OPTIMIZATION OF PEDESTRIAN LEG INJURY PROTECTION USING A BIOFIDELIC HUMAN LEG

Dominique Cesari, François Bermond, Yves Caire, Robert Bouquet
INRETS, Institut National de Recherche sur les Transports et leur Sécurité
109, Avenue S. Allende, case 24, 69675 BRON cédex, FRANCE

ABSTRACT

Pedestrians sustain injuries to their legs very frequently. These injuries are related to contact with vehicle front ends and may have long term consequences. A deformable instrumented mechanical leg has been designed for protecting the risk of pedestrian leg injuries based upon injury tolerance parameters. This paper will discuss the biofidelity of the mechanical leg, its capability to estimate the risk of injuries relative to different mechanisms, and will show, with comparative tests, the possibility of the device to provide technical solutions to optimize pedestrian leg protection.

GENERAL CHARACTERISTICS OF PEDESTRIAN ACCIDENTS

Accident statistics show the importance of pedestrian injuries in traffic accidents. In accidents with passenger cars, pedestrian injuries occurring during the first phase of impact concern mainly the legs. The body then rotates onto the car bonnet, resulting in head impacts generally on or just below the windscreen. Injuries to the leg, and more especially to the knee, are generally not life-threatening but often have long term consequences with possible pennanent disability to mobility. Elderly pedestrians are overrepresented, and they are less likely to escape from the impact, even in low speed urban collisions (Appel et al, 1975 ; Lestrelin et al, 1985 ; Tharp and Ismgos, 1976 ; Danner et al, 1979). In high speed crashes, head injuries, often severe, predominante.

These observations were the basis for conducting research dealing with the response of the human knee hit form its side (Kazjer et al, 1990 ; 1993). These research studies provided a better understanding of knee response when loaded bending and shearing.

EVOLUTION OF INSTRUMENTED MECHANICAL LEG PROTOTYPES

The EEVC Working Group 10, in its first interim report (EEVC, 1990), discusses methods for the test to evaluate pedestrian protection : "Two main mechanisms may be involved in producing pedestrian leg injuries : bending moment and shearing force".

To assess protection of pedestrians against leg injuries, it is proposed to propel an instrumented mechanical leg against a car front face. This test device is composed of a leg (without foot) and a thigh. The knee consists of a short bar attached through a hinged joint to both components of the extremity. On each side of this bar, there is a deformable element to correctly reproduce the force/angle history. The angles between the thigh and the leg, and the knee bar are recorded through two potentiometers. Through such a design, the shearing force (Z type deformation of the knee joint) and the bending moment (V type deformation) can be determined.

Based on the results of cadaver tests, INRETS have designed an adult leg impactor that includes the knee and adjacent segments of the lower extremity. Besides measurement of angles, the leg is fitted with two accelerometers.

First Prototype

The first prototype (Cesari et al, 1991) was designed on the basis of a 50th percentile dummy leg. The top of the thigh was cut and the ball of the joint was replaced by an interface device aimed to sustain and control the posture of the leg during the motion before the impact. The external shape was similar to a human shape.

The main components are : a thigh, a leg, a foot. The flesh was moulded in polyurethane foam and the skeleton made with steel tubes and assembly steel parts. The ankle joint is very simple and stiff in the lateral direction.

The knee joint which is the most important point of the device is completely new. The tibia and the femur are symmetrically made of aluminium alloy parts. A link articulated at each component of the extremity by two parallel axes allows the relative displacement of the tibia and the femur in a vertical plane as measured by their angles. It is therefore possible to determine the deformations related to shearing and to bending.

Two deformable rods control the kinematics of the knee by their shape and material. They simulate the ligaments which tighten the knee and control its initial position.

Second Prototype

To have a better repeatability in the results, a second prototype of the leg was redesigned to be cylindrical. Drawings made used Computer Assisted Drawing which allows greater precision. The characteristics of this leg in terms of anthropometry were derived from Robbins et al (Robbins et al, SAE 831617, 1983). This facilitated the appropriate reproduction of mass and centre of gravity locations for both thigh and leg.

Two rotational potentiometers were located at the extremities of the link bar, to replace the original cam/optical transducers which were not linear and had durability problems. The leg accelerometers remain at the same location.

Reconsideration of the Flesh Characteristics

We have performed tests to characterise the dynamic response of human flesh in the area of the initial impact (external side of the leg below the knee). To reproduce as close as possible the damping effect of the human flesh, a high hysteresis polyurethane foam (called "comfort foam") was selected. To give a better durability, a 6 mm thick skin made of neoprene was placed over the flesh. It has been demonstrated that this skin does not affect the response of the leg.

Third Prototype

The second prototype had correct sizes, mass distribution and centre of gravity locations ; however the moment of inertia of thigh and leg were far too different from the human ones.

To change the values of moment of inertia, we had to modify several components at knee level, and at femur and tibia by changing the shape of the materials used in order to have a different density.

Evolution of Deformable Bars

The first tests were made using cylindrical rods made of aluminium alloy. These tests showed that they were too weak in bending. We therefore added spring steel wire in the middle to keep the deformation in the elastic mode for a larger time and also to be closer to human knee behaviour in bending. These rods proved to be too stiff in shearing.

Therefore, a new design was made in order to take into account specifications in both shearing and bending. A comparative analysis of different material helped us to select deformable elements made of heat treated carbon steel (XC 18).

However, when using these deformable elements they deform non symmetrically around knee axis which makes the interpretation of test results more complicated to separate deformations due to shearing from those due to bending. This absence of symmetry is due to a buckling effect on the compressed side of the deformable element.

To avoid this difficulty, the deformable elements were redesigned with a "double bridge" shape. The thigh and leg components are designed to deform by shearing whereas bending moment deformations are concentrated in the central part. The material remains the same as for the previous design.

Figure 1 shows the design of the new deformable elements. Static tests in pure bending and pure shearing have shown their capability to deform in a human like manner under controlled loading.

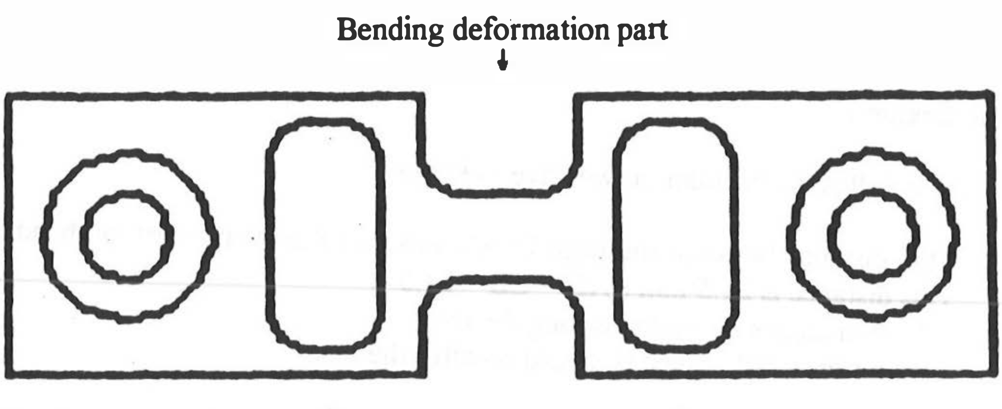
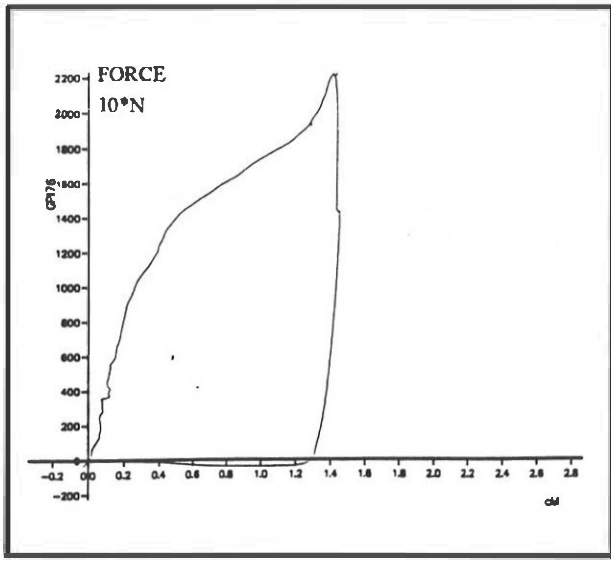


Figure 1 : New deformable elements.

Figure 2 and figure 3 are the records of force deformation (shearing) and moment deformation (bending) characteristics of the leg equipped with the new deformable components. It is interesting to notice that the bending trace is very similar to the human one, and even if these elements appear to be relativity stiff in shearing the have a human like response.



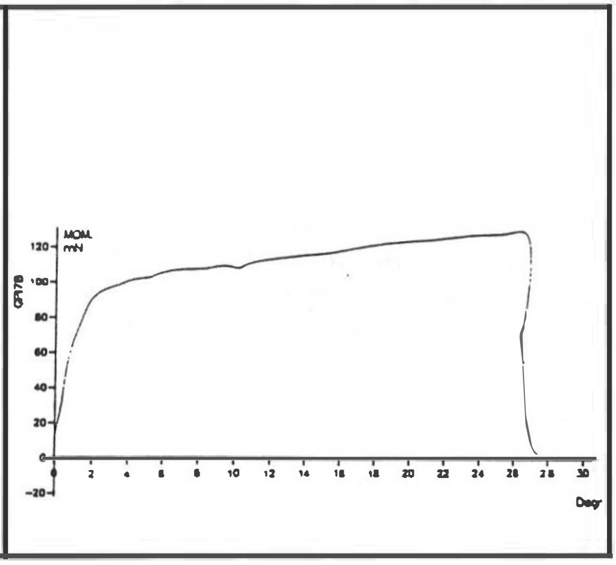


Figure 2 : Shearing static test result. **Figure 3 : Bending static test result.**

Calculation for bending and shear deflexion

M is the middle of the bend part [DC]. We admit that the bending of the ligament is like an arc of a circle. In that case, M is on the continuation of the segment [B1C1], and the translation is the orthogonal distance between [B1C1] and [B2C2] (Figure 4).

Bending :

$$d = a+b$$

Shear deflexion :

For the shear deflexion calculation, we have to know :

- the distance between the transducer's axis and the location of the bending moment. This distance is 21.5 mm (AD = CB = 21.5).
- the two angles measured during the test.
- the distance "c", which is measured after the test.

$$AB2 = 21.5 * (\cos a + \cos b) + c * \cos[\arcsin(21.5 * (\sin a - \sin b) / c)]$$
$$H = [35.5 - AB2 * \sin b / \sin(P-a-b)] * \sin(a+b)$$

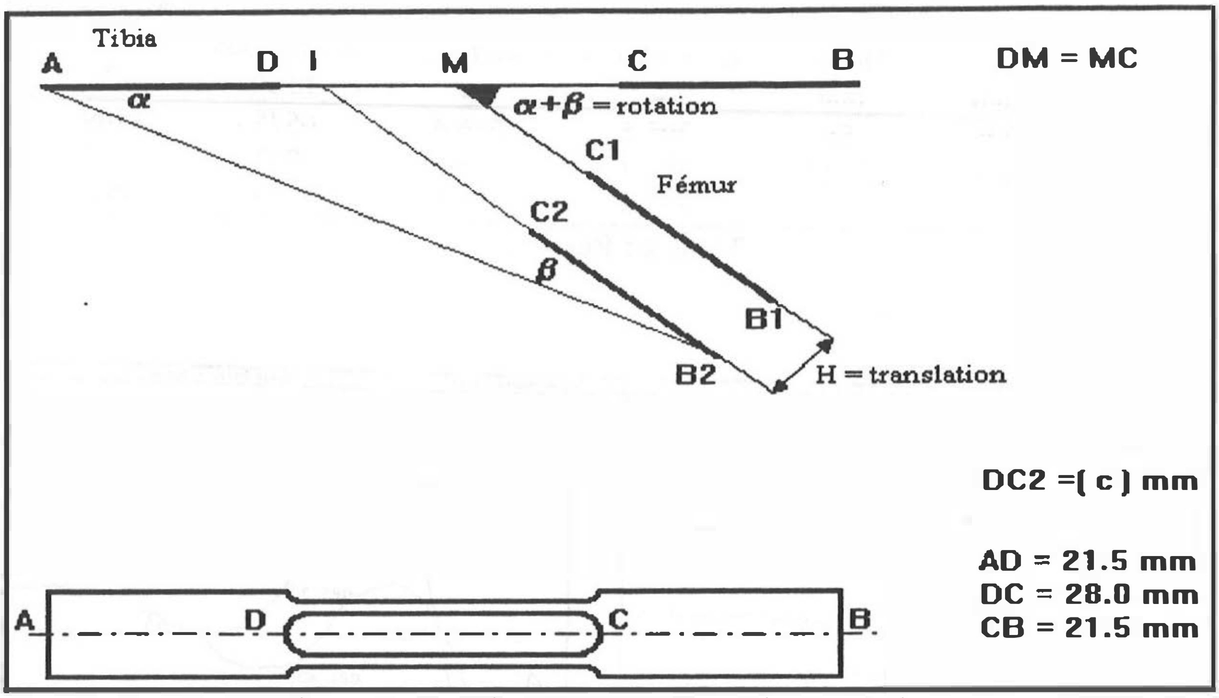


Figure 4 : Bending and shear deflexion analysis.

CAR TEST RESULTS

The mechanical leg has been used in several tests with different passenger cars. These tests did not show any important problems concerning the durability, the repeatability and the impact severity to input change of the mechanical leg.

It is important to check that the mechanical leg can take into account the variations in parameters which are directly related to the protection of pedestrians in car accidents.

It has been demonstrated (Cesari et al 1989) that the height above the ground of the initial contact is a parameter directly related to the risk of knee injuries. The most favorable situation is approximately 35 cm above the ground.

To check if the mechanical leg response is directly related to the bumper height, tests using the same car were performed at three bumper heights : normal, 44 mm and 88 mm below normal position.

Tables 1 and 2, and figures 5 and 6 give the results of three tests made with the same medium size mass-production vehicle for the three bumper heights.

Test N°	Speed Km/h	Bumper Height mm	Tibia Max. angle degree	Femur Max. angle degree	Bending angle degree	Shearing displ. mm
GPI 45	33.8	St	32.3	5.3	37.9	16.1
GPI 39	34.0	St-44	21.9	2.74	24.6	11.7
GPI 40	34.4	St-88	12.5	0.19	12.6	7.7

Table 1 : Results.

Test	Speed	Bumper Height	Tibia Upper acc. x	Tibia Lower acc. x	Angular acceleration	Moment
N°	Km/h	mm	g	g	rd/s²	mN
GPI 45	33.8	St	295.4	216.4	6575	1709
GPI 39	34.0	St-44	292.7	245.2	3993	1038
GPI 40	34.4	St-88	292.0	301.9	1733	451

Table 2 : Results.

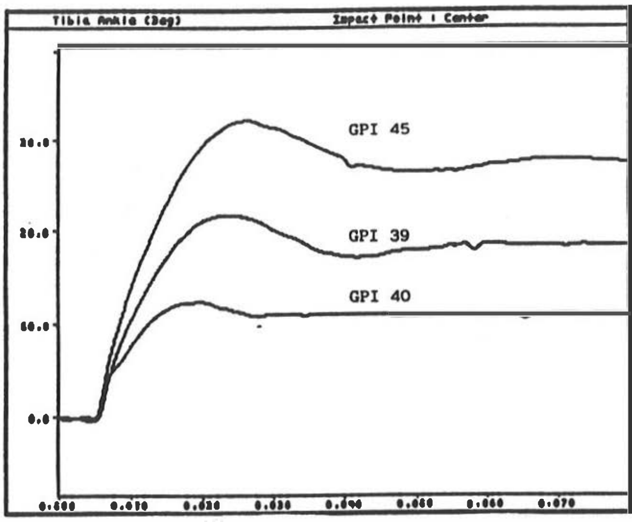


Figure 5 : Results.

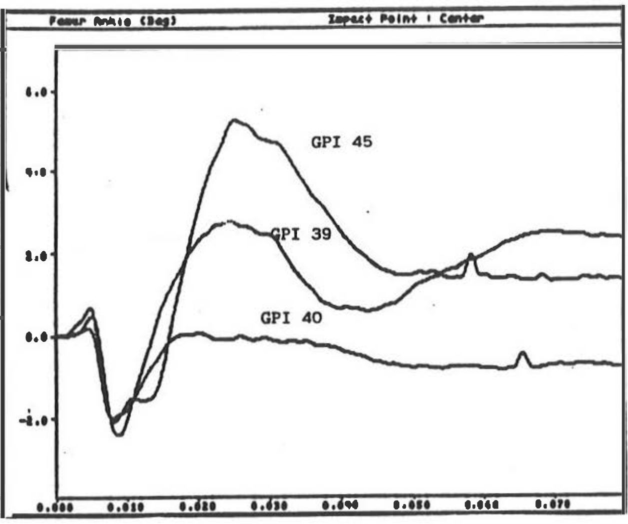


Figure 6 : Results.

These results show clearly that bending angle and shearing displacement are decreased when the bumper is lowered. The ratios between lowest and normal positions are respectively 1 to 3 and 1 to 2, and for the lowest bumper position, the maximum bending angle remains below, although not substantially, the proposed limit of 6 mm, but the car tested did not include any modification aimed to improve pedestrian protection.

The bumper tibia acceleration is in the same order of magnitude for the three tests. However, the tibia angular acceleration and bending moment decrease when the bumper is lowered. If we accept that the risk of bone fracture is directly related to the value of bending moment at impact point, the proximal tibia acceleration is then not sufficient to predict the risk of tibia fracture.

The response of the mechanical leg has to take into account the stiffness of the impacted area. To check its sensitivity to stiffness of the impact site, two tests were performed on the same car, the first one in the middle of the bumper (deformable area far from the attachment), and the second one in front of the bumper fixation which is a much stiffer area.

Test results as indicated in tables 3 and 4 and figures 7 and 8 show a great difference compared to the bumper centre test. Tests in front of the fixation give increased injury related parameter values between 60 % to 150 % ; the response of the mechanical leg is clearly sensitive to the change of the impacted area stiffness.

Test N°	Speed Km/h	Bumper Height mm	Tibia Max. angle degree	Femur Max. angle degree	Bending angle degree	Shearing displ. mm
GPI 49	33.9	St	10.2	5.80	16.0	3.5
GPI 51	33.7	St	25.9	14.2	40.4	7.1

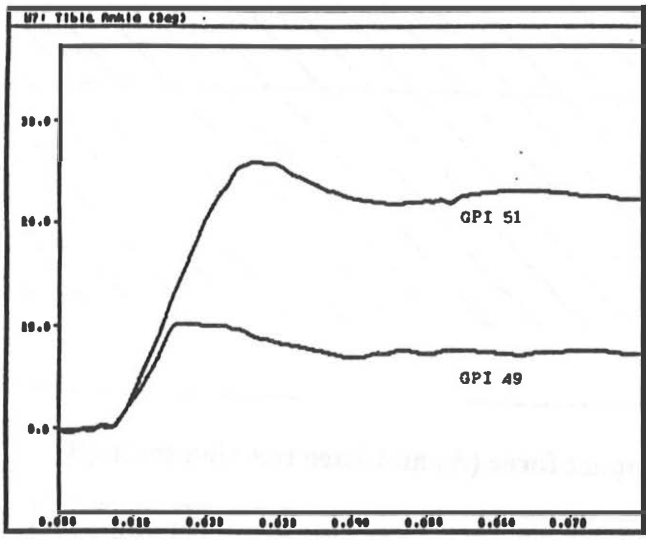
GPI 49 : bumper centre test
GPI 51 : bumper fixation test

Table 3 : Results.

Test N°	Speed Km/h	Bumper Height mm	Tibia Upper acc. x g	Tibia Lower acc. x g	Angular acceleration rd/s²	Moment mN
GPI 49	33.9	St	166.8	184.6	2809	730
GPI 51	33.7	St	262.3	312.7	6101	1586

GPI 49 : bumper centre test
GPI 51 : bumper fixation test

Table 4 : Results.



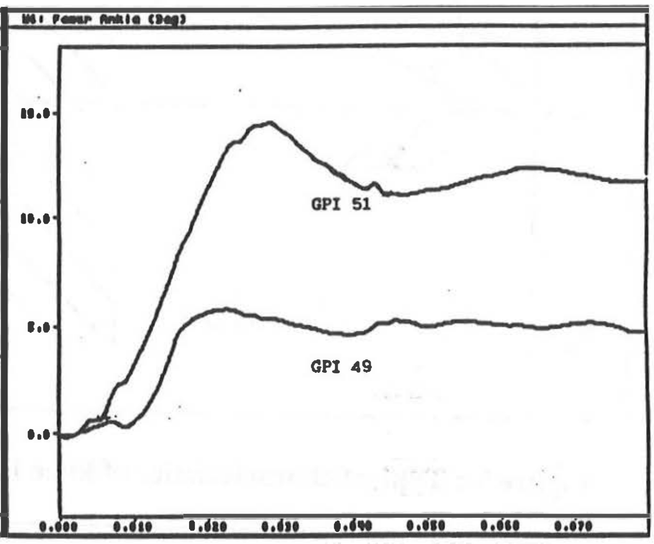


Figure 7 : Results. **Figure 8 : Results.**

COMPARISON OF BEHAVIOUR BETWEEN LEG AND MECHANICAL LEGS

Two main mechanisms can be involved when a knee injury occurs in a pedestrian accident : bending between thigh and leg, and shearing at knee level.

The mechanical leg is aimed to be able to predict the risk of injuries corresponding to these two mechanisms. The two rotational transducers determine at every moment the relative position of the thigh and the leg, and the deformations due to shearing and to bending. The use of displacement transducers (instead of force transducers) makes the prediction of injury occurrence more accurate, especially in bending where the effect of the duration of force application is more important and the deformation, and consequently the risk of injury, can increase without any change in force value.

The effects of shearing and bending on a human leg hit from the external side were analysed through series of cadaver impact tests at different speeds (around 20 and 25 km/h for each mechanism).
These tests have provided information concerning the timing of injury production, the type of injuries produced and the level at which they occur.

Figure 9 shows a typical force/time history in a shearing test. According to the analysis of these results, it is assumed that the injury occurs very soon after the initial contact. The maximum of bending moment and deformation, on the contrary, occurs much later (see figure 10).

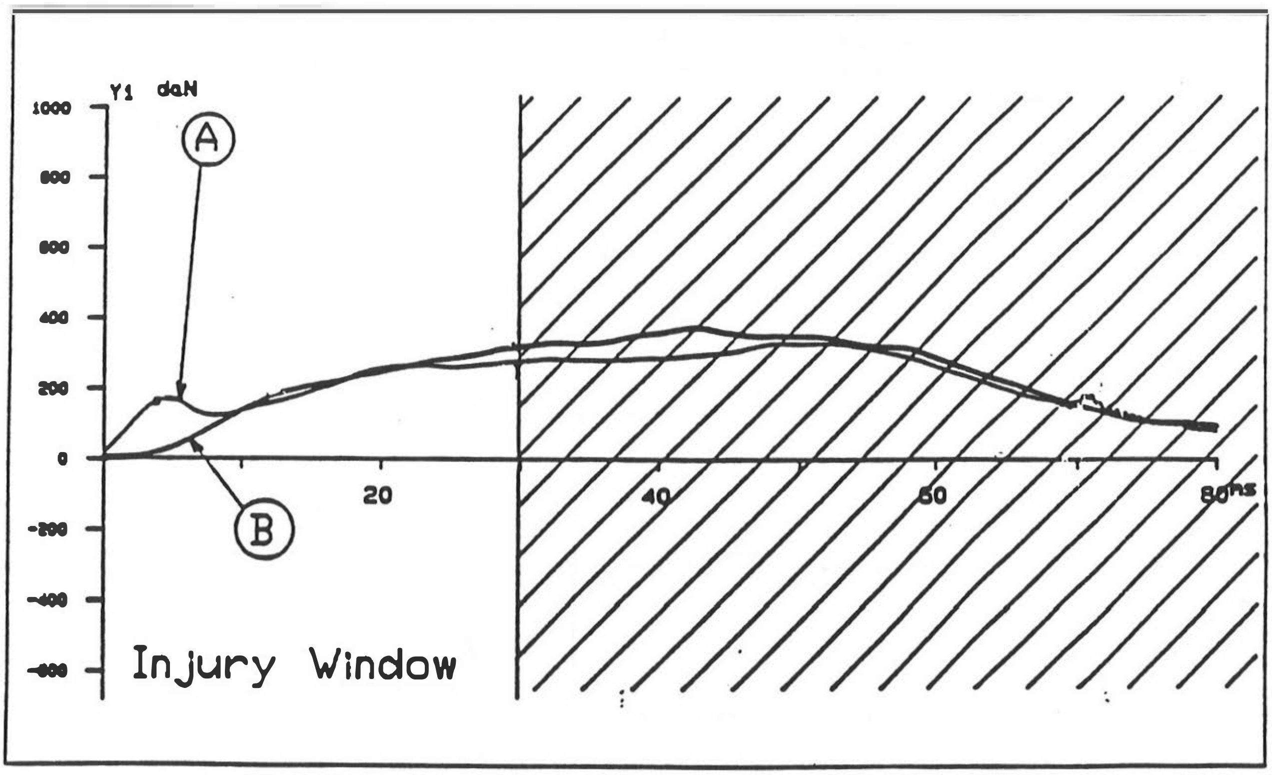


Figure 9 : Typical characteristics of knee impact force (A) and knee reaction force (B).

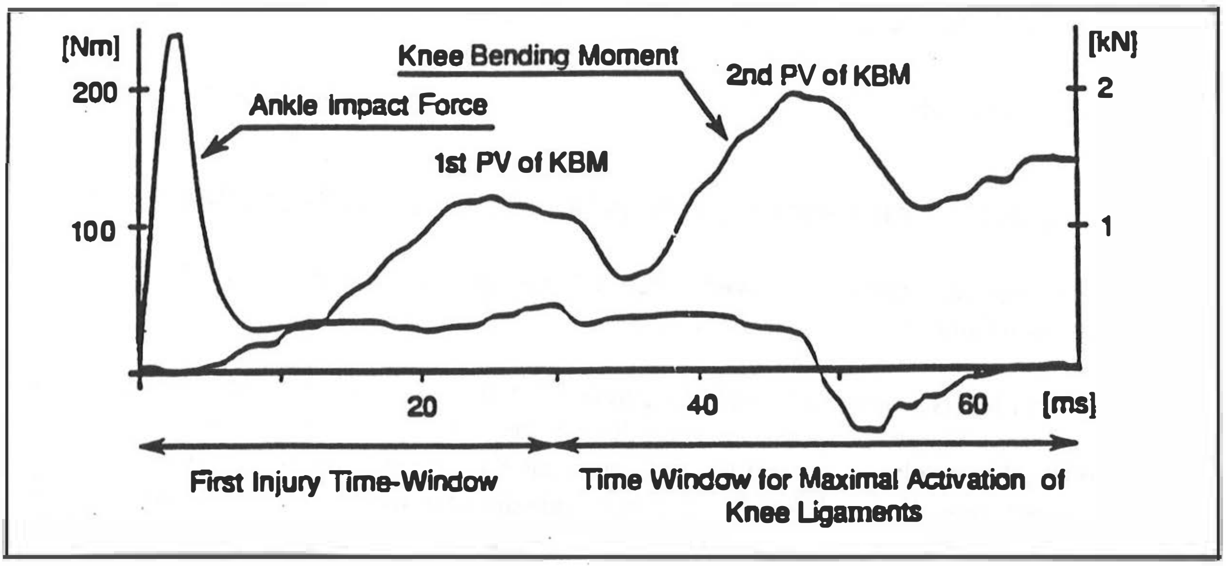
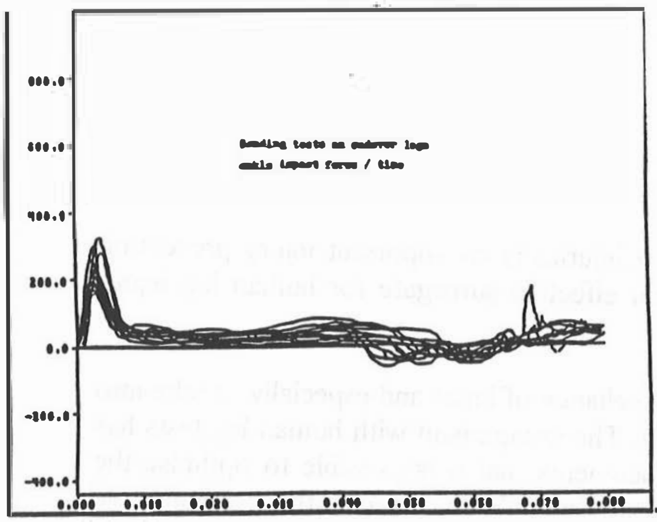


Figure 10 : Knee bending moment versus time from a typical test (20 Km/h).

These tests were duplicated using the mechanical leg and the results are indicated in figure 11 and 12.



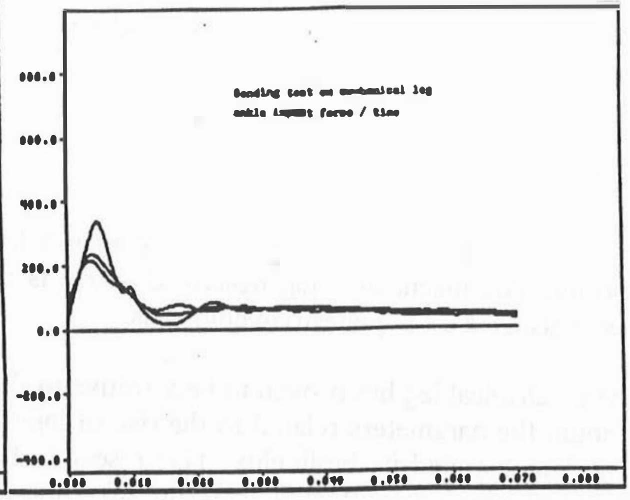
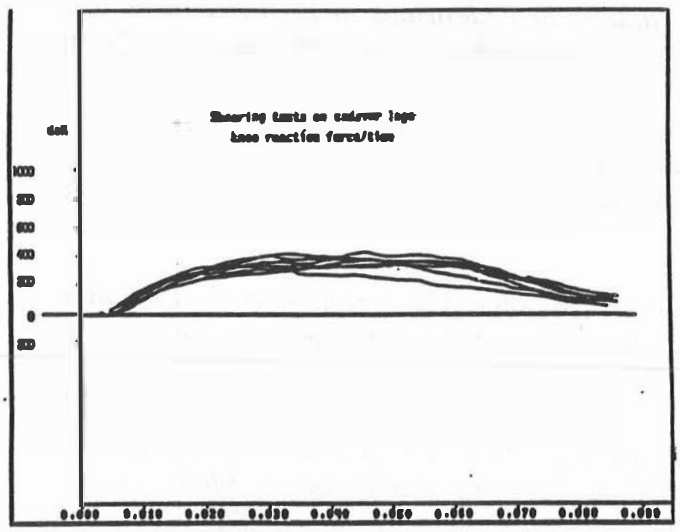


Figure 11 : Results. **Figure 12 : Results.**

Considering bending tests, comparison of figure 11 and 12 shows thar the force/time histories are very similar to those of the tests performed with a human leg. The initial peak is in the same order of magnitude for both models, and the plateau corresponding to tests with the mechanical leg is within the envelope of the values reached with the human leg, but closer to the upper limit. However, cadavers usually represent an older population with a corresponding lower tolerance and lower mass.

The mechanical leg shearing tests give results similar but with some differences in comparison with human leg tests (see figure 13 and 14).



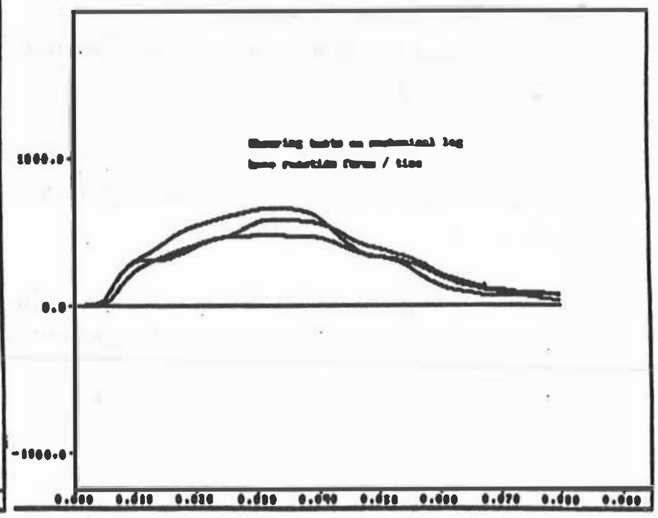


Figure 13 : Results. **Figure 14 : Results.**

Considering the knee impact force, the mechanical leg tests are associated with an initial peak which is much higher than in tests with the human leg. The knee reaction force/time histories have similar shapes for the two models, but the maximum is higher with the mechanical leg. Again because the population tested is older than the population at risk, the true difference is certainly less.

CONCLUSIONS

The protection of pedestrians especially against leg injuries is an important injury prevention priority. The mechanical leg described above is an effective surrogate for human leg injury mechanisms in a car-pedestrian collisions.

The mechanical leg has proved to be sensitive to the change of input and especially to take into account the parameters related to the risk of injury. The comparison with human leg tests has also demonstrated its biofidelity. This research documents that it is possible to optimise the design of the car front ends in terms of shape and materials to improve the protection of pedestrians against leg injuries.

REFERENCES

Appel H., Stürtz G., Gotzen L., *Influence of impact speed and vehicule parameteron injuries of children and adults in pedestrian accidents.* Proceeding of the 1975 international IRCOBI conference.

Cesari D., Cavallero C., Roche H., *Mechanisms producing lower extremity injuries in pedestrian accident situations.* Proceeding of the 33rd AAAM conference (1989).

Cesari D., Alonzo F., Matyjewski M., *Subsystem test for pedestrian lower leg and knee protection.* Proceeding of the 10th International Technical Conference on Experimental Safety Vehicles. (1991)

Danner M., Langwieder K., Wachter W., *Injuries to Pedestrians in Real Accidents and their Relation to Collision and Car Characteristics.* Proceeding of the 23th Stapp Car Crash Conference (1979).

Kajzer J., Cavallero C., Ghanouchi S., Bonnoit J., Ghorbel A., *Response of the knee joint in lateral impact : effect of shearing loads.* Proceeding of the 1990 international IRCOBI conference.

Kajzer J., Cavallero C., Bonnoit J., Morjane A., Ghanouchi S., *Response of the knee joint in lateral impact : effect of bending moment.* Proceeding of the 1993 international IRCOBI conference.

Lestrelin D., Brun-Cassan F., Fayon A., Tarriere C., *Vehicle Pedestrian Head Impact: A Computer Method for Rating a Profile Without Previous Mathematical Modelisations.* Proceeding of the 10th International Technical Conference on Experimental Safety Vehicles (1985).

Robbins D.H., Schneider L.W., Snyder R.G., Pflug M., Haffner M., *Seated posture of vehicle occupants.* Proceedings of the 27th Stapp conference (1983), 831617.

Tharp K.J., Tsongos N.G., *Injuriy Severity Factors - Traffic Pedestrian Collisions.* Proceeding of the 1976 international IRCOBI conference.