Leg Biomechanical Response in Pedestrian Impact and its Incidence on Regulations

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Abstract: Head and leg injuries are the most frequent and severe pedestrian injuries.This paper is aimed at comparing the leg biomechanical response with the test conditions and the requirements of new regulations (EC directive and pedestrian GTR) and to propose directions for improved regulations intended to protecting pedestrians against leg injuries. This is based on PMHS full scale test results, on numerical simulations using a finite element leg model, and standard impactor test results.
Keywords: Pedestrian, safety, test method, biomechanics, injury criteria

1 Introduction

Since a few years, pedestrian protection in traffic accident is considered as a main priority by regulatory bodies and has focused the necessary attention from car industry.

Research organizations have developed the knowledge needed in the fields of accident analysis and recontruction, impact biomechanics and assessment methods necessary to improve pedestrian protection.

This report summarizes a collaborative research performed in the field of pedestrian protection in accident, which has just been completed.

It covers accident reconstructions and biomechanical full scale tests aimed at developing global knowledge of pedestrian biomechanical response in realistic test conditions, the analysis of pedestrian leg response using a numerical simulation approach and a discussion on the current subsystem test methods.

2 Full scale tests using PMHS

Within the research programme dealing with pedestrian safety improvement, 4 full scale tests using PMHS in a standard test procedure and two reconstructions of real accidents were performed.

2.1 Standard tests with PMHS

Those 4 tests were performed using a different mass production car for each of them ; the details of test conditions and test results were recently published [1].

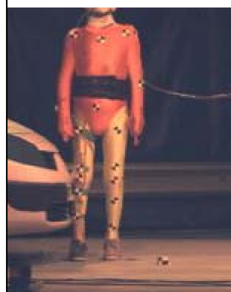
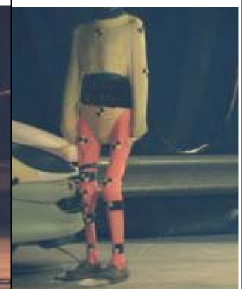
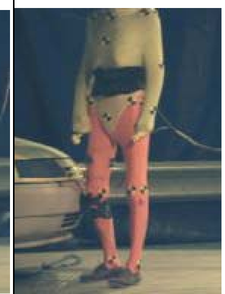
Table 1 summarizes the characteristics of PMHS used for these tests. The PMHS were used in accordance with the ethical rules applicable in France, and the results were normalized using the procedure widely accepted to correct the weight differences.

Table 1. Cadaver Physical data

	Test01	Test02	Test03	Test04
Gender	M	M	M	M
Age	88	74	85	80
Height (cm)	175	185	161	175
Weight (kg)	67	86	44	62

The test conditions are summarized in Table 2.

Table 2. Test matrix

Subject position	 standard	 standard	 Real position	 Real position
Speed	39.2km/h	39.7km/h	29.7km/h	37.2km/h
Vehicle	Small sedan	Large sedan	Small sedan	Large sedan

The results of tibia and head responses are listed in Table 3.

Table 3. Head and leg injury criteria

	Test n° 1		Test n° 2		Test n° 3		Test n° 4	
	Time (ms)	Peak (g)	Time (ms)	Peak (g)	Time (ms)	Peak (g)	Time (ms)	Peak (g)
Head accel	124	89.7	117	66.7	175	103.4	174	112.5
HIC	NA			117		1004		119
Right tibia accel	2.9	138	4.9	244	5.5	88.4	9.4	242.8

Table 3 contains acceleration based injury criteria for head and leg impacts.

All head impacts occur in the windscreen, not close to the windscreen frame, allowing an important deformation of the windscreen.

In Test n° 3, the HIC value is just above the threshold of 1,000.00, whereas for the other tests, the HIC value is very low, even if Test n° 3 was performed at a lower speed. The car involved in Test n° 3 is higher than the others with a more vertical windscreen which would limit the sliding effect of the body on the windscreen and then, increase the head contact severity.

There is a large variation in tibia acceleration response, but it was not possible to establish correlations with injury risk.

Table 4 shows the distribution of leg injuries for right and left legs. Test n° 1 produced a larger number of injuries, whereas the PMHS sustained less injuries for the three other tests.

Knee ligament injuries were more frequent on the right knee (first impacted leg) than on the left one, and medial collateral ligament rupture seems typical for the first impacted leg.

The PMHS of test n° 3 did not receive any knee ligament injury, but fractures to the extremities of the femur and the tibia, and this test was performed at a lower speed corresponding to 45% less energy.

Table 4. Leg injuries distribution

	Test 01		Test 02		Test 03		Test 04	
	R	**L**	**R**	**L**	**R**	**L**	**R**	**L**
Knee ligaments								
MCL	x						x	
LCL		x		x				
ACL	x		x				x	x
PCL	x							
Articular capsule	x	x						
Fracture of the femur								
internal condyle	x	x			x	x		
external condyle		x						
Fracture of meniscus		***x***						
Fracture of the tibia								
plateau	x	x		x				x
diaphysis			x					
spine		x						
malleolus					x			
Fracture of the fibula								
diaphysis			x		x			
malleolus								x

Figure 1 shows the kinematics of leg and upper torso during the impact.

For leg kinematic analysis, we have selected the times 0 ms (at the initial contact), 10 ms (intermediate) and 25 ms (maximum leg deformation). It has to be noted that the maximum of tibia acceleration occurs much earlier than the maximum knee deformation.

Head kinematic was analyzed during a period of time of 15 ms before the head contact (time - 15 ms) and the head contact itself. It was not possible to see big differences in the kinematic, and for all tests, the right arm stayed between the bonnet and the upper body.

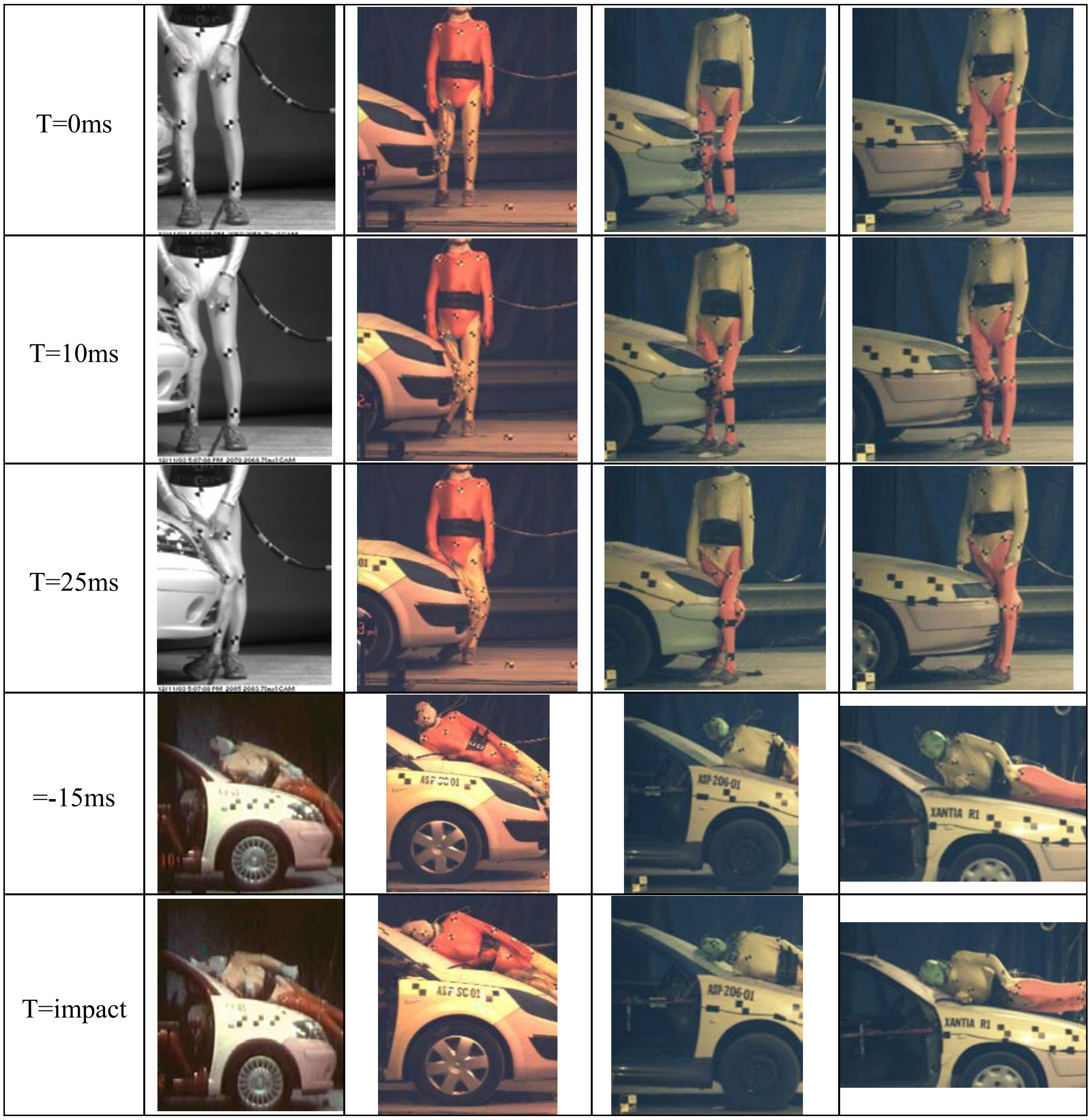


Figure1 Pedestrian leg and head kinematics

3 Numerical simulation of leg response

Full scale tests with PMHS allowed to determine the pedestrian kinematic and the global response of body components such as they leg or the head, but do not allow to analyse detailed local response. There is then a need to use a different technique to analyse leg and knee response and to understand the role of different components during the impact. For that purpose we have decided to perform numerical simulations using a FEM leg model.

3.1 Materials and methods

The LLMS models used for this work were either an isolated leg model or a leg model coupled to an Hybrid III 50 percentile rigid dummy model in order to take into account the effects of the whole human body kinematics during the test. The details of LLMS model (from design to validation) were not reported in this paper as they were already largely published [2] [3]

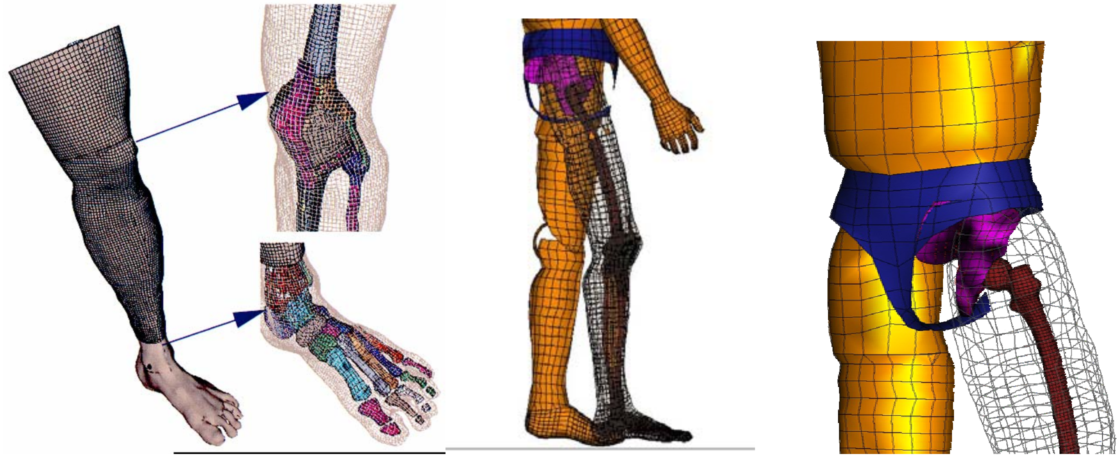


Figure 2 LLMS model (left: leg only, right: leg attached to an hybrid III model)

The coupling consisted in adding a part of the pelvis bone to the initial pelvis rigid body component. The initial geometry of a hybrid pelvis was modified in order to ensure repositioning of the model up to the standing position. The upper proximal femur to the head of femur was considered as a rigid body. The hip joint was then defined using a mathematical joint at the centre of the femoral head. Rotations at the hip joint were defined using torque versus angle user functions in a local skew system (cf. figure 2).

3.2 Previous work

Several papers published during the during the last years [4] [5] have used this approach to determine human leg response in pedestrian impact. For these simulations a standard FEM car front (same car as test 1 of PMHS tests) hits a LLMS leg model. The simulations were performed at the same impact speed (11 m/s), but it was possible other test parameters, such as car stiffness or relative position of the leg versus the car, as indicated on figure 3.

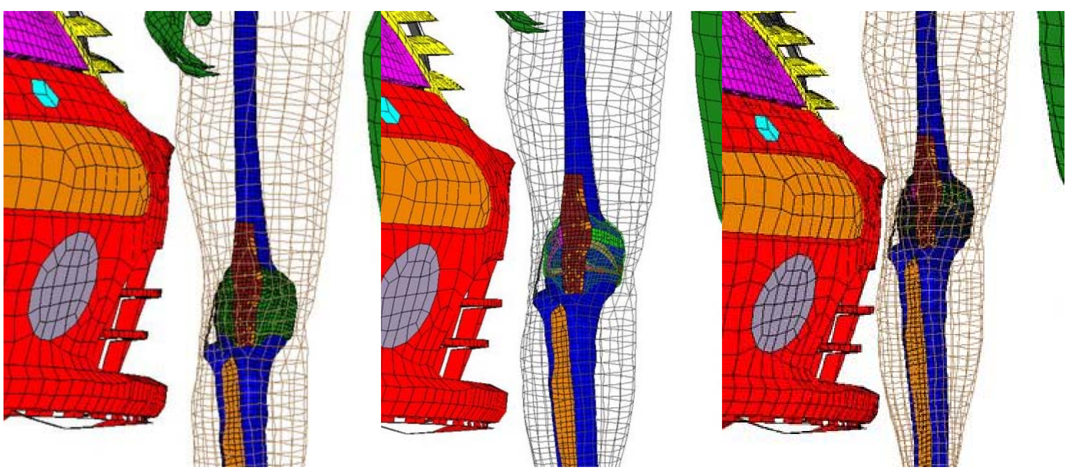


Figure 3 Simulation conditions to study bumper height

These studies have allowed determining injury mechanisms and protection criteria for the knee in pedestrian impacts. They confirm the role of the medial collateral ligament which is the most extended ligament in the knee. These simulations also confirmed the two main mechanisms: lateral bending and femur to tibia shearing. The corresponding tolerance values were estimated at 18° to 20° in bending and 13 mm in shearing. These values were considered when the new GTR for pedestrian safety was developed.

3.3 Influence of upper body on leg and knee response

The European directive and EuroNCAP use subsystem test impactors to evaluate pedestrian safety. For leg to bumper impacts a free flight articulated leg impactor is propelled against a car front, and test results are based on tibia acceleration, maximum knee bending angle and maximum shearing displacement. It is proposed to use this test when the initial contact is at knee level or below, which raises the question of pedestrian safety evaluation when impacted by a high bumper car, such as a 4X4 car. The main reason for which it is not proposed to use leg impactor on high bumper cars is the influence of pedestrian upper body (which is not included in the leg impactor) when the impact occurs above the knee. To understand the influence of upper body we performed simulations in two conditions: impact against an isolated leg model, and impact against a hybrid III with a LLMS leg model. These tests were made in the three bumper height conditions indicated on figure 4.

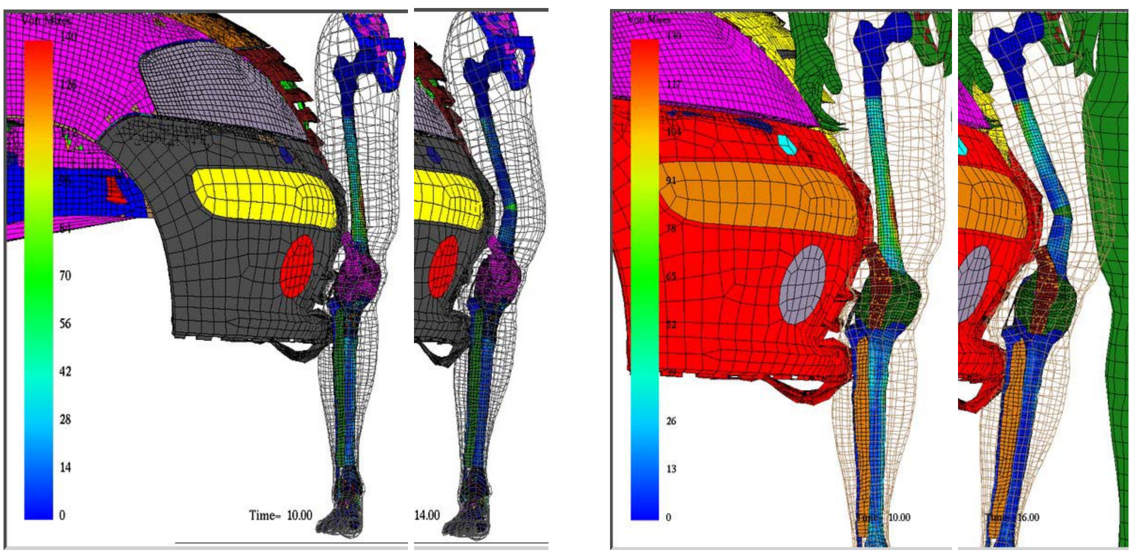


Figure 4 Leg response for high bumper car impacts (left: isolated leg, right: Hybrid III+leg)

Figure 4 shows the leg and knee responses when impacted above the knee in two conditions: LLMS leg model alone, which is similar to standard lg impactor impact, and LLMS leg model attached to a Hybrid III numerical model. Analysis of kinematics shows very similar responses in the two conditions: the deformations occur at the same time with the same amplitude, and the injuries are found at the same locations. For the two other impact conditions, the same results were found, showing almost identical responses for the different impact locations (impact above the knee at 1/3 of the femur length, impact just above the knee, and impact at the knee level.

Figure 5 contains variations versus time of shearing displacements (left) and bending angle (right). For each of the 3 components, this figure allows to compare knee response for the leg alone LLMS model, and when this leg model is attached to the Hybrid III rigid body model through the hip joint. This analysis shows that with and without upper body mass the knee responses are identical, at least up to injury threshold: the two curves are almost superimposed from time 0ms to over 12 ms; ligament rupture would occur at before this time. This is an indication that, even when the initial impact is above the knee the impact against an isolated leg gives the same result than an impact against a full body. This result would allow to use the leg impactor also for testing car with high bumper, at least in the range of the simulation performed for this evaluation.

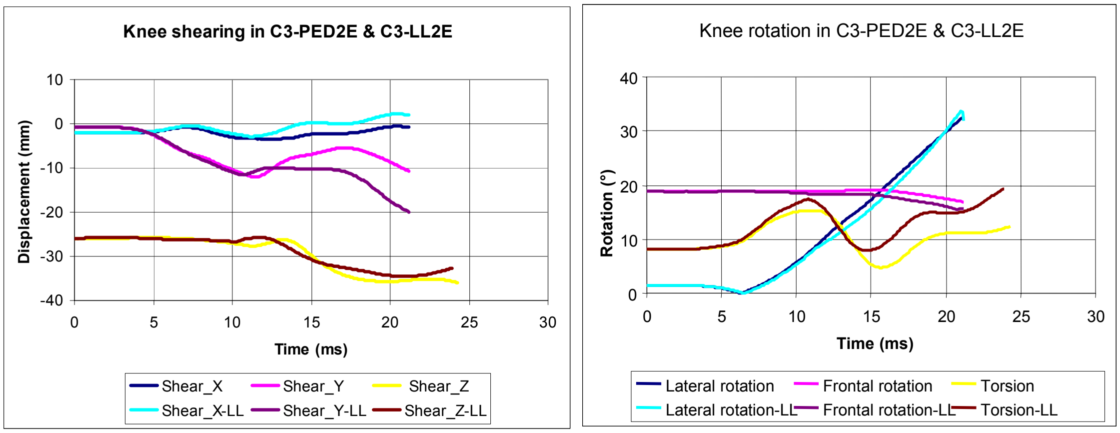


Figure 5 Knee shearing displacement and bending angle with and without upper body

4 Analysis of European test procedure

The test procedures used in the European regulation, and by EuroNCAP are based on the test procedure developed by EEVC [6], as indicated on figure 6, and which includes four main impactors: the leg impactor (bumper test), the upper leg impactor (bonnet leading edge) child head impactor (bonnet front) and adult head impactor (bonnet rear).

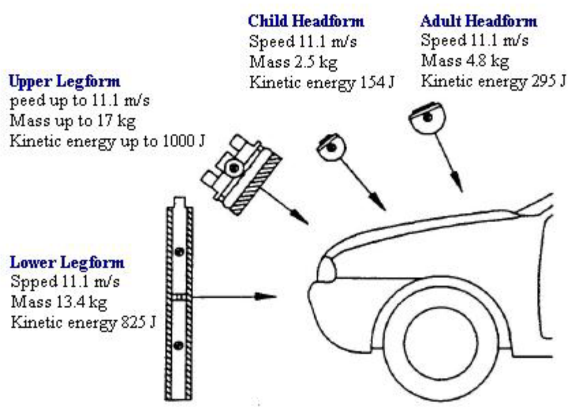


Figure 6 EEVC test procedure

4.1 Leg impactor

Experimental research and simulations have confirmed the injury mechanisms taken in consideration by the leg test for knee injury prediction: knee bending which is the most frequent, and knee shearing. Originally, EEVC has proposed a limit of 15° for bending, and 6mm for shearing. Recent research results tend to suggest higher values: 18° to 20° in bending and 13mm in shearing. These values are probably rather conservative, as they are based on PMHS responses, which would correspond to the less resistant part of the population. The research also indicates that this test could be used in tests with high bumper cars, unlike it is today.

4.2 Upper leg impactor test

Figure 7 shows car bonnet leading edge deformation after a PMHS test, and after a standard upper leg impactor test against bonnet leading edge. Comparison of deformations shows clear differences: in PMHS test the crush is very small, and the body slid on the bonnet without producing high impact force; in that test the cadaver did not sustain any injury to the pelvis or to the femur. The standard test produce important localised crush producing high contact force; this test would not allow the car to pass the requirements of the European regulation.

Figure 7 Bonnet leading edge deformation from impactor test (right) and in PMHS test (left)

This confirm previous work demonstrating that the bonnet leading edge test is not reproducing what is occurring in real accident, and would require modifications which are not needed to protect pedestrians.

5. Conclusions

Full scale PMHS tests associated to numerical simulations allowed to improve biomechanical knowledge in the field of pedestrian accidents, especially tolerance values for knee injuries. It also allowed to determine new limits for the use of leg impactor in standard tests to assess pedestrian leg injuries, especially for high bumper cars.

Finally these tests have demonstrated the lack of realism of the bonnet leading edge test using upper leg impactor which is not able to reproduce correctly relevant injury mechanisms occurring in pedestrian accidents.

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