC).

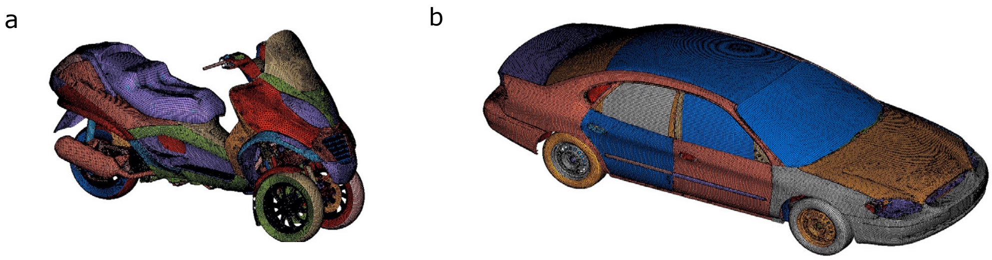

Fig. 1. (a) MP3; (b) Taurus.

The leg protector device consisted of polyethylene bars connected to a leg cover sheet throught adhesive. The function of the bars was to protect the lower limbs from a side impact.

Hybrid III 50th male (Guha (2014)) was selected as the best dummy CAE model compromise for the simulations to calculate the selected safety parameters. Hybrid III 50th male was the closest dummy to the ISO Motorcyclist Anthropometric Test Dummy (MATD) suggested by the ISO 13232 (2005), which provides standardised methods and procedures for the development and evaluation of the protective equipment for riders. MATD has frangible bones

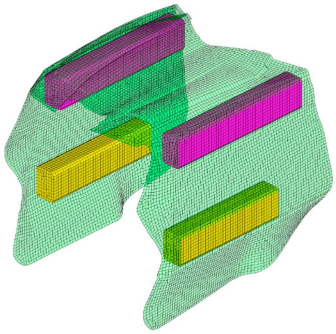

Fig. 2. Leg protector.

that need to be replaced after each test, leading to a huge increase of costs. Hybrid III was the baseline for MATD development, and it is often used as replacement, as in the present study. Being the dummy not validated for side impacts, the evaluation was performed through a comparison of the simulations results with and without the protector.

The five analysed configurations (Fig. 3) differed in the relative heading angle (RHA) between the longitudinal axes of the impacting vehicle and the scooter driving direction. The RHA was set to 45° (C45), 60° (C60), 90° (C90), 120° (C120) and 135° (C135). In C45 and C60 the car has a velocity component concurrent with the scooter velocity, while in C120 and C135 the car has a velocity component opposite to the scooter velocity.

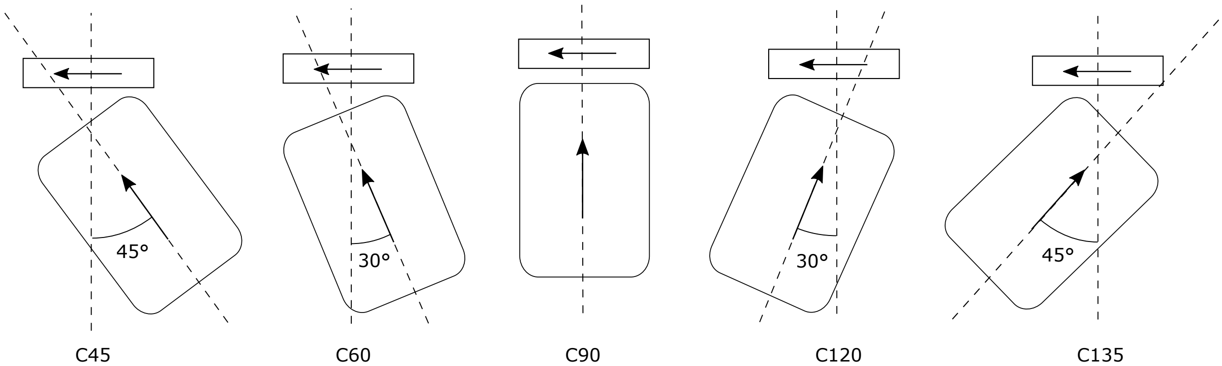

Fig. 3. Impact configurations: the stretched rectangles represent the scooter, the large ones the impacting vehicle and the arrows the travel directions.

Two different sets of simulations were performed:

- moving-stationary (with stationary scooter and impacting car moving at 5m/s)
- moving-moving (scooter and impacting car moving at 5m/s)

Each configuration was simulated with and without the protector fitted on the scooter. Seven parameters were evaluated in this study: five of them related to the lower limbs, the other two related to the upper part of the body. These parameters were selected in order to assess the protective effect of the protector on the legs, head and chest. The parameters were extracted in the first set of simulations (without the protector) both in the stationary-moving (Tab. 1) and in the moving-moving (Tab. 2) configurations. The maximum value of each parameter was extracted jointly from the two sets of simulations. They were used as limit values and as scale factor for the parameters evaluated in the simulations with the protector.

3. Results

The results were scaled down compared to the maximum values determined in the first sets of simulations (without the protector). The stationary-moving simulations (Tab. 3) show that the protector provided a protection to the lower limbs in each configuration. The tibia axial force in the configurations C45 and C120 increased compared to the corresponding configuration without the protector, but the limit value was not exceeded. The same considerations apply to the upper body (head and chest) protection in configurations C45, C60, C120 and C135. Only in configuration C90 the HIC_{36} value topped the limit by 7%.

Table 1. Results for the stationary-moving configurations without the protector.

Safety parameters	C45	C60	C90	C120	C135
Femur axial force	0.30	0.26	0.18	0.26	0.30
Femur bending moment	0.84	0.69	0.52	1.00	0.80
Femur twisting moment	0.67	0.95	1.00	0.96	0.76
Tibia axial force	0.12	0.21	0.22	0.27	1.00
Tibia bending moment	0.84	0.71	0.62	0.79	1.00
HIC_{36}	0.29	0.50	1.00	0.50	0.57
Chest acceleration	0.26	0.20	0.29	0.20	0.11

Table 2. Results for the moving-moving configurations without the protector.

Safety parameters	C45	C60	C90	C120	C135
Femur axial force	0.45	0.10	0.19	1.00	0.69
Femur bending moment	0.41	0.35	0.64	0.96	0.58
Femur twisting moment	0.40	0.59	0.94	0.77	0.30
Tibia axial force	0.10	0.10	0.24	0.22	0.48
Tibia bending moment	0.48	0.44	0.77	0.85	0.63
HIC_{36}	0.64	0.64	0.64	0.36	0.86
Chest acceleration	0.16	0.18	1.00	0.55	0.15

Table 3. Safety assessment of the protector in stationary-moving configurations. Color coding indicates the values decreased (green) and increased (red) with the introduction of the protector.

Safety parameters	C45	C60	C90	C120	C135
Femur axial force	0.26	0.20	0.08	0.13	0.11
Femur bending moment	0.72	0.46	0.46	0.65	0.40
Femur twisting moment	0.32	0.48	0.80	0.48	0.46
Tibia axial force	0.13	0.17	0.09	0.42	0.37
Tibia bending moment	0.73	0.33	0.53	0.72	0.94
HIC_{36}	0.36	0.29	1.07	0.14	0.29
Chest acceleration	0.27	0.22	0.18	0.11	0.14

In the moving-moving configurations (Tab. 4), the protector did not provide the same level of leg protection. In 3 out of 5 configurations (C60, C90 and C135) 4 to 5 parameters had higher values compared to the configuration without the protector, and 1 parameter exceeded its limit value. In configuration C120 only one parameter worsened, but it exceeded the limit (HIC_{36}).

In both sets of simulations, the protector had a restraining effect on the rider kinematics during the impact: the rider may have a delayed ejection, with smaller amplitude compared to the base configuration, or no ejection at all. As example, in Fig. 4 and Fig. 5 are reported the two moving-moving configurations in which the parameters (tibia bending moment in configuration C60 and chest acceleration in configuration C90) had a marked variation due to

Table 4. Safety assessment of the protector in moving-moving configurations. Color coding indicates the values decreased (green) and increased (red) with the introduction of the protector.

Safety parameters	C45	C60	C90	C120	C135
Femur axial force	0.09	0.21	0.65	0.39	0.21
Femur bending moment	0.32	0.77	0.39	0.86	0.71
Femur twisting moment	0.48	0.69	1.00	0.54	0.35
Tibia axial force	0.09	0.15	0.19	0.13	0.28
Tibia bending moment	0.41	1.21	0.80	0.79	0.63
HIC_{36}	0.14	0.36	0.43	1.57	1.07
Chest acceleration	0.15	0.34	4.05	0.17	0.18

the changing of the kinematics caused by the presence of the protector. In Fig. 4 is shown the comparison of the configuration C60 with and without protector in the moving-moving case. The simulation has a duration of 315ms and 4 frames were reported in the image, respectively at 0*ms*, 105*ms*, 210*ms* and 315*ms*. In the simulation without the protector, the dummy was not retained by the scooter and it lay completely on the car bonnet at about 385*ms*. Differently, in the presence of the device, the dummy's legs were blocked by the bars of the protector and the dummy posture was twisted. In addition the dummy was still partially connected to the scooter and thus it participated to its kinematics and dynamics. This caused the bending of the left lower leg and the subsequent increase of the tibia bending moment above its limit value.

In Fig. 5 is shown the configuration C90 in the moving-moving case. In this case the scooter had a velocity equal to that of the car at the moment of impact; as a consequence, the motorcyclist was projected towards the ground and not towards the bonnet of the car (simulation without the protector). Instead, the protector restrained the rider's legs during the impact causing an unnatural twist of the chest, as it can be seen in the fourth frame. Consequently, the chest acceleration increased markedly.

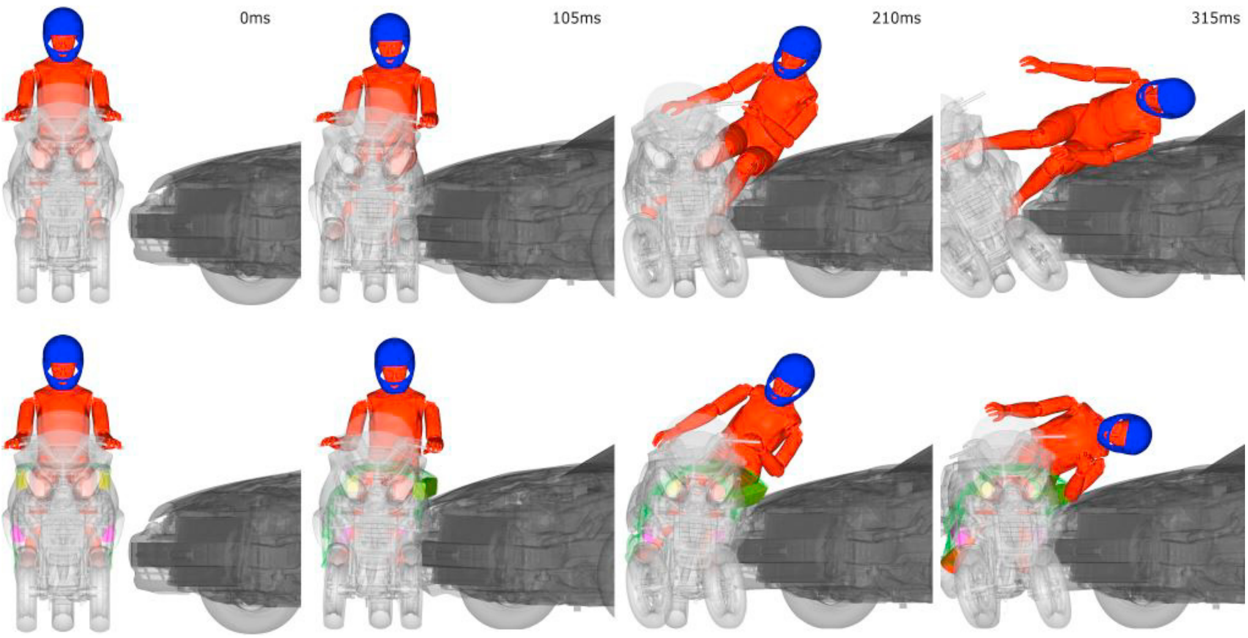

Fig. 4. Configuration C60, moving-moving.

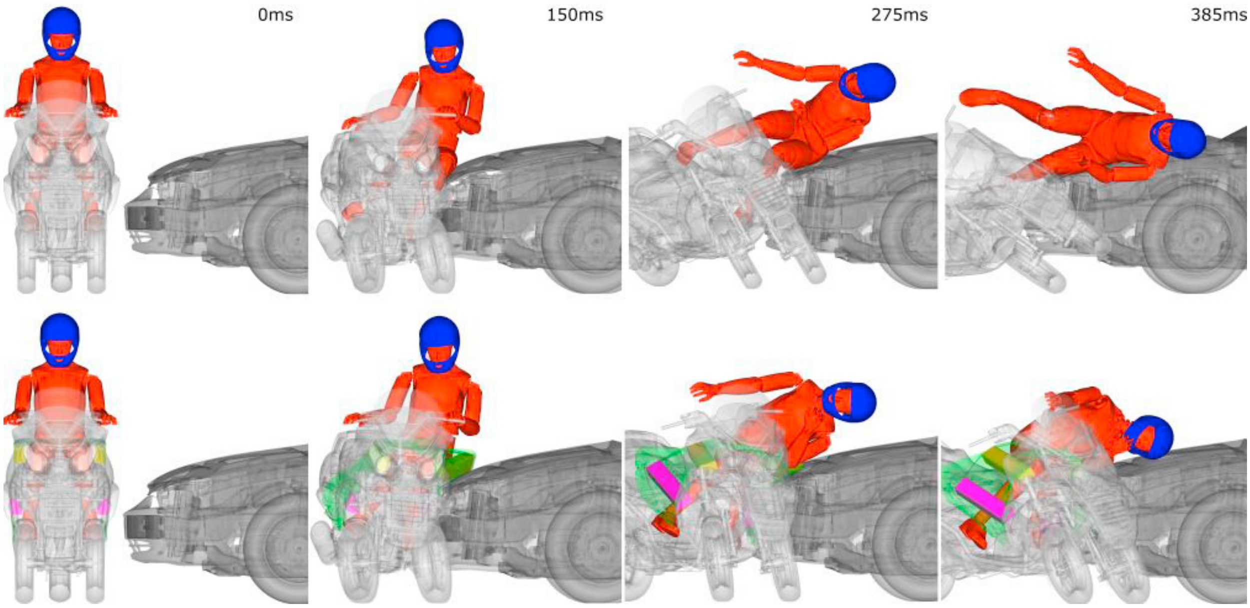

Fig. 5. Configuration C90, moving-moving.

4. Discussion

This paper describes the preliminary analysis of a concept for a new leg protector, aimed to reduce lower limb injuries in side impacts at low speed. Studies made on leg protectors over the years highlighted that the design of a leg protector should take into account two important factors: the risk of increasing head and chest injuries, and the transfer of injuries from the lower part of the leg (by bending), to the upper part of the leg (by twisting).

The results show that lower limb injury parameters are improved in stationary-moving simulations, although tibia axial force increased with the introduction of the protector in configuration C45 and C120, but still below the limit. In this set of configurations only the HIC_{36} value exceeded the limit value (C90). However its limit value was very low (14) compared to the value defined in Hutchinson et al. (1998) (1000), approximately two orders of magnitude smaller than the absolute reference. Thus, although no absolute references were used in this work, it is possible to state that the exceeding of the limit value, with the multiple reported in Tab. 3, does not pose any harmful condition. In fact the difference of the measured value to the biomechanical limit is large enough to compensate for all the uncertainties associated with the use of Hybrid III. The same considerations apply also for the results of the moving-moving configurations.

In moving-moving simulations the protector was not effective in configurations C60, C90 and C135. Nonetheless the tibia axial force has improved throughout all the configurations and the tibia bending moment in 3 out of 5 configurations. In parallel the femur twisting moment increased in 4 out of 5 configurations. Thus the current version of the leg protector device tends to transfer the injuries from the tibia to the femur, as found in literature. In all simulations the protector introduces a retention effect that globally changes the rider's kinematic. The side bars hold the riders legs in place during the collision, delaying the riders ejection.

The maximum values of the upper body parameters are generated in the impact of the specific body region with the car, and not during the initial contact of the car with the scooter. Therefore, the rider's safety is strongly dependent on the geometry of the car. Nonetheless, in the presented crashes, the modifications to riders kinematic have shown a detrimental effect on the chest injuries in the configuration C90 moving-moving. Indeed, the presence of the protector causes a sudden twist of the chest (Fig. 5), causing a high increase of its acceleration.

A limitation of this study is the use of a dummy model, which is not validated for lateral impacts. Currently there are no validated dummies for complex kinematic conditions as those encoutered in the later impact of cars vs. PTWs. In fact, available dummies were developed for car applications, where the kinematics of frontal and lateral impact are well separated and more controlled, because of the presence of the seat belts. Future studies may take into consideration the use of a numerical human body model (e.g. Thums) that may allow to overcome this limitation and thus to perform an absolute evalutation of the protective performance of the device and of the injuries of the rider.

The results demonstrate the need for further development of the leg protector, to improve the protective performance and eliminate the load transfer effects highlighted in this work. The starting point for improving the protector are mainly moving-moving configurations C60, C90 and C135, identified as the most critical ones for the performance of the protector. Their in-depth analysis will provide information to drive the re-design of the protector.

5. Conclusion

A leg protector for scooter was developed and its effectiveness was evaluated through crash tests reproduced in a virtual environment. The leg protector had a protective effect in the stationary-moving configurations reducing most of the safety parameters, but not in the moving-moving configurations. The presence of the bars caused a restriction of the leg movements, affecting both the kinematics and thus the safety parameters of the rider. The results also confirmed the findings of the literature, i.e. the transfer of the loads from the lower legs (by bending) to the upper legs (by twisting) due to the introduction of the protector. These preliminary results represent a valuable starting point for the development of the protector.

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