# MATHEMATICAL SIMULATION
# OF THE PEDESTRIAN LEG IN LATERAL IMPACT

F.BERMOND[*], D.CESARI[*], F.ALONZO[*], M. MATYJEWSKI[**]

[*] INRETS 109 avenue Salvador Allende case 24 69675 BRON cédex FRANCE
[**] WARSAW UNIVERSITY OF TECHNOLOGY Nowowiejska 22/24. 00-665 WARSAW POLAND

## Abstract

*A mathematical dynamic model of the pedestrian leg in lateral impact was developed with the two dimensional MADYMO (TNO) computer programs. This model will be used to test car fronts in order to estimate the severity of knee joint lesions and to predict the risk of leg injuries in car/pedestrian accidents. The effect of the bumper and the grill stiffness, of the bumper height and of the position and the value of the mass representing the upper body will be evaluated.*

*Results of this model were compared with those obtained with an instrumented mechanical leg used in the bumper impact test. This mechanical leg was developed by INRETS for a joint program involving several European research institutes, sponsored by the European Communities to evaluate the protection offered by a car in a pedestrian collision. The model was improved until it minimizes the difference in the results of these two approaches.*

## Statistical analyses for pedestrian accidents

Pedestrians are not protected when they are crossing a street and are impacted by vehicles. The number of people injured in Europe, USA and Japan decreased from 33,000 in 1970 to 18,000 in 1986 (1) (fig.1). Since then, this number seems to be steady, especially in Japan (2). Figure 2 shows that the number of pedestrians killed as compared to the total number of road-related deaths in 1986 ranges from 15% in the USA to 28% in Japan. In Japan, this percentage is very high and the number of pedestrians and vehicle occupants killed is very similar, respectively 3,000 and 4,000 (3).

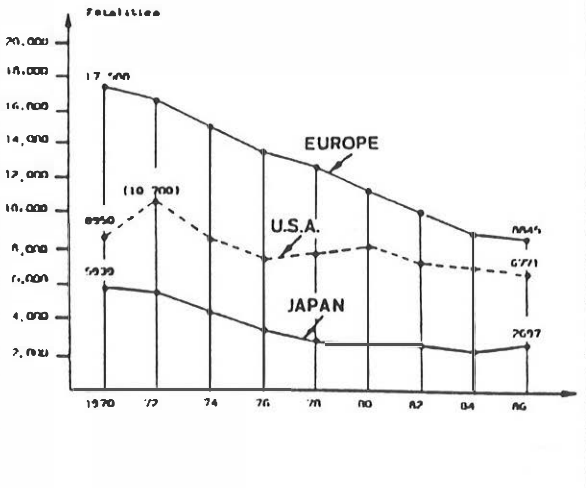

Figure. 1 : Evolution of the number of pedestrian fatalities in Europe, U.S.A. and Japan, between 1970 and 1986 (1).

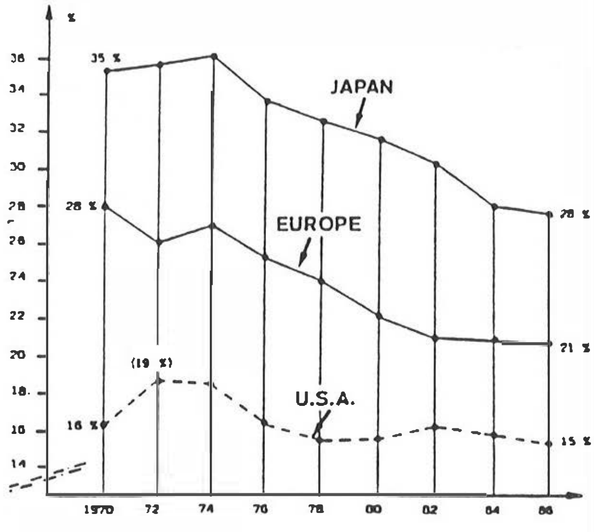

Figure 2 : Evolution (in %) of the proportion of pedestrians killed among all road fatalities in Japan, Europe and U.S.A., between 1970 and 1986 (1).

Two main age groups are significantly represented in Europe (1) :
- children under 16 whose percentage as compared to the number of pedestrians killed decreased from 21% in 1976 to 15% in 1986,
- adults over 64 whose percentage increased from 13% to 14% for the same period.

Recent statistical data are not available from other countries - such as developing countries.
Despite a reduction in the number of pedestrians killed, their number remains very high. This is the reason why pedestrian protection is the subject of a great number of research studies.

**Analysis of injury types for impacted pedestrians**
Injuries caused by the vehicle are especially attributable to the bumper or the bonnet leading edge striking the lower body region, while injuries to the head result from impacts onto the bonnet or the windscreen.

An analysis of different injuries in impacted pedestrians showed (fig.3) the significant number of leg injuries (4), ranging from 65% to 80%. All these injuries were not fatal, but they led to very severe disabilities and impairments, generally for a long duration. In some cases, they demonstrated an irreversible character, especially when the speed of the vehicle involved was higher than 30 km/h. The main injuries observed in adults (5) relate to bone segment fractures, femur-tibia or fibula, articular troubles especially at the knee ligament level and soft tissues of the whole leg. In children (6), numerous fractures of long bones, especially the femur, can be observed.

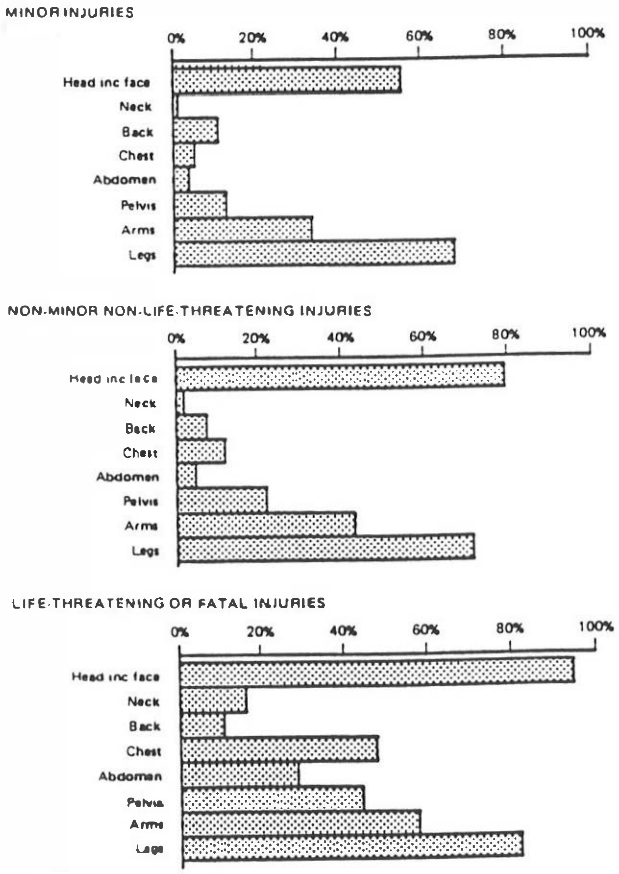

**Figure 3 : Pattern of Injury by overall injury severity for 568 pedestrians with minor injuries, 739 pedestrians with non-minor non-life-threatening injuries and 253 pedestrians with life-threatening or fatal injuries-frontal contacts, all Injuries counted (4).**

**Description of the accident**
The shape of a car front has an influence on the pedestrian kinematics, not only on its trajectory but also on the velocity of each body segment. The kinematics of a pedestrian is a major factor in determining the occurrence of contacts between the different body segments of a pedestrian and areas of a vehicle, or the ground and also the impact velocity of these contacts (7).

The shape of a vehicle front is therefore important because it can influence the location, occurrence and severity of impacts to different body segments against a vehicle and the ground (8).

**Majority crash simulation**
There are many methods of pedestrian accident simulation :

- Full-scale tests in which a vehicle hits a dummy (9) or a cadaver.
- Rig tests in which an impactor simulating a segment of human body hits a chosen area of a vehicle (10) or an impactor simulating a chosen area of a vehicle hits a segment of human body (11).
- Subsystem test methods to evaluate pedestrian protection (12).
- Mathematical modelling of a vehicle hitting a pedestrian (13-14).

**Methodology**
The analysis proposed is the one selected within the framework of a joint program carried out by several European research institutes, and supported by the European Economic Community. It consists in classifying the problems and entrusting each laboratory equipped with the appropriate means with the mission of studying and creating a system aimed at assessing the aggressiveness level of the different vehicle parts which are likely to impact the corresponding body segment of the impacted pedestrian.

Thus, from the beginning of the year 1990, the Laboratory of Impacts and Biomechanics of INRETS, in Bron, has been entrusted with the study and the development of:

- a leg provided with a biofidelic knee joint, at least as regards to global behaviour and stiffness under lateral loads which integrates high performance measurement systems and is able to transmit, for all the impact duration, the variation of kinematic parameters (angles, translations, accelerations, forces, etc...),
- a propulsion system allowing the reproduction of the leg impact on the front part of the vehicles tested,
- techniques, methods and calculation means enabling the acquisition, processing and interpretation of the parameters specific to such a research (15).

A mathematical modelling of a pedestrian leg has been elaborated and optimized by comparing the results with those obtained with the instrumented mechanical leg in order to reproduce the car pedestrian impact conditions and to assess the effects of bumper heigth and stiffness, of the position and the value of the mass representing the upper part of the body.

**Design and specifications of the leg/bumper subsystem**
Taking into account the results of accident analysis and pedestrian biomechanical research, the following specifications were selected :

- Articulated mechanical leg.
- Free motion during the impact.
- Humanlike mass distribution between lower leg and thigh.
- Adult leg simulation.
- Biofidelic force/angle relationship for the knee.
- Measurement of bending and shearing deformation at the knee level.
- Measurement of lower leg acceleration.

A special knee joint was designed in order to correctly reproduce the mechanisms producing knee injuries, (fig. 4). This knee is symmetrical in the horizontal and vertical planes.

It consists of two main parts connected to the femur and the tibia respectively. Two deformable bars reproduce the biofidelic force/angle history. These square section bars are made of aluminium with a 6 mm diameter steel rod inside. This enables to record the slope of the force/angle history even in the permanent deformation zone of aluminium. The continuity between the thigh and the lower leg is ensured by a rigid link articulated at each extremity.

For the test the mechanical leg is propelled by a small sled which is stopped just before the impact, and then the leg continues in a free motion. In fact during the free travel, because of the gravity effect, the mechanical leg moves also slightly down, but this can be accurately predicted by kinematic theory.

The model developed corresponds to an adult leg. The knee with the double articulation is also equipped with two identical deformation transducers. Each transducer measures the angle between the link and one of the two main extremities of the leg. Adding these two angles gives the variation in the angle between the thigh and lower leg. If the two angles have different values, this indicates that a shearing process was involved simultaneously with bending, as indicated in figure 5.

The measurement of the knee deformation enables the prediction of injuries in the knee area only. To check the protection provided against long bone fractures it is proposed to use the peak acceleration measured at the upper extremity of the tibia, which is directly related to the impact force caused by the bumper.

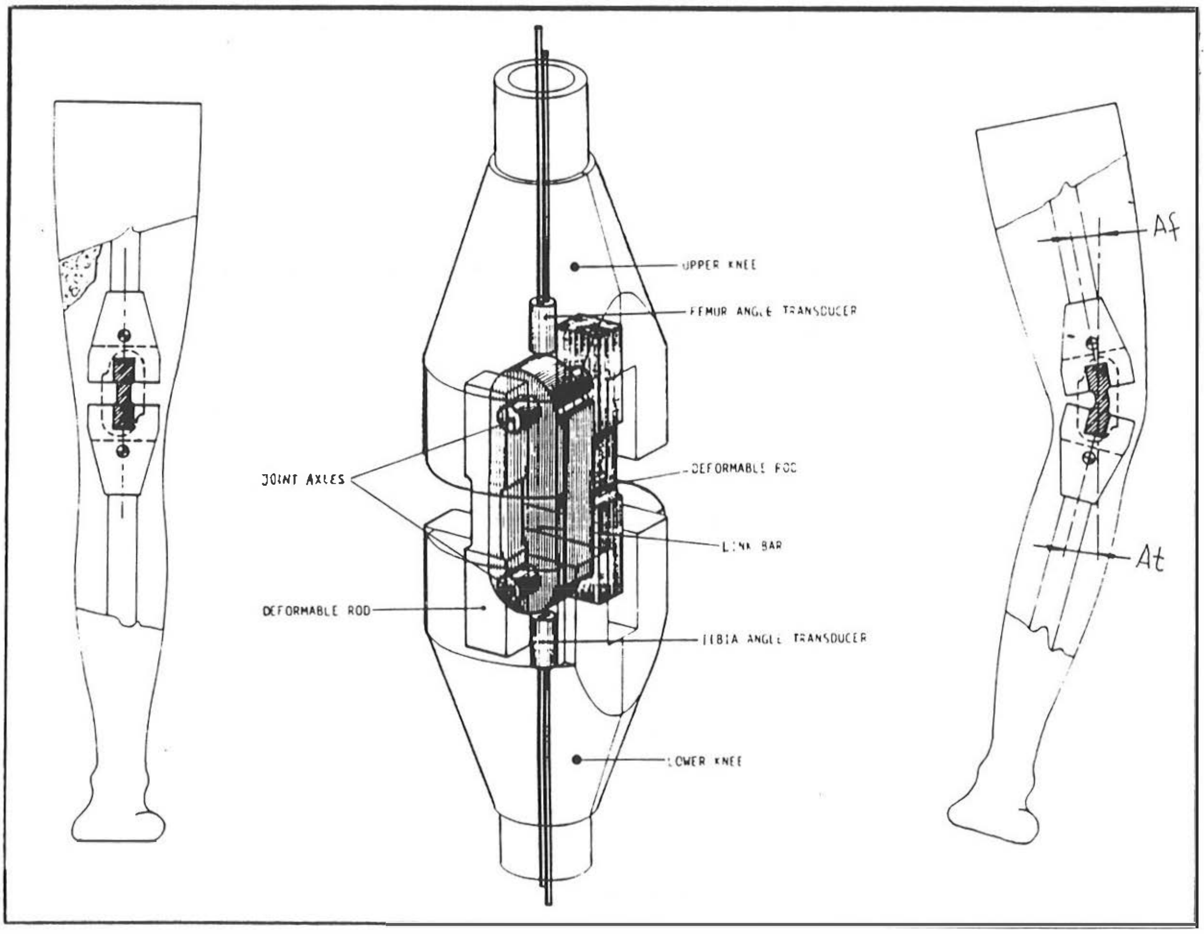

**Figure 4 : Principle of the pedestrian knee model (15).**

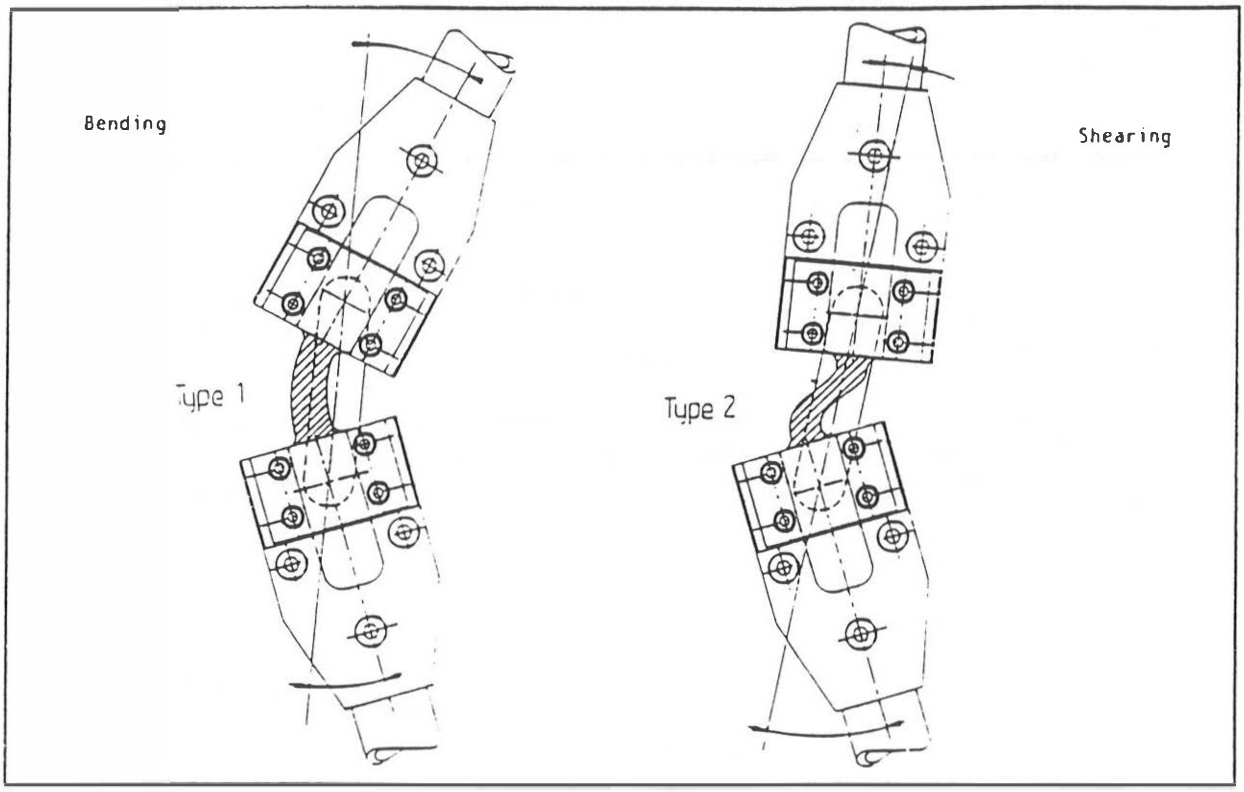

Figure 5 : Deformation process of the mechanical knee (15).

## Protection criteria

To verify the risk of leg injury in car/pedestrian impacts, three protection criteria should be used. The biomechanical data necessary to establish such parameter values are limited and the proposed values have to be confirmed :

- Limit of angle variation between the thigh and the lower leg : 15°. This is based on cadaver tests (16).
- Limit of shearing displacement between the upper tibia and lower femur extremities. There are few biomechanical data dealing with leg tolerance to shearing load. Based on the results of 20 cadaver tests, a limit of 5 mm corresponding to 3 kN is proposed (11).
- Limit of upper tibia longitudinal acceleration (car reference) : 150 g, based on available biomechanical test results.

## Mechanical leg properties

Table 1 gives the main mechanical leg properties that were measured during dynamic tests.

| | Weight Kg | Length m | Distance * CG/KJC m | Inertia Kg m*m |
|---|---|---|---|---|
| Upper leg | 8.7 | 0.42 | 0.218 | 0.079 |
| Knee | 0.35 | 0.09 | | 0.00026 |
| Lower leg | 3.7 | 0.41 | 0.17 | 0.045 |
| Foot | 1.02 | 0.1 | 0.43 | 0.0008 |

Table 1 : Mechanical leg properties.
* CG : Center of gravity ; KJC : Knee Joint Center.

**Leg mathematical model**

The software used is the 4.3 version of the two-dimensional Madymo program (17). The leg description is made by associating ellipses representing the mechanical leg such as the thigh, the knee (in fact the flexible beam in the knee joint), the lower part of the leg and the foot, linked by connecting elements (figure 6). For each component, we used the same properties as the mechanical leg (Weight, lenght, Distance center of gravity and the knee joint center and inertia).

We have measured the stiffness of the flexible beam in bending and shearing and the results obtained were used to define the stiffness of the joint between the knee/upper leg and the knee/lower leg.

To describe the car, we use the data available from Madymo databases (18) (for example the stiffness of bumper, grill and hood). So, the front part of the vehicle is represented by one ellipse for the bumper and one for the grill and a plane for the hood.

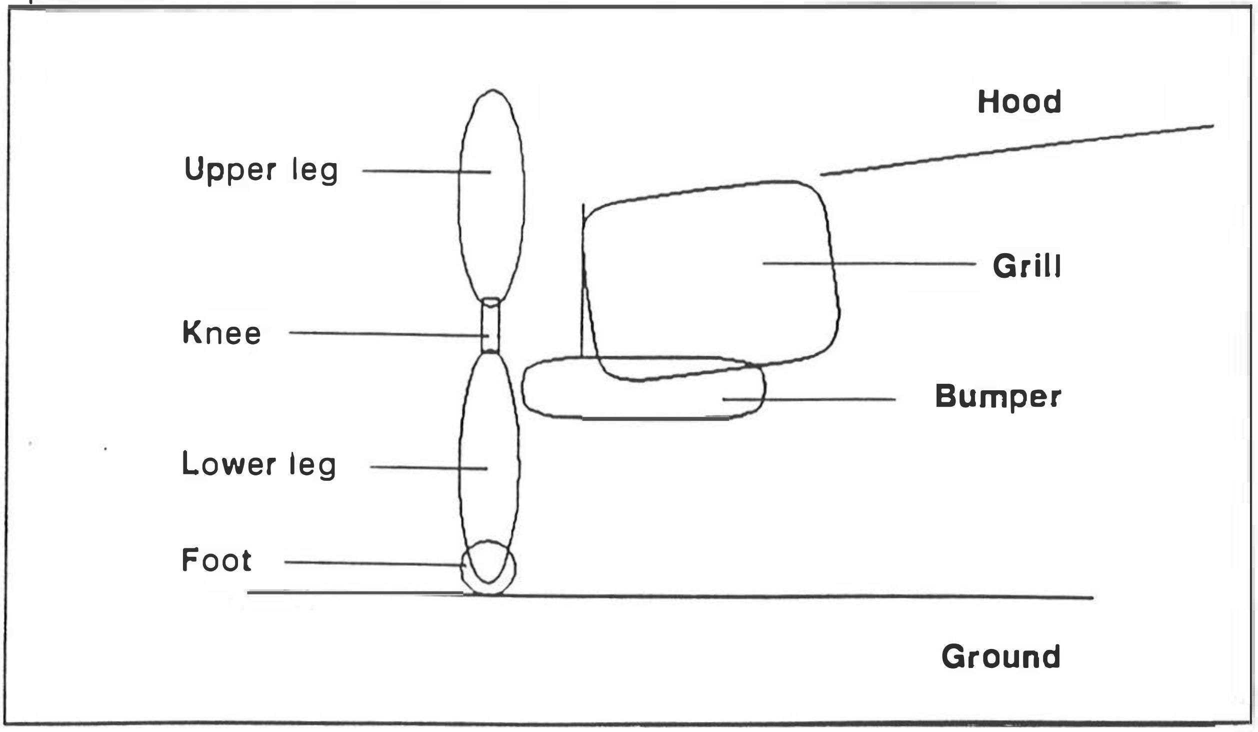

Figure 6 : The leg model with the front part of the vehicle.

We thus obtained a global kinematics of the leg impacted by the front part of a vehicle, acceleration curves of the tibia, femur and knee, force resultants at the leg/bumper contact level, tables of maximum and minimum angle values between two components, e.g the upper and lower parts of the leg.

Under experimental conditions of the instrumented mechanical leg, modelling parameters have been optimized in order to obtain results in accordance with the tests performed. The seven leg subsystem tests were performed with an impact velocity ranging between 30 and 32 kph (Table 2).

During each test we have measured the angles between the knee link and the tibia and the femur, and the upper tibia acceleration in the direction of impact. A high speed video camera was also used. Seven tests were performed. The vertical distance between the knee and the bumper varied from -0.03 to 0.2 metres.

There is no ground friction in this model. Some additional Madymo simulations were made to confirm that ground friction has little influence on the knee joint angle. The reversal of the actual movements (car standing, leg moving) does not change the results significantly.

| Test n° | Impact Speed km/h | * Vertical Offset (m) |
|---|---|---|
| GPI 01 | 29.24 | +0.065 |
| GPI 03 | 31.9 | +0.090 |
| GPI 04 | 31.9 | 0.000 |
| GPI 05 | 28.9 | -0.030 |
| GPI 07 | 29.5 | +0.020 |
| GPI 08 | 29.6 | +0.100 |
| GPI 09 | 29.64 | +0.195 |

**Table 2 : Mechanical leg test conditions.**

* Vertical Offset : Vertical distance between knee and bumper at impact.

The parameters to determine contact-interaction between the different parts of the leg and the car front are the main parameters which were tuned.

**Results**

We present the results when the vertical distance between the knee and the bumper is -0.200 metre.

Figure 7 illustrates kinematics after impact. The vehicle speed is 30 kph and the bumper is striking the lower leg during the first 20 ms and after, the grill hits the knee and the bonnet hits the upper leg.

Figure 8 shows the acceleration curves for the lower leg (tibia), the upper leg (femur) and the knee (center of gravity) as a function of the first 40 ms. The resultant force from the lower leg against the bumper is also presented. The highest acceleration values are located around 15 ms which correspond to the time of impact between the bumper and the lower leg. The values between the knee and the grill and between the upper leg and the hood located around the 28 ms are lower.

We present results for seven vertical distances between the knee and the bumper : -0.200 ; -0.100 ; -0.035 ; 0 ; 0.035 ; 0.100 ; 0.200 metre.

Table 3 gives the maximum values of knee acceleration and leg/knee contact forces. The knee acceleration is the most important when the bumper hits the knee. The leg/knee contact force is the most important when the bumper hits the upper leg.

Table 4 illustrates the maximum torques at the joint levels, upper leg/knee and knee/lower leg. Table 5 presents the maximum and minimum values for relative angles between the knee and the upper or lower leg. The values are directly dependent on the vertical distance between the knee and the bumper. The smaller this distance is, the higher the results are.

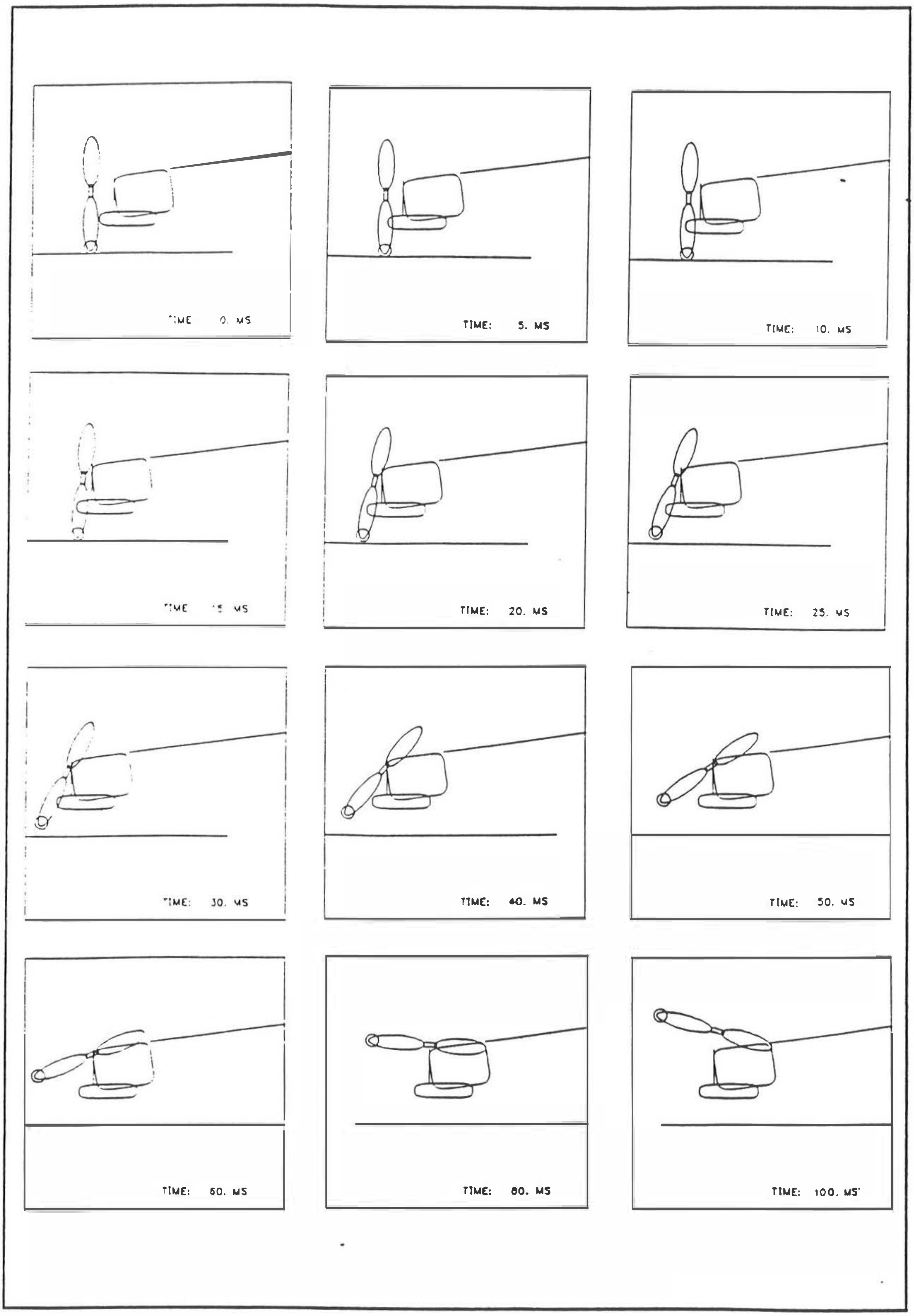

**Figure 7 : Movement of the leg, vertical offset -0.2 metre.**

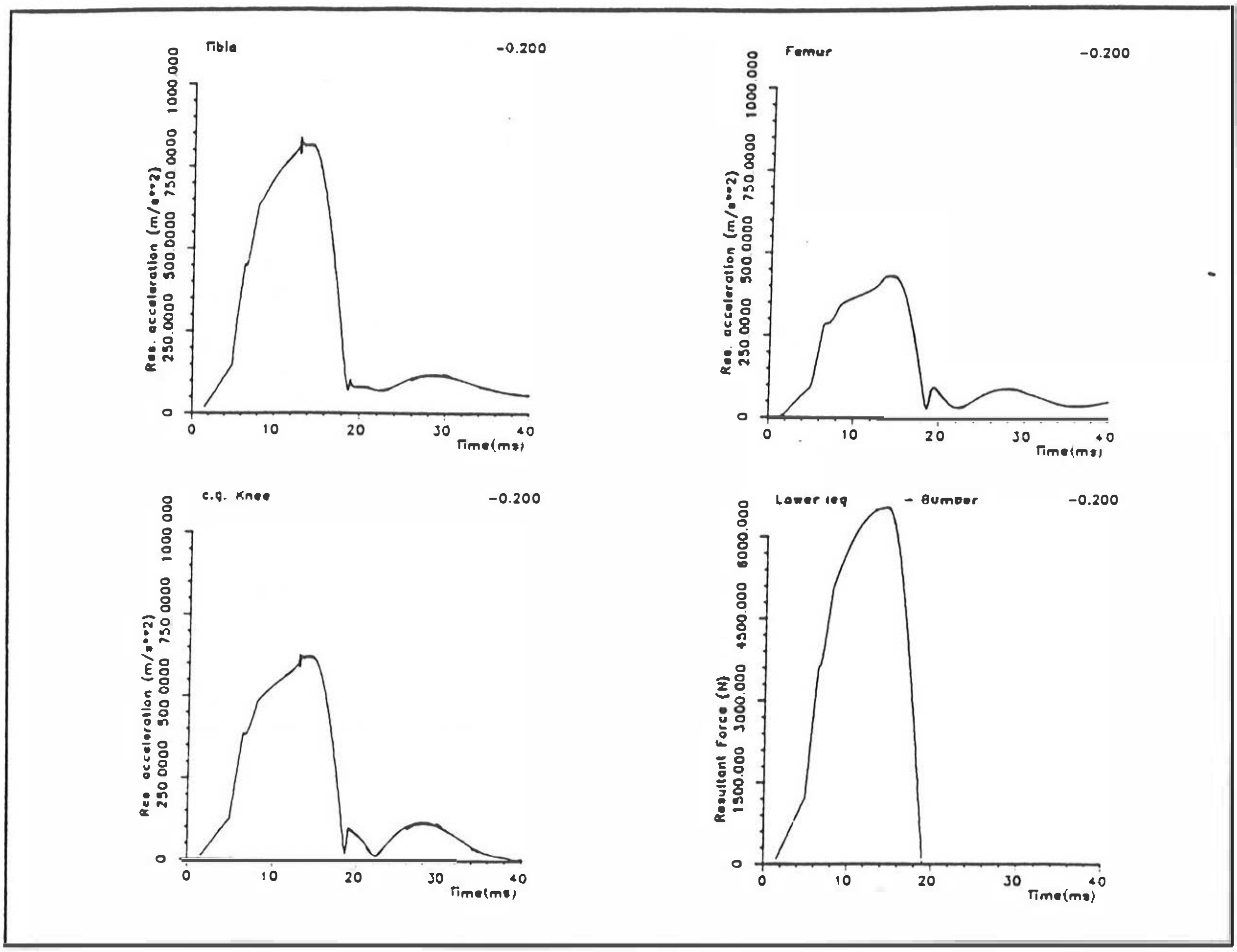

**Figure 8 : Force and acceleration, vertical offest -0.2 metre.**

| | Maximum resultant | |
|---|---|---|
| * Vertical Offset (m) | Accelerations Knee<br>(m/s**2) time (ms) | Force<br>(N) time (ms) |
| -0.200 | 628 12.95 | Lower leg-Bumper<br>6537 14.37 |
| -0.100 | 904 8.72 | Lower leg-Bumper<br>7116 10.84 |
| -0.035 | 1046 10.03 | Knee-Bumper<br>5988 27.97 |
| 0 | 968 8.59 | Knee-Bumper<br>6518 15.75 |
| 0.035 | 1149 8.16 | Knee-Bumper<br>6049 13.81 |
| 0.100 | 828 7.75 | Upper leg-Bumper<br>8111 19.87 |
| 0.200 | 513 11.52 | Upper leg-Bumper<br>8061 18.30 |

**Table 3 : Acceleration and force.**
* Vertical Offset : Vertical distance between knee and bumper at impact.

|  | Maximum / Minimum resultant torque |  |
|---|---|---|
| * Vertical Offset (m) | Knee-Upper leg (Nm) time (ms) | Knee-Lower leg (Nm) time (ms) |
| -0.200 | 112 39.84 | 26 26.16 |
|  | -17 26.16 | -94 15.09 |
| -0.100 | 315 16.25 | 336 34.19 |
|  | -313 34.19 | -461 16.37 |
| -0.035 | 493 16.75 | 60 40.06 |
|  | -60 40.06 | -610 13.66 |
| 0 | 573 13.97 | 3.29 2.12 |
|  | 000 00.00 | -542 15.28 |
| 0.035 | 619 12.44 | 3.38 2.94 |
|  | 000 00.00 | -544 15.87 |
| 0.100 | 494 20.62 | 411 37.91 |
|  | -406 37.97 | 358 24.81 |
| 0.200 | 139 19.93 | 68 32.65 |
|  | -66 32.68 | -84 22.80 |

**Table 4 : Maximum and minimum torque.**

|  | Maximum / Minimum relative joint angle |  |
|---|---|---|
| * Vertical Offset (m) | Knee-Upper leg (rad) time (ms) | Knee-Lower leg (rad) time (ms) |
| -0.200 | 0.0020 27.03 | 0.0124 15.81 |
|  | -0.0147 40.03 | -0.0032 27.41 |
| -0.100 | 0.0399 35.06 | 0.1402 21.16 |
|  | -0.0418 17.22 | -0.0432 35.31 |
| -0.035 | 0.0005 4.06 | 0.2500 23.56 |
|  | -0.1703 23.94 | 0.0000 00.00 |
| 0 | 0.0000 00.00 | 0.2074 23.62 |
|  | -0.2452 23.47 | -0.0005 2.66 |
| 0.035 | 0.0000 00.00 | 0.2168 23.91 |
|  | -0.2644 23.25 | -0.0003 3.34 |
| 0.100 | 0.0577 40.03 | 0.0737 27.87 |
|  | -0.1918 25.09 | -0.0604 40.03 |
| 0.200 | 0.0085 33.68 | 0.0109 23.65 |
|  | -0.0183 20.84 | -0.0087 33.68 |

**Table 5 : Maximum and minimum relative joint.**

* Vertical Offset : Vertical distance between knee and bumper at impact.

This model is applicable for impacts below the knee joint. When the bumper impacts the leg impactor above the knee joint, contact force is applied close to the upper leg centre of mass, so rotation of the upper leg is small, the result of which is a smaller knee joint angle.

## Conclusions

The aim of this research program was to evaluate the risk of pedestrian leg injuries when impacted by a car front. To achieve this aim, a mechanical intrumented leg was designed and its performance was evaluated.

The concept selected for this design has proved to work well : the deformations by bending and by shearing in the knee area and a force related parameter for lower leg impacts can be quantified.
Mathematical simulations show the capability of the mechanical leg to integrate the differences in shape and stiffness affecting the risk of injury, and this was confirmed by the tests performed.

The response of the soft tissue of the leg is not optimized. For this first step a standard dummy flesh was used ; however, it seems advisable to replace it by a less elastic foam, having a higher hysteresis. It will also be necessary to evaluate the repeatability, as well as the durability of the mechanical leg.

We still have to simulate other use conditions of the model as a function of the bumper and grill stiffness, as a function of the mass of the remaining body, as well as the vehicle speed influence.

Both aspects of modelling and development of an instrumented mechanical leg still require a lot of tests.

## References

(1) **H. Vallée, C. Thomas, C. Tarrière.**
Pedestrian Casualities : the Decreasing Trend.
Twelfth International Technical Conference on Experimental Safety Vehicles, Göteborg, Sweden, May 29 - June 1, 1989, pp 1273-1278.

(2) **Hideyuhl, K. Ono.**
The Present Situation of Pedestrian Accidents in Japan.
1990 International IRCOBI Conference on The Biomechanics of Impacts, Bron, France, 1990, September 12-14, pp 283-291.

(3) **Ishlkawa, K. Yamazakl, K. Ono, A. Sasakl.**
Current Situation of Pedestrian Accidents and Research into Pedestrian Protection in Japan.
Thirteenth International Technical Conference on Experimental Safety Vehicles, Paris, France, November 4-7 , 1991, 91-S3-O-05.

(4) **S.J. Ashton, G.M. Mackay.**
Car Design for Pedestrian Injury Minimization.
Seventh International Technical Conference on Experimental Safety Vehicles, Paris, France, June 5-8, 1979, pp 630-640.

(5) **A. Manoll.**
Adult Pedestrian Injuries - Medical Aspects.
Biomechanics and Medical Aspects of Lower Limb Injuries, San Diego, California, October 29-30, 1986, SAE P-186, 861928, pp 109-114.

(6) **S.J. Ashton.**
Child Occupant and Child Pedestrian Leg Injuries.
Biomechanics and Medical Aspects of Lower Limb Injuries, San Diego, California, October 29-30, 1986, SAE P-186, 861929, pp 115-128.

(7) Report by a working group of the European Experimental Vehicle Committee.
Pedestrian Injury Accidents.
Ninth International Technical Conference on Experimental Safety Vehicles, Kyoto, Japan, November 1-4, 1982, pp 638-671.

(8) **L. Grösch, W. Heiss.**
Bumper Configurations for Confliting Requirements : Existing Performance Versus Pedestrian Protection.
Twelfth International Technical Conference on Experimental Safety Vehicles, Göteborg, Sweden, May 29 - June 1, 1989, pp 1266-1273.

(9) **K. Higuchi, A. Akiyama.**
The effect of the Vehicle Structure's Characteristics on Pedestrian Behavior.
Thirteenth International Technical Conference on Experimental Safety Vehicles,
Paris, France, November 4-7, 1991, 91-S3-O-10.

(10) **J. Harris.**
Proposals for test Methods to Evaluate Pedestrian Protection for Cars.
Thirteenth International Technical Conference on Experimental Safety Vehicles,
Paris, France, November 4-7 , 1991, 91-S3-O-06.

(11) **J. Kajzer, C. Cavallero, S. Ghanouchi, J. Bonnoit, A. Ghorbel.**
Response of the Knee Joint in Lateral Impact : Effect of Shearing Loads.
1990 International IRCOBI Conference on The Biomechanics of Impacts,
Bron, France, 1990, September 12-14, pp 293-304.

(12) **J. Harris.**
A Study of Test Methods to Evaluate Pedestrian Protection for Cars.
Twelfth International Technical Conference on Experimental Safety Vehicles,
Göteborg, Sweden, May 29 - June 1, 1989, pp 1217-1225.

(13) **E.G. Janssen, J.S.H.M. Wismans.**
Experimental and Mathematical Simulation of Pedestrian - Vehicle and Cyclist - Vehicle Accidents.
Tenth International Technical Conference on Experimental Safety Vehicles,
Oxford, England, July 1-4, 1985, pp 977-988.

(14) **E.G. Janssen, J.J. Nieboer.**
Sub-System Tests for Assessing Pedestrian Protection Based on Computer Simulations.
1991 International IRCOBI Conference on The Biomechanics of Impacts,
Berlin, Germany, 1991, September 11-13, pp 263-285.

(15) **D. Cesari, F. Alonzo, M. Matyjewski.**
Subsystem test for Pedestrian Lower Leg and Knee Protection.
Thirteenth International Technical Conference on Experimental Safety Vehicles,
Paris, France, November 4-7, 1991, 91-S3-O-08.

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

(17) **H.A. Lupker, P.J.A. de Coo, J.J. Nieboer, J. Wismans.**
Advances in Madymo Crash Simulations.
International Congress and Exposition, Detroit, Michigan,
February 25 -March 1, 1991, SAE SP-851, 910879, pp 135-146.

(18) MADYMO Databases and Applications.
Version 4.3 (Avril 1990), TNO Road-Vehicles Research Institute
The Hague, the Netherlands, Department of Injury Prevention.