INTERACTION BETWEEN HUMAN LEG AND CAR BUMPER IN PEDESTRIAN TESTS

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ABSTRACT

This paper contains the results of 20 cadaver pedestrian tests in which the pedestrian is impacted by a car platform fitted with an adjustable bumper. It shows the effect of bumper height and impact speed on pedestrian leg kinematics, pedestrian leg injuries, and bumper/leg forces, and it includes a method for determining the equivalent mass of the leg during the impact.

The finding contained in this paper would help to determine the parameters necessary for designing a pedestrian leg protection sub system test.

SCOPE OF THE PROBLEM

Protection of pedestrians in cases of collisions by cars is a difficult matter, and it is necessary to understand clearly what happens during the impacts between the car structures and the pedestrian body parts. Analysis of pedestrian accidents shows that two body segments are most frequently involved in pedestrian accidents (1) : the lower limbs injured at the beginning of the collisions by contact with the car front face (generally the bumper) and the head which may hit the windscreen frame. The area of the car which may be impacted by body segments have a variable stiffness and this makes impossible to evaluate the protection offered by a car in pedestrian impact by a full scale test.

This has encouraged the scientists to develop evaluation test procedures based on sub-system tests (2). However before proposing a sub-system test method, it is important to determine the impact parameters (speed and trajectory at the impact of the evaluated body segment) the mass, the shape and the stiffness of the body segment model, the injury parameters representing the injury mechanisms, and the relationship between the value of those parameters and the human tolerance to injuries.

This paper will investigate the problem of lower limb injuries protection and the determination of impact conditions.

KINEMATIC OF PEDESTRIAN LEGS IN CAR IMPACTS

The "Laboratoire des Chocs et de Biomécanique" of INRETS has a great experience of researches in the field of pedestrian protection (3, 4, 5, 6)

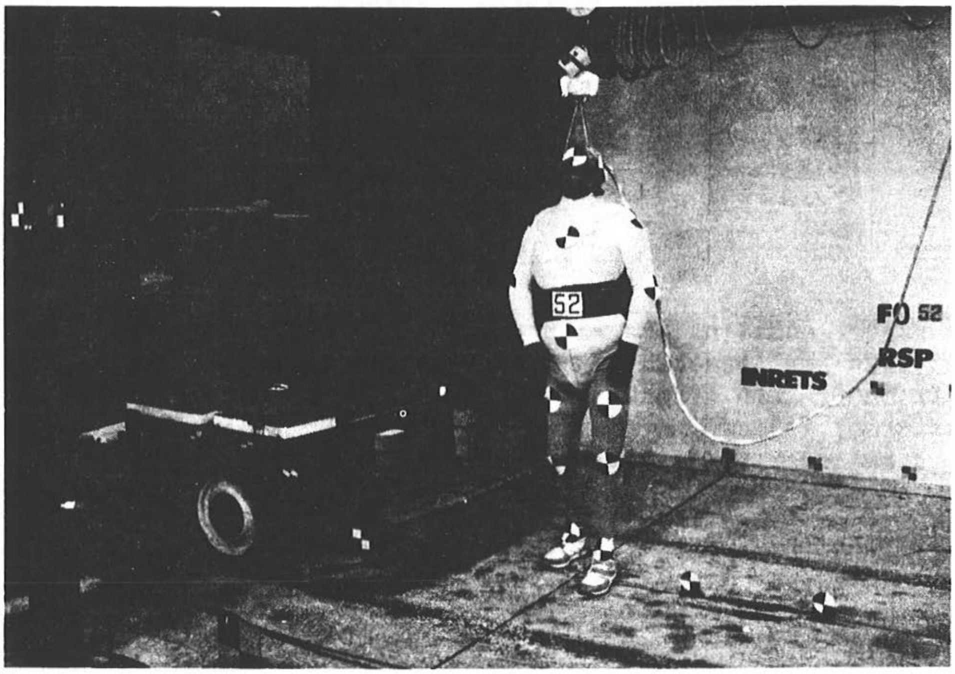


FIGURE 1 : TESTS SET UP

Twenty cadaver pedestrian test were performed using a car platform fitted with an adjustable bumper (fig 1) as impacting car. The bumper was equipped with two force transducers located at the attachements of the bumper to the platform structures.

Table 1 gives the conditions of the tests. The impact speed varies in the range of 20 to 39 km/h (5,56 to 10,83 m/s). The bumper height was adjusted with reference to the ground and the knee level. As the cadaver height varies in a large amount instead of choosing a fixed values for the bumper height, we have choosen five values of the ratio between the bumper height and the length of the lower leg expressed in % of the lower leg length : a value of 100 % corresponds to a bumper at the level of the knee. In all the tests the same bumper model is used. Two high speed movie cameras take the pictures necessary to determine the kinematic of the legs. In all the tests, the pedestrian was hit laterally on ~~its right side, and was in a~~ walking situation with the two feet on the ground.

Bumper Height (%) / Impact speed (km/h)	60	75	90	105	120
20	1	1	1	3	1
32	1	3	1	2	1
39	1	1	1	1	

Table 1 : Tests matrix

General kinematic of the leg

The bumper pushes first the right leg of the cadaver in the direction of the car motion. At the beginning the foot does not move and the ankle is thightened. The second leg is involved by the collision 15 to 20 ms after the first one.

Table 2 indicates the values of the variation of the angle between the lower leg and the thigh is a R.L. plane. This table for the right (first impacted) leg shows clearly that the deformation at knee level depends from the bumper height : when the bumper height is equal to 60 % of the knee level above the groung there is a very small variation of the angle between the thigh and the lower leg ; this angle variation is in the direction of pushing the knee of the impacted leg outside of its original position. The 60 % bumper height is equal to 300 mm for a 50 percentile male pedestrian ; this value is just below the proposal of bumper height for minimizing the bending force in the knee joint (7). It is noticeable that this value is slightly lower than the location of the lower leg C.G. (3).

Fig 2 gives the values of knee angle variation in relation to bumper height. This figure contains important informations concerning the influence of the impact speed and of the bumper height on leg deformation at knee level. First the influence of the bumper height is very important : the bumper height which corresponds to "zero knee bending should be around 65 % (325 mm) above the ground.

Bumper Height (%)	60	75	90	105	120
Impact speed (km/h)					
20	-8	-17	-36	-40**	-36
32	+9	-22**	-32	-52*	-49
39	+6	-20	-38	-57	

* Average of two tests ** average of three tests

KLBA : Angle defined by the tigh and the lower leg in the vertical plane perpendiculaire to the sagittal one.

Table 2 : Variation of KLBA (°)

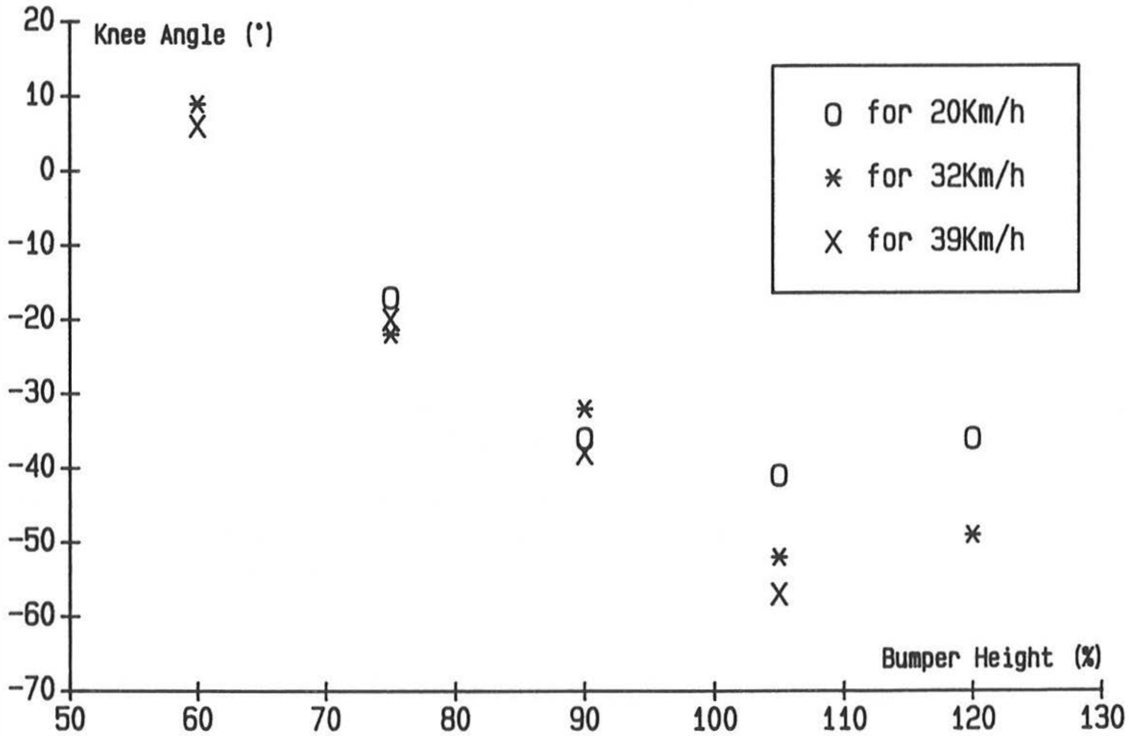


FIGURE 2 : KNEE ANGLE VARIATION

When this parameter increases, the deformation ~~angle of the knee gets~~ up, the maximum corresponding to about 100 % or 500 mm for the 50 th percentile pedestrian.

The influence of the impact speed is not so important for low bumper, the same magnitude of knee deformation is found, whatever the impact speed ; when the bumper height is higher (90 % and more) the lower impact speed (20 km/h) corresponds to the lower knee deformation, whereas there is no significant difference for the two other impact speed values.

PEDESTRIAN LEG INJURIES

Most of the cadavers sustained leg injuries due to car impact ; however these injuries are not of the same type for all the tests.

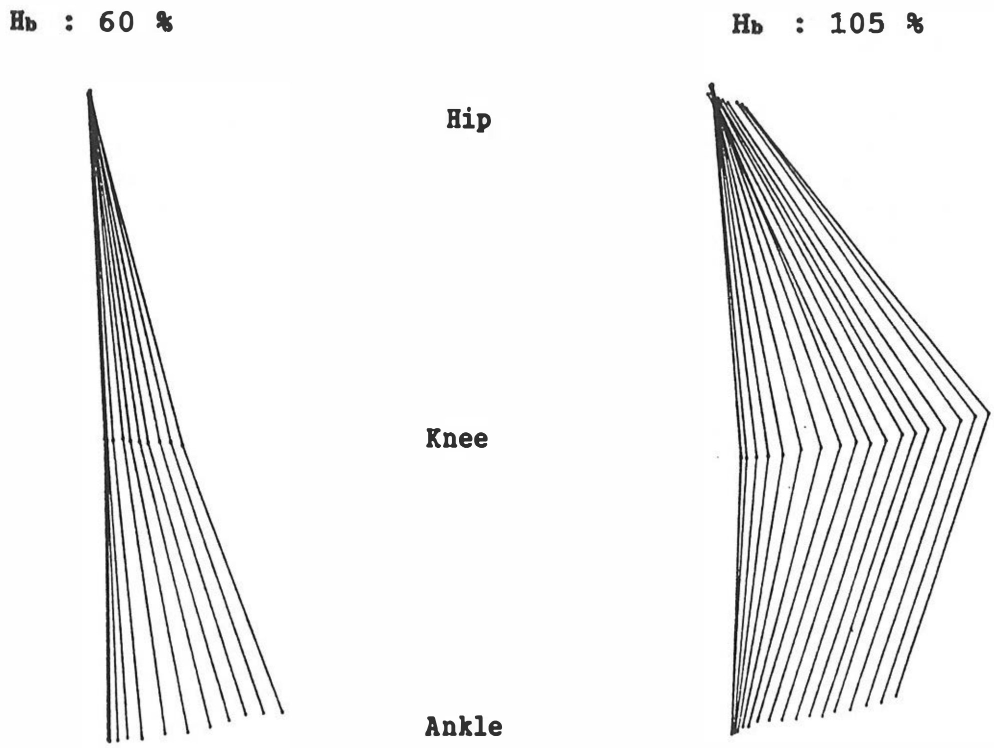
. Analysis of leg injuries sustained by cadavers is complicated ; the AIS scale is not detailed enough to describe precisely the severity of the injuries sustained. We have classified the injuries in two types : joint injuries and long bone (out of joints) injuries : the first one are more complex and may indice long term consequences, whereas generally those who sustained the second one recover completely. Only AIS 2 or more injuries are considered. AIS 1 ones are associated with the cases of no injury.

Table 3 contains the type of leg injuries. It is noticeable that there is no joint injury for bumper height equal to or below 75 % (380 mm). For higher bumper height there is always joint injuries except in one case. These findings can be related to knee bending : low bumper height corresponds to small leg bending and low risk of injury at knee level. Fig 3 gives two examples of leg deformations and associated injuries for two bumper heights at same impact speed. The impact speed is also related to injury severity. This is especially true when the impact speed gets up from 20 to 32 km/h, but there is no obvious difference between 32 and 39 km/h.

Impact speed (km/h) \ Bumper Height (%)	60	75	90	105	120
20	N.N	Y.N	N.Y	N.Y	N.Y
32	Y.N	Y.N	N.Y	Y.Y	N.Y
39	Y.N	Y.N	Y.Y	Y.N	

Y means AIS 2 or more injury
N means AIS 1 or less injury

Table 3 : Injury to long bones (first) or at knee level (second)



Impact Speed 32 km/h

FIGURE 3 : LEG DEFORMATIONS

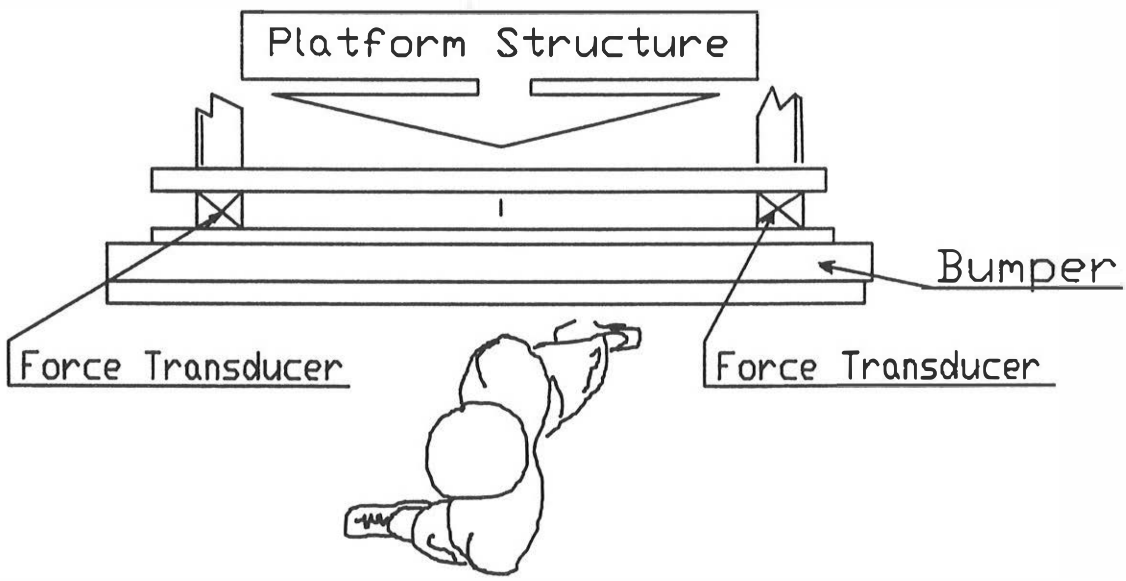


FIGURE 4 : FORCE MEASURING SYSTEM

PEDESTRIAN LEG LOADINGS

In all the tests the "bumper force" is recorded trough two force transducers located at the attachment of the bumper to the platform structure (see figure 4)

The typical shape of the bumper force trace is a two peaks one, as shown by figure 5. The first peak corresponds to the loading of the right leg, which is impacted first, whereas the second peak is related to the impact on the left leg.

The bumper force value is corrected taking into account the actual mass of each cadaver ; the corrected value corresponds to a 50 th percentile male (73 kg) assuming a linear relationship between impact force and total body mass.

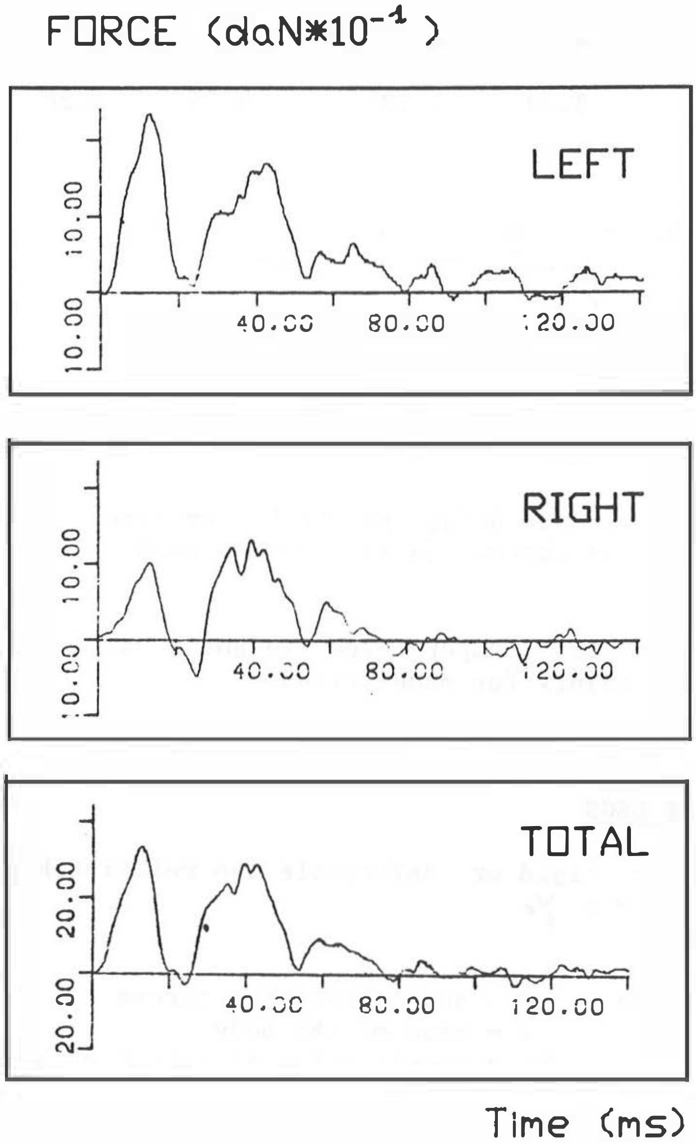


FIGURE 5 : EXAMPLE OF FORCE RECORDS ON BUMPERS

Table 4 contains the values of peak forces corrected to take into account the actual weight of each cadaver.

Bumper height (%) / Impact speed (km/h)	60	75	90	105	120
20	1.83	1.90	1.75	1.98	2.16
32	4.47	4.12	3.54	5.79	5.21
39	3.54	5.10	5.05	4.98	

Table 4 : Bumper peak force related to left leg impact (KN)

This table shows that the impact speed has a great influence on the value of the bumper force ; this is especially true when comparing the results of 20 km/h tests with those of 32 km/h tests ; however there is much less difference between 32 and 39 km/h tests.

The effect of the bumper height on the bumper force does not appear to be obvious : there is no change in the bumper peak force value when the bumper height varies.

This indicates that the bumper force is not a sufficient indicator to predict the risk of leg injury for pedestrians

EQUIVALENT MASS OF THE LEGS

For a body, either rigid or deformable the relationship between force and acceleration is : $F = m\,\gamma_c$

where : F = sum of external forces
m = mass of the body
γ_c = acceleration at center of gravity

after a double integration with initial conditions equal to zero, the previous equation becomes :

$$\int_0^t \int_0^t F(dt)^2 = m \int_0^t \int_0^t . \gamma_c (dt)^2 \qquad [1]$$

or :

$$\int_0^t \int_0^t F(dt)^2 = m.s\ (t) \qquad [2]$$

with s (t) = displacement of C.G at the time t. For each leg there is a specific force F_r and F_l which can be calculated from the forces recorded at the bumper attachement taking into account fig 6, and the equations for force and momentums equilibrium.

$$F_r = \frac{-x_1}{x_1 - x_2} R_1 + \frac{1 - x}{x_1 - x_2} R_2 \qquad [3]$$

and

$$F_l = \frac{x_1}{x_1 - x_2} R_1 - \frac{1 - x_1}{x_1 - x_2} R_2 \qquad [4]$$

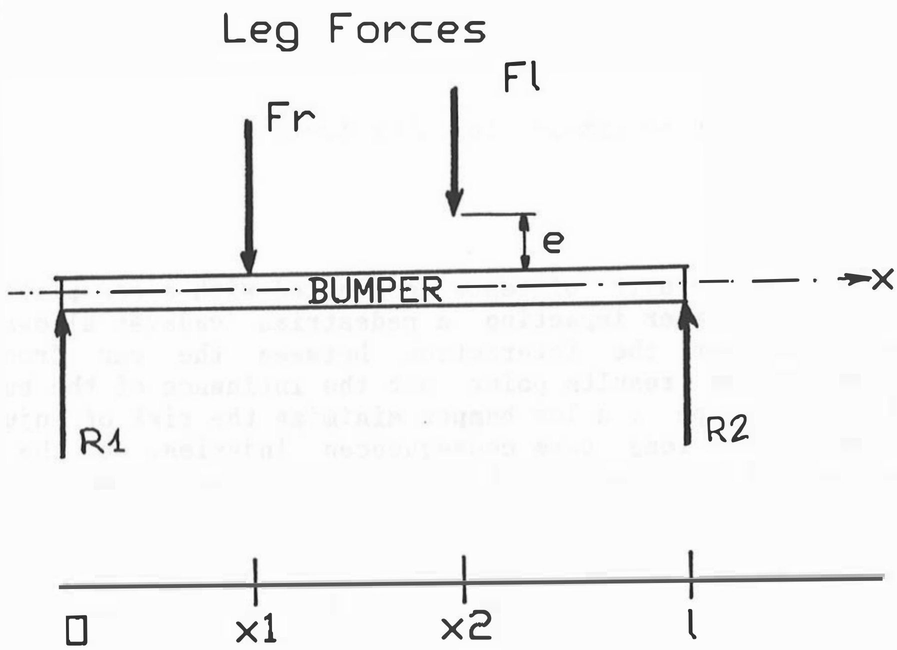


FIGURE 6 : PRINCIPLES OF FORCES EQUILIBRIUM

The parameters x_1 and x_2 are determined by the position of the contact point between the right leg and the bumper. x_1 can be measured before the impact, and the distance between the two legs at the level of the bumper allows to determine the value of x_2.

From equation [2]

$$m = \frac{\int_0^t \int_0^t F_1 \, (dt)^2}{s\,(t)} \qquad [5]$$

s (t) can be determined from the impact speed considering that during the leg contact, the car speed is constant, equal to the impact speed.

Application to tests :

Test n° 50 (impact speed : 5.833 m/s ; bumper height : 60 % of the knee level)

$s\,(t) = 1.167$ m at 200 ms

$\iint F \, (dt)^2 = 4.1\ N.s^2$ at 200 ms

$$m = \frac{4.1}{1.167} = 3.51 \text{ kg}$$

The same method can be applied to other tests

CONCLUSIONS

Analysis of the results of tests conducted with a car platform fitted with an adjustable bumper impacting a pedestrian cadaver allows to have a better understanding of the interaction between the car front and the pedestrian legs. These results point out the influence of the bumper height in terms of injury type : a low bumper minimize the risk of injuries at the knee joint, which are long term consequences injuries. On the apposite a bumper height as it is presently is correlated to knee ligaments ruptures or tears.

Analysis of bumper forces values shows that leg injuries can occur with a peak force as low as 2 KN ; it indicates also that the bumper force is not a sufficient parameter to predict the risk of injury, especially it does not distinguish the type of injury.

The method to determine the equivalent mass of the leg during the impact is applicable to the cadaver tests and this calculation allows to choose the mass of the leg model to be used in a pedestrian sub system test.

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