A COMPARATIVE STUDY BETWEEN SUBSYSTEM AND GLOBAL APPROACHES FOR THE PEDESTRIAN IMPACT

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ABSTRACT

In order to improve the pedestrian safety during an impact with a vehicle, subsystem tests have been defined to evaluate the aggressiveness of the front-end of cars. These subsystems tests have to be reproducible and are representative of the three decomposed impacts of the pedestrian with the car: lower leg on the bumper, upper leg on the hood, head on the hood or the windscreen. The velocity, angle and mass of the adult headform impactor and its impact area are invariable parameters. Upper legform impactor parameters are determined by vehicle characteristics. Lower legform impactor parameters are invariable (velocity and positioning). Nevertheless, these decoupled tests do not take into account the influence of the whole body on impacts. Therefore, it appears important to compare these subsystem tests with global conditions observed in real accidents. The objective of this paper is to perform this work on two French vehicles. Concerning the global conditions, four full-scale experimental tests with PMHS and the associating multibody numerical simulations were performed in classical (lateral impact for the pedestrian, centred for the vehicle) and real configurations.
In that way, two real accidents have been chosen in this impact configuration with a velocity value close to 40 km/h. Each reconstruction of accidents is based on In-Depth Accident Investigation first. Then, a parametric study using multibody models, validated with an experimental test, gives a hypothetic initial configuration of the accident. This configuration is used to put on an experimental reconstruction. Then, results from numerical and experimental studies are compared for the adult headform, the upper legform and the lower legform impacts. Finally, a global comparison is analysed more specifically on injuries not include on the subsystem approach. These injuries are also compared to Accidental Database to know whether their proportion is important or not.

INTRODUCTION

From 1980 to 2001, pedestrian accident proportion decreased in France. Since 2001, this tendency has been reversed and from 2004, pedestrian accident proportion has increased up to 16% of total French road accidents [ONISR, 2007].
The standard pedestrian accident configuration is characterised by a vehicle frontal Impact (67%), a pedestrian lateral Impact (80-90%) and velocities lower to 50 km/h (85 %) [Robertson et al., 1966, Ravani and al., 1981, EEVC, 1982 and 1998, IHRA, 2001].

In 1998, the EEVC (European Enhanced Vehicle-safety Committee) published a pedestrian protection evaluation report [EEVC, 1998]. This

document led to a European directive (2003/102/EC) applied in October [EC-OJ, 2003]. The objective was to improve the pedestrian safety by reducing the aggressiveness of the front end of the cars regarding pedestrians. This regulation is decomposed in two phases. The phase one is already in application while the phase two is carried out. Moreover, EEVC report led to consumerist tests. In Europe, Euro NCAP tests are performed in order to defend consumers.
Four subsystem tests reproduce and represent the three decomposed pedestrian impacts with the car: lower leg, upper leg, adult head and child head. Test protocols are based on a specific impact configuration which corresponds to the standard one, with about 30-40 km/h vehicle velocity.
From existing data in the field of accident statistics, biomechanics and test results of EEVC report, subsystems limitation parameters evaluate front-end vehicle aggressiveness with acceleration, HIC, force, moments, knee lateral shearing and bending HIC parameters. Head and leg subsystems tests protocols and injury criteria are independent of the vehicle. Concerning the upper leg protocol, it is dependant of the geometry vehicle.

Therefore, it appears important to compare these subsystem tests with global conditions observed in real accident. The objective is in particular to evaluate the influence of the whole body on the kinematics because it is not taken into account in subsystems tests. What can be the disparities on the different impact characteristics (lower leg, upper leg and head impact) when all the pedestrian body is considered (global configuration) and when it is decoupled in several body segments (subsystem tests)? The aim of this paper is to perform this work on two French vehicles and two global configuration types.

METHOD

General overview

Three types of pedestrian impact configurations were analysed and compared in this work.
The first configuration corresponded to the impact protocols defined by the subsystems tests performed in the framework of the Euro NCAP consumerist tests [Euro NCAP, 2004]. These experimental results were considered as the reference because they were compared with global conditions. However, the subsystem “Child Head” was not studied because it could not be compared with the others configurations described below (the two real accidents involved adults).
The second configuration was a global configuration corresponding to a standard accident (lateral impact on the pedestrian side and centred on the front of the vehicle). Two complementary approaches were used to study this configuration. An experimental one based on full scale tests using PMHS subjects and then a numerical one based on the associated multibody simulation.
The third configuration concerned real accidents which have been reconstructed from an in-depth accident investigation. These real accidents have been selected close to the standard configuration. Such as for the previous global configuration, both experimental and numerical approaches have been used. But in this case, the numerical reconstruction was made firstly with multibody simulations before the experimental reconstitution [[b]Serre and al., 2006].
This study was applied to two different vehicles: a Peugeot 206 and a Renault Twingo.
So, in all, four full-scale experimental tests with PMHS and the corresponding multibody simulations were performed in addition to the Euro NCAP consumerists tests.

Sub-system tests

NCAP tests procedures are effectives in Europe (Euro NCAP), US (USNCAP), Japan (Japan NCAP) and Australia (ANCAP). The Euro NCAP introduced pedestrian protection since 1999. Modifications have been done in 2005 to introduce vehicle evaluation with a four stars scale. Tests methods and injury criterions are based on the 1998’s EEVC report.
This method, proposed by the EEVC (Figure 1, [Davies and Clemo, 1997]) represents adult head, child head, upper leg and lower leg impacts. Four instrumented subsystems are projected on specific vehicle areas to constitute six configurations:

- **Adult head** to **windscreen**
  Output parameters: HPC, maximal acceleration
- **Adult head** to **bonnet**
  Output parameters: HPC, maximal acceleration
- **Child head** to **bonnet**
  Output parameters: HPC, maximal acceleration
- **Upper leg** to **bonnet leading edge**
  Output parameters: force and moment
- **Upper leg** to **bumper**
  Output parameters: force and moment
- **Lower leg** to **bumper**
  Output parameters: knee bending and shearing, maximal acceleration

Adult head to bonnet, child head to bonnet and upper leg to bumper were not analysed in this work. Firstly real and standard accidents included two adults. So child impact was not compared. Secondly, head impacts were located on the windscreen, so head impact to bonnet is not analysed. Thirdly, upper leg to bumper impact is used for SUV (Sport Utility Vehicle) and real accidents vehicle type is a sedan one.

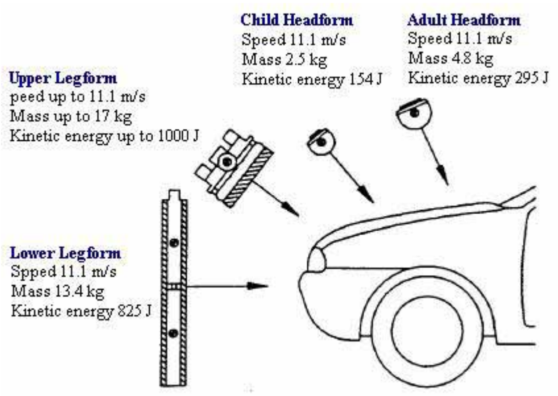

Figure 1. Pedestrian protection test methods proposed by EEVC WG10

Standard configuration tests

In this configuration, pedestrian had a standard posture corresponding to a walk and a road crossing. The pedestrian impact was lateral (right side) and the vehicle one was frontal, located in the centre of the front end.

About the full-scale experimental tests, they had been performed using Post Mortem Human Subjects (PMHS). They were preserved at 3°C in Winkler's preparation [Winkler, 1974]. This injection method allows to keep supple the sampling and to preserve for several months the soft tissues elasticity. Medical team checked the joint range of physiological mobility. X-Rays radiographs of the body were taken and an anatomist surgeon checked the osseous integrity in two planes (sagittal plane and frontal plane).

The subject is instrumented with accelerometers fixed on tibia, femur, pelvis, sternum, cervical vertebrae and head. (Figure 2)

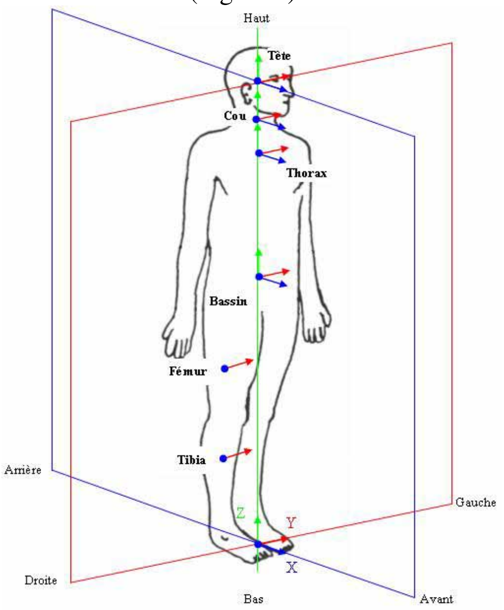

Figure 2. PMHS sensors location

At the beginning of tests, subject had a standing position maintained by an electromagnetic system linked to the pedestrian head (Figure 3). Ten milliseconds before impact, this system released the subject.

A horizontal catapult propelled the car. From three to seven high-speed video cameras operating at 1000 frames per second were placed in order to record the kinematics during the impact event.

Figure 3. Experimental subject initial position

Concerning the numerical approach, full scale crashes simulations were performed using Madymo software [[a]Serre and al., 2006]. The pedestrian model is composed by thirty-five rigid bodies, thirty-five joints and eighty-two ellipsoids. Mechanical characteristic joints and bodies were based on biomechanical data [Yamada, 1970] [Kajzer, 1999]. The model can predict lower leg fracture and head injury criterion:

- Ten bodies connected by joints compose lower legs. Two rupture criteria are fixed, shearing force and bending moment.
- Head injuries are evaluated by the HIC criterion.

The vehicle model represents the front end of a sedan vehicle type (windscreen, bonnet, bumper and spoiler) [Glasson and al., 2000]. Fourteen parameters compose its geometry (Figure 4). Mechanical properties of the different parts of the car have been implemented from the Euro NCAP experimental tests.

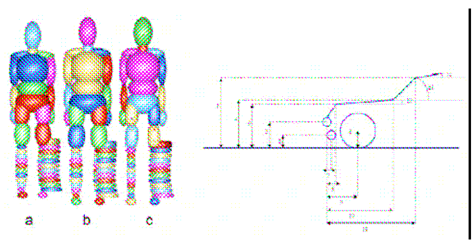

Figure 4. Pedestrian and vehicle numerical models (Madymo®)

Pedestrian and vehicle models were validated qualitatively and quantitatively in a pedestrian impact configuration with experimental tests comparison jointly by Chalmers University, Faurecia and Laboratory of Applied Biomechanics of INRETS [Yang et al., 1993], [Glasson et al., 2000]. These tests were realised with PMHS and several different geometric vehicles (sedan) with impact velocity from 30 km/h to 40 km/h [Cavallero and al., 1983].

In this work, two full-scale experimental tests with PMHS and the associating multibody numerical simulations were performed in this standard configuration. Characteristics of numerical and experimental tests are resumed in Table 1.

Table 1.
Standard configuration tests characteristics

	Peugeot 206		Renault Twingo	
	Exp.	**Num.**	**Exp.**	**Num.**
Impact type	Frontal centred	Frontal centred	Frontal centred	Frontal centred
Vehicle Velocity	8.9 m/s	8.9 m/s	8.9 m/s	8.9 m/s
Subject size	1m54	1m54	1m58	1m60
Subject mass	46 kg	46 kg	61.5 kg	60 kg
Subject age	86 years	-	86 years	-

Real accident configuration tests

Concerning the real configuration, a global methodology has been defined in order to propose a reliable accident reconstruction [[b]Serre and al., 2006]. This methodology gathered three complementary approaches (Figure 5).
Each accident reconstruction was based on In-Depth Accident Investigation first. Then, a parametric study using multibody models gave a hypothetic initial configuration of the accident. This configuration was used to put on an experimental reconstitution and to validate the reconstruction.

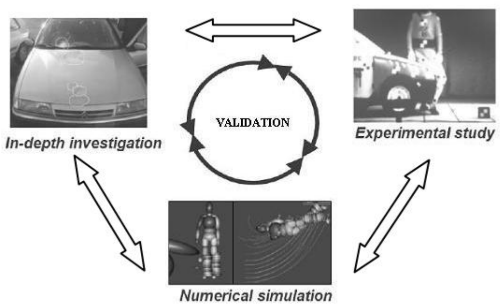

Figure 5. Different approaches in the reconstruction method

Accidents were chosen from an in-depth investigation performed at the laboratory Accidental Mechanism Department of INRETS [Girard, 1993]. These accidentologic data gave information to develop a first hypothetic configuration. From this, a numerical parametric study was realised to fix unknown parameters such as the vehicle velocity, its deceleration, the initial pedestrian position, etc. Each result was compared to accidental data to be validated or not. For example, Figure 6 shows the kinematics for two different initial pedestrian postures. After iterative simulations, configuration which was closest to real accidental data was selected. Only this final reconstruction configuration is presented in this work. Finally, from this most probable numerical reconstruction, an experimental test was realised with the closest conditions.
Characteristics of numerical and experimental tests are in Table 2.

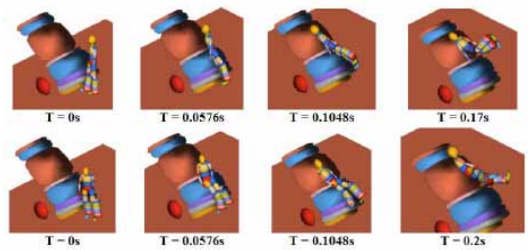

Figure 6. Example of two different configurations

Table 2.
Real configuration tests characteristics

	Peugeot 206		Renault Twingo	
	Exp.	**Num.**	**Exp.**	**Num.**
Impact type	Frontal shift	Frontal shift	Frontal shift	Frontal shift
Vehicle Velocity	8.3 m/s	8.3 m/s	11.2 m/s	12.2 m/s
Subject size	1m61	1m65	1m60	1m60
Subject mass	44 kg	55 kg	65 kg	60 kg
Subject age	85 years	> 50 years	64 years	> 50 years

RESULTS

Vehicle 1: Renault Twingo

Head Impact

Head impact parameters (Table 3) have been calculated in the vehicle skew for experimental and numerical results. Head angle and velocity correspond to a pre-impact time (5 ms before). Head acceleration and HIC were calculated during impact.

For all Sedan vehicles, Euro NCAP head/windscreen impact angle is 65 degrees. In both standard configuration (numerical and experimental tests), angle values are close. These values are half the Euro NCAP angle value. In real configuration, numerical (21°) and experimental (42°) head impact angle values are different.

Nevertheless, these values are lower than Euro NCAP defined angle.

For all Sedan vehicles, Euro NCAP head/windscreen impact velocity is 11.1 m/s. In standard configuration tests, velocities are lower than Euro NCAP value. In real configuration, results are close to Euro NCAP.

For the Euro NCAP Renault Twingo test, maximal impact acceleration result is 94 g and HIC is 486. In standard and real configuration, maximal impact accelerations are around 1.5 higher (up to 180) while HIC is lower. Because in the real experimental configuration case, a crash sensor record was failed, no data are provided in axe X. Acceleration resultant could not be calculated.

Table 3.
Head impact parameters results for Renault Twingo

	Basic Conf.		**Real Conf.**		**Sub System**
	Exp.	**Num.**	**Exp.**	**Num.**	
Angle	30°	28°	42°	21°	65°
Velocity (m/s)	-	8.1	12.5	9.3	11.1
Acc. (g)	153	154	y: z:	180	94
HIC	423	261	-	316	486

Upper leg impact

The upper leg impact parameters (Table 4) correspond to thigh impact. Upper leg angle represents thigh angle. Velocity corresponds to thigh impact velocity. Force represents the contact of thigh with the bonnet and the moment is the internal thigh bending moment. In experimental tests these parameters were not measured.

For Renault Twingo vehicle, Euro NCAP upper leg/bonnet impact angle is 41.3°. In standard and real configurations, numerical values are respectively 35° and 48°. Euro NCAP value is included in these results.

For Renault Twingo vehicle, Euro NCAP upper leg/bonnet impact velocity is 6.91 m/s. In both configurations, velocities are close to this defined value.

For the Euro NCAP Renault Twingo test, impact force is 5100 N and bending moment is 312 N.m. In both configurations, Forces are lower than Euro NCAP value and bending moment are close.

Table 4.
Upper leg parameters results for Renault Twingo

	Numerical basic Conf.	**Numerical real Conf.**	**Sub System**
Angle	35°	48°	41.3°
Velocity	6.7 m/s	7.4 m/s	6.91 m/s
Strain	2370 N	1800 N	5100 N
Moment	365 N.m	300 N.m	312 N.m

Lower leg impact

Knee bending and shearing in experimental tests are not calculated due to the lack of accuracy to separate the two phenomenons of translation and flexion.

For all Sedan vehicles, Euro NCAP lower leg/bumper impact velocity is 11.1 m/s. Real configuration velocity is close to Euro NCAP value while standard configuration velocity is lower.

For the Euro NCAP Renault Twingo test, maximal impact acceleration is 205 g. Standard and real configuration results vary from 190 to 320 g.

For the Euro NCAP Renault Twingo test, maximal knee bending is 33 degrees. Numerical results from both configurations are much lower.

For the Euro NCAP Renault Twingo test, maximal knee shearing is 4.2 mm. Results from both configurations are close to this value.

Table 5.
Lower leg parameters results for Renault Twingo

	Basic Conf.		**Real Conf.**		**Sub System**
	Exp.	**Num.**	**Exp.**	**Num.**	
Velocity (m/s)	8.9	8.9	11.2	11.1	11.1
Acc. (g)	190	320	324	290	205
Bending	-	8°	-	4°	33°
Shearing (mm)	-	8	-	6.4	4.2

Vehicle 2: Peugeot 206

Head Impact

The head impact parameters (Table 6) have been calculated in the same way than Renault Twingo parameters. However, the Peugeot 206 subsystem test has been done in the localisation showed in the Figure 7. This localisation is an aggressive part of the windscreen border. In the reality, the contact between pedestrian head and windscreen occurs around the centre of this vehicle part. Values can not be compared because of this difference.
Because in the standard experimental configuration case, a crash sensor record was failed, no data are provided in Y axe. Acceleration resultant could not be calculated.

For all Sedan vehicles, Euro NCAP head/windscreen impact angle and velocity are respectively 65 degrees and 11.1 m/s.
In standard configuration, numerical head angle (42°) and experimental head angle (61°) are different. In real configuration, numerical and experimental angles are equivalent (42° and 45°). These values are lower than Euro NCAP value except for the experimental standard configuration test.
In standard and real configurations, velocities are lower than Euro NCAP value.

Table 6.
Head parameters results for Peugeot 206

	Basic Conf.		Real Conf.		Sub System
	Exp.	Num.	Exp.	Num.	
Angle	61°	42°	42°	45°	65°
Velocity (m/s)	10.6	7.1	8.3	6.9	11.1
Acc. (g)	x: 74 z: 63	42.5	122.7	108	-
HIC	-	138	155	654	-

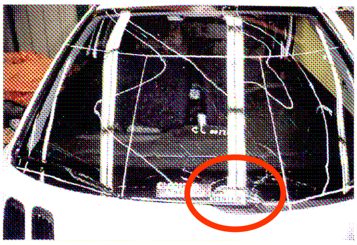

Figure 7. Impact location of Sub-system tests for the Peugeot 206 evaluation

Upper leg impact

For Peugeot 206 vehicle, Euro NCAP upper leg/bonnet impact angle is 34°. In standard and real configurations, numerical values are respectively 30° and 34°, close to Euro NCAP value.

For Peugeot 206 vehicle, Euro NCAP upper leg/bonnet impact velocity is 7.9 m/s. In both configurations, velocities are lower than this defined value.

For the Euro NCAP Peugeot 206 test, impact force is 2819 N and impact bending moment is 382 N.m. In both configurations, forces are lower than Euro NCAP value. Concerning bending moment, numerical value in standard configuration is lower and in real configuration is close to Euro NCAP result.

Table 7.
Upper leg parameters results for Peugeot 206

	Numerical basic Conf.	Numerical real Conf.	Sub System
Angle	30°	30°	34°
Velocity	5.9 m/s	4.8 m/s	7.9 m/s
Strain	1950 N	1470 N	2819 N
Moment	265 N.m	360 N.m	382 N.m

Lower leg impact

For all Sedan vehicles, Euro NCAP lower leg/bumper impact velocity is 11.1 m/s. In both configurations, velocities are lower.

For the Euro NCAP Peugeot 206 test, maximal impact acceleration is 150 g. Standard and real configuration results vary from 100 to 360 g.

For the Euro NCAP Peugeot 206 test, maximal knee bending is 30°. Results from both configurations are close to this value.

For the Euro NCAP Peugeot 206 test, maximal knee shearing is 4 mm. Numerical results from both configurations are much higher.

Table 8.
Lower leg parameters results for Peugeot 206

	Basic Conf.		Real Conf.		Sub System
	Exp.	Num.	Exp.	Num.	
Velocity (m/s)	8.9	8.9	8.3	8.3	11.1
Acc. (g)	360	170	100	155	150
Bending	-	32°	-	40°	30°
Shearing (mm)	-	27	-	32	4

DISCUSSION

Head impact

Impact angle values are lower than Euro NCAP value except for one case.
Angles vary with vehicle geometry and between simulations and experimental tests for some cases. Result variability between numerical and experimental tests seems to be the consequence of articular behaviour variability of PMHS and articular behaviour invariability of numerical pedestrian model.
This variability between vehicle types seem to be the consequence of geometrical vehicle parameters (windscreen angle), PMHS size, weight and articular laxity.

Impact velocities are globally lower than Euro NCAP defined value, except for Peugeot 206 tests in real configuration. In this test, vehicle velocity is close to Euro NCAP accident configuration (11.1 m/s). Euro NCAP head velocity seems to be relevant.

With impact velocities, lower than Euro NCAP one, maximum accelerations during impacts are one and half higher. In opposition, HIC is lower.
These differences can be explained by variability of parameters like impact angle, impact velocity and material behaviour used to represent pedestrian head in Euro NCAP tests.

What can be the disparities on the head impact characteristics when all the pedestrian body is considered (global configuration) and when it is decoupled in the head subsystem?
From these results, head angle seems to be overvalued while velocity seems to be relevant. Concerning head angle in Euro NCAP, it is defined with regard to a horizontal line and not to the windscreen line. It should be more adapted to fix head subsystem angle with windscreen orientation.

Upper leg impact

Upper leg angle in standard and real configuration, for numerical and experimental tests, are close to Euro NCAP value. Moreover, angles seem to be dependant from vehicle. Euro NCAP upper leg angle value and its vehicle specificity might be relevant.

Euro NCAP Renault Twingo velocity is included between real and standard configuration thigh velocities.
About Peugeot 206 results, velocities are lower than Euro NCAP velocity. Peugeot 206 impact velocity seems to be overvalued for upper leg impact. Nevertheless, impact velocity vehicle dependence seems relevant.

Impact forces are always lower than Euro NCAP results. This test seems to overvalue this impact parameter.

Euro NCAP thigh bending moments seem to be relevant. In Renault Twingo case, Euro NCAP value is close to numerical results and in the Peugeot 206 case, Euro NCAP value is higher than results.

What can be the disparities on the upper leg impact characteristics when all the pedestrian body is considered (global configuration) and when it is decoupled in the upper leg subsystem?
From these results, vehicle velocity dependence, vehicle angle dependence and angle values seem to be relevant. About velocities parameter, it seems to be relevant for Renault Twingo vehicle and maximized for Peugeot 206 vehicle. Nevertheless, impact forces are too high in Euro NCAP configuration.

Lower leg impact

Leg impact velocity corresponds to impact vehicle velocity. Standard tests were realised with an 8.9 m/s vehicle velocity. In real configuration, Peugeot 206 case corresponds to a crash velocity close to Euro NCAP configuration.

Between experimental and numerical tests, maximum acceleration values vary. These differences seem to come from vehicle geometry, pedestrian initial position, cadaveric rigidity and mechanical properties of numerical models.
Moreover, Euro NCAP results do not maximised real and standard configuration results. In these last configurations, it is the vehicle which impact pedestrian. In Euro NCAP protocol, it is the leg which impact the vehicle.

In the Renault Twingo case, the low lateral knee bending in standard configuration comes from knee kinematics. Indeed, the first knee kinematical movement is a lateral flexion (8°), then a posterior flexion (13°) and torsion (16°). In this case, initial pedestrian position corresponds to a right leg ahead and the impact side is on the right. During the first time of impact, pedestrian turn progressively his back to the vehicle. So, posterior flexion is maximized, lateral flexion is minimized. Knee lateral shearing is minimized too, and it is close to Euro NCAP value.
In real configuration, for Renault Twingo case, pedestrian turn back a little to the vehicle. His kinematics movement minimized lateral bending and shearing.
These cases are not critical pedestrian leg case for knee injured kinematics.

In Peugeot 206 cases, maximum of lateral knee bending are more important and reach 32° and 40°, close to Euro NCAP results. Lateral knee shearing reaches 27 and 32 mm. These kinematics are different with Renault Twingo ones. Lateral knee bending and shearing are maximised.

What can be the disparities on the lower lag impact characteristics when all the pedestrian body is considered (global configuration) and when it is decoupled in the lower leg subsystem?
From these results, Euro NCAP velocity value seems to be relevant. Lower leg sub-system seems to represent critical value in lateral bending, while it do not correspond to critical value in lateral shearing for knee.

CONCLUSION

The aim of this work is to compare Euro NCAP subsystem protocols and results with two full-scale configurations, standard and real, in order to evaluate disparities on the different impact characteristics when all the pedestrian body is considered (global configuration) and when it is decoupled (subsystem tests). Full-scale configurations are performed on two French vehicle using two complementary approaches, numerical simulation and experimental tests.
Some differences have been observed between subsystem characteristics and body segment impacts coming from full-scale configurations.
Concerning head impact, the defined angle by Euro NCAP is globally higher and could be adapted with the vehicle geometry. The corresponding defined velocity by Euro NCAP seems to be adapted.
Concerning the upper leg impact, all Euro NCAP parameters are relevant to the global configurations except for the fixed Peugeot 206 velocity which is maximized.
Concerning lower leg impact, subsystem protocol parameters are adapted, represents knee bending critical case but does not represent knee shearing critical case.
This work has been done only on two vehicles (Renault Twingo and Peugeot 206) but will be extended to other vehicles in order to evaluate more accurately the influence of vehicle geometry, speed, etc. New vehicles which have a good evaluation in Euro NCAP will be tested in particular.

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