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Protection of Pedestrians Against Leg Injuries

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ABSTRACT

Pedestrian sustain very frequently injuries to their legs. These injuries are related to the contact with vehicle front end and may have long term consequences.

Taking into account biomechanics of the leg mechanisms injuries a deformable instrumented mechanical leg was designed.

The purpose of this mechanical leg is to predict the risk of leg injuries for a pedestrian, on the basis of the values of parameters recorded during a test.

This paper will discuss the biofidelity of the mechanical leg, its capability to separate the risk of injuries corresponding to different mechanisms and show with comparative tests the possibility of the device to select technical solutions allowing to optimise the protection of pedestrians against leg injuries.

GENERAL CHARACTERISTICS OF PEDESTRIAN ACCIDENTS

Accident statistics show the importance of pedestrian victims when hit in traffic accident. In accidents with passenger cars, pedestrian injuries occurring during the first phase of impact concern mainly the legs. Then after bending of the body on the car bonnet, the head impacts the car generally on or just below the windscreen.

Injuries to the leg and more especially to the knee are generally not life threatening but have often long term consequences with possible permanent disability. The mobility behaviour of the victim is often greatly affected and in many cases without to its initial characteristics.

The pedestrian is generally hit when he is crossing a road with an impact direction close to the perpendicular of its motion axis ; elderly are over represented and they are less likely to escape from the impact even at car low speed (Appel and al. 1975, Lestrelin and al 1985).

This type of accident generally occurring urban areas, the car speed at impact is relatively low most of time below 30 km/h (Tharp and Ismgos, 1976 ; Danner et al, 1979). In high speed cases, head impacts are at the origin of very severe injuries which become predominant.

These observations were the basis for conducting researches dealing with the response of the human knee hit from its side (Kazjer et al 1990, 1993). These researches allowed to have a better understanding of the knee behaviour when loaded in bending and in shearing.

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 pedestrian against leg injuries, it is proposed to propel an instrumented mechanical leg against a car front face. This leg is composed of a lower leg (without foot) and an upper leg. The knee consists in a short bar attached through a hinged joint at each extremity to the upper and the lower leg. On each side of this bar, there is a deformable element to correctly reproduce the force/angle history. The angles between the upper and lower leg and the knee bar are recorded through two potentiometers. Such a design allows to determine the shearing force (Z type deformation of the knee joint) and the bending moment (V type deformation)

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

EVOLUTION OF INSTRUMENTED MECHANICAL LEG PROTOTYPES

The first prototype (Cesari et al, 1991)

The first prototype 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 then similar to a human shape.

The main components are : a thigh, a lower leg, a foot. The flesh was moulded in polyurethane foam and the skeleton made with steel tubes and assembly steel part. 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 upper extremity of the tibia and the lower extremity of the femur are symmetrically made aluminium alloy parts. A link articulated at each extremities by two parallel axis allows the relative displacement of the tibia and the femur in a vertical plane by the measurement of its angle versus the tibia and versus the femur it is possible to determine the deformations related to shearing and to bending.

Two deformable rods controls the kinematics of the knee. They simulate the ligaments with tighten the knee and control its initial posture ; the shape and the material constituting these deformable rods.

The second prototype

To have a better repeatability in the results, we have decided to redesign the leg being cylindrical. Drawings made using CAD allowed to be very precise and this may facilitate possible evolution. The characteristics of this leg in terms of anthropometry were derived from paper SAE 831617 (Robbins et al, 1983) ; especially mass and centre of gravity locations for both upper and lower legs were correctly reproduced.

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 lower leg accelerometers remain at the same location.

Reconsideration of the flesh characteristics

We have performed tests aimed to characterise the dynamic response of human flesh in the area of the initial impact (external side of the lower 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.

The third prototype

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

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

Evolution of deformable bars

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

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 it appears that in bending it deforms non symmetrically around knee axis and this makes more complicated the interpretation of tests results to separate deformations due to shearing from those due to bending. This absence of symmetry is due to buckling effect on the compressed side of the deformable element.

To avoid that difficulty we have redesigned the deformable elements with a "double bridge" shape : the two extremities are aimed to deform by shearing whereas bending moment deformations are concentrated in the central part. The material remains the same as for the previous design.

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].

Bending :

$$d = a+b$$

Shear deflexion :

For shear deflexion calculation we have to know :

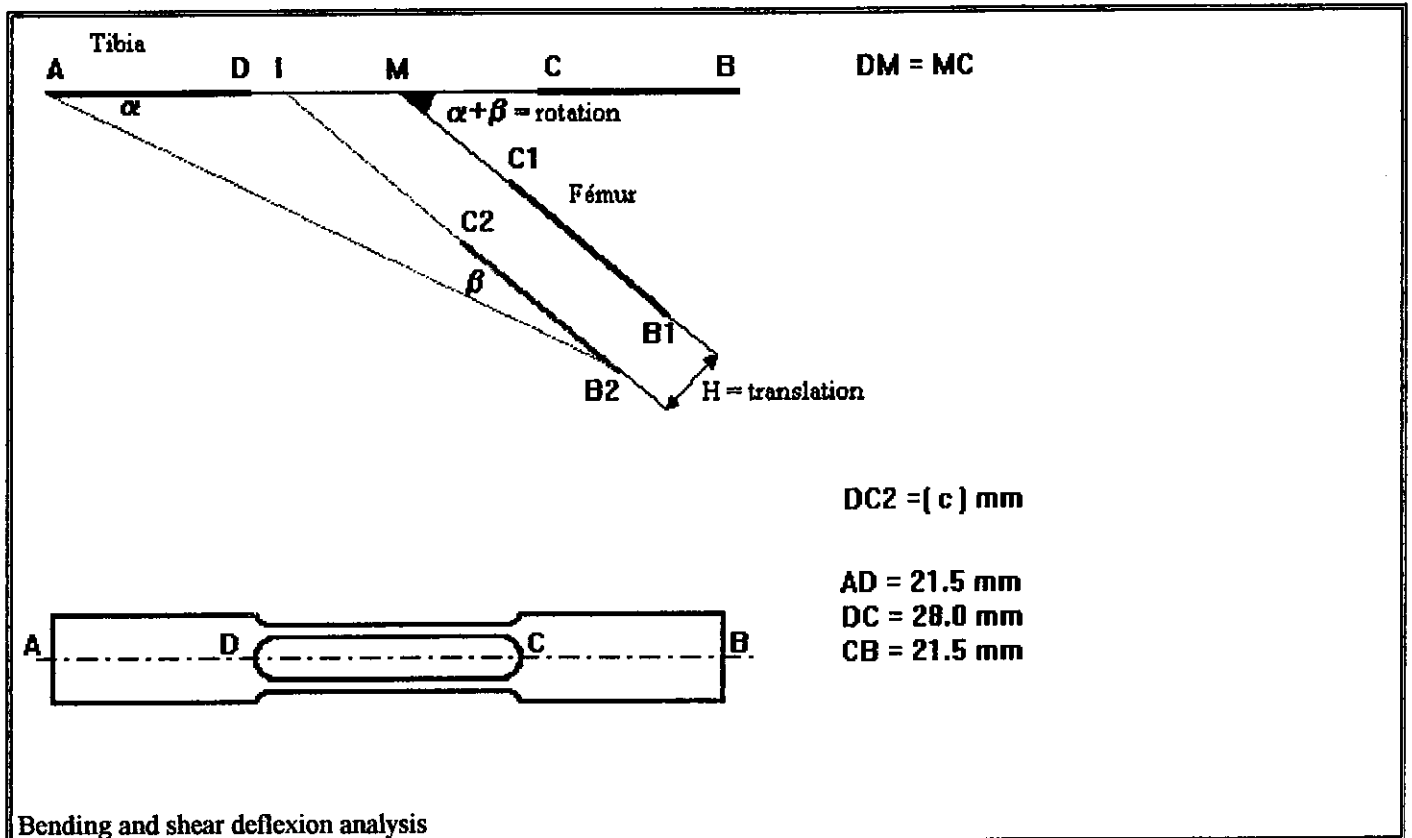
The distance between the transducer's axe and the bend part place. This distance is 21.5 mm (AD = CB = 21.5)

The two angles measured during the test.

The distance "c", which is measured after the test.

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

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



Bending and shear deflexion analysis

Fig.: 1

CAR TEST RESULTS

The mechanical leg has been used in several tests with different passenger car ; these tests did not show any important problem concerning the durability, the repeatability and the severity to input change of the mechanical leg.

It seems important to check that the mechanical leg can take into account the variations in parameter 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 : low impact (at approximately 35 cm above the ground) corresponds to a better protection.

To check if the mechanical leg response is directly related to the bumper height, we have performed on the same car, by changing the relative position between the leg and the bumper, tests at three bumper heights : normal, 44 mm below normal and 88 mm below normal position. Tables 1 and 2 and figures 2 and 3 give the results of three tests made with the same (medium size) mass production vehicle for the three bumper heights.

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 the proposed limit of 6 mm but not too far 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 lowering the bumper. If we accept that the risk of bone fracture is directly related to the value of bending moment at impact point, the upper 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 impacted part stiffness two tests have been 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.

Tests results as indicated in tables 3 and 4 and figures 4 and 5 show a great difference: compared to the bumper centre test. Test in front of the fixation gives injury related parameters values increased by 60% to 150%; the response of the mechanical leg is clearly sensitive to the change of impacted area stiffness

Test	Speed	Bumper Height	Tibia	Femur	Bending angle	Shearing displacement
N°	Km/h	mm	Max. angle degree	Max. angle degree	degree	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

Test	Speed	Bumper Height	Tibia	Tibia	Angular acceleration	Moment
N°	Km/h	mm	Upper acc. x g	Lower acc. x g	rd/s ²	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

Test	Speed	Bumper Height	Tibia	Femur	Bending angle	Shearing displacement
N°	Km/h	mm	Max. angle degree	Max. angle degree	degree	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

Test	Speed	Bumper Height	Tibia	Tibia	Angular acceleration	Moment
N°	Km/h	mm	Upper acc. x g	Lower acc. x g	rd/s ²	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

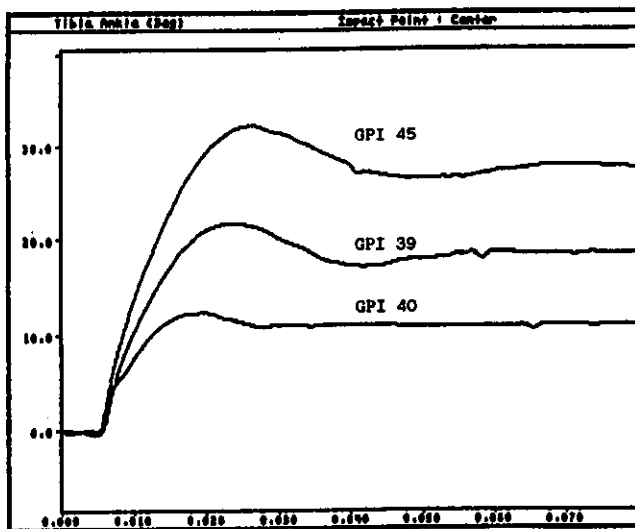


Fig: 2

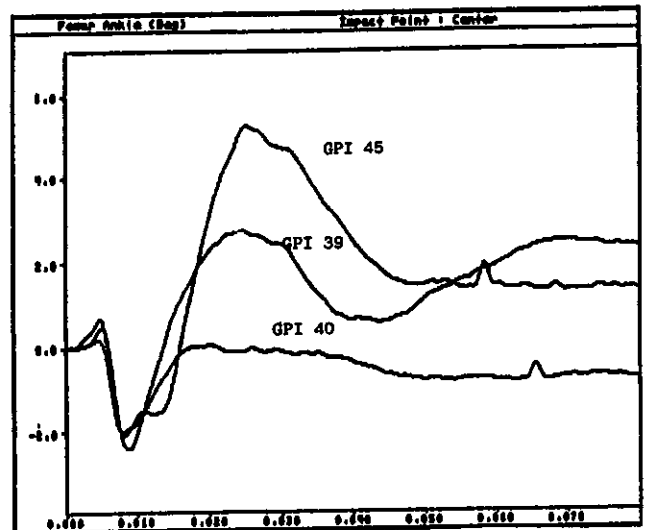


Fig: 3

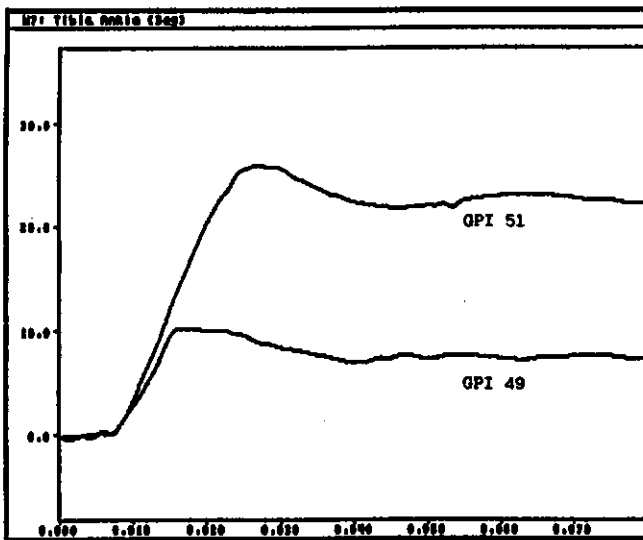


Fig: 4

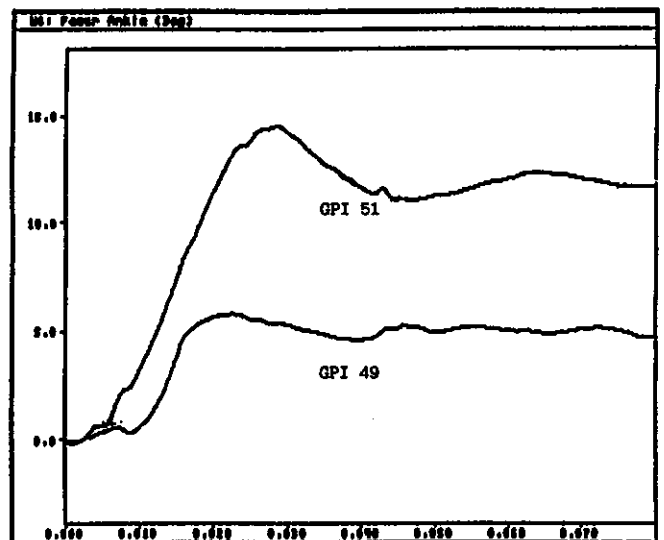


Fig: 5

COMPARISON OF BEHAVIOUR BETWEEN LEG AND MECHANICAL LEGS

Two main mechanisms can be involved when a knee injury occurs in a pedestrian accident : they are bending between upper and lower legs 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 allow to determine at every

moment the relative position of the upper and the lower leg and then the deformations due to shearing and to bending. The use of displacement transducers (instead of force transducers) makes more accurate the prediction of injury occurrence as, especially in bending the effect of the duration of force application is important and the deformation (and then 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 mechanisms).

These tests have provided information concerning the timing of injury production, the type of injuries produced and the level at which they occur.

Fig.: 6 shows a typical force time history in a shearing test and according to the analysis of these results it assumed that the injury occurs very soon after the initial contact. On the opposite the maximum of bending moment and deformation occurs much later (see fig 6)

These tests were duplicated using the mechanical leg and the results are indicated in figure 9

Considering bending tests the force time histories are very similar to those of the tests performed with 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 close to the upper limit ; however we have to remember that human legs correspond to a population older (and then having a lower tolerance) than the average, and also having a lower mass.

The mechanical leg shearing tests give results similar but with some differences in comparison with human leg tests.

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 remains an important injury prevention problem. The mechanical leg above described has proved that it takes into account the main leg injury mechanisms involved in a pedestrian accident.

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. It is then possible to optimise the design of the car front ends (shape and materials) to improve to protection of pedestrians against leg injuries.

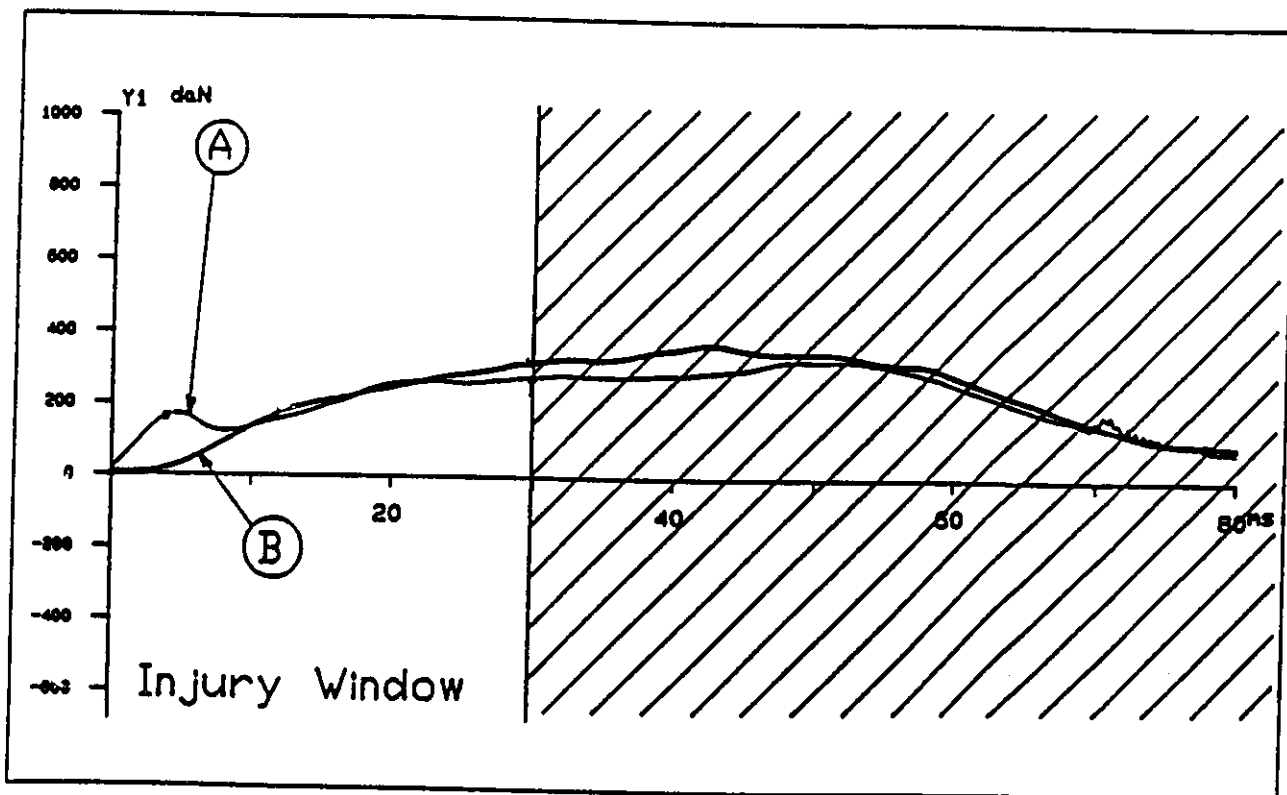


Fig.: 6: Typical characteristics of knee impact force (A) and knee reaction force (B).

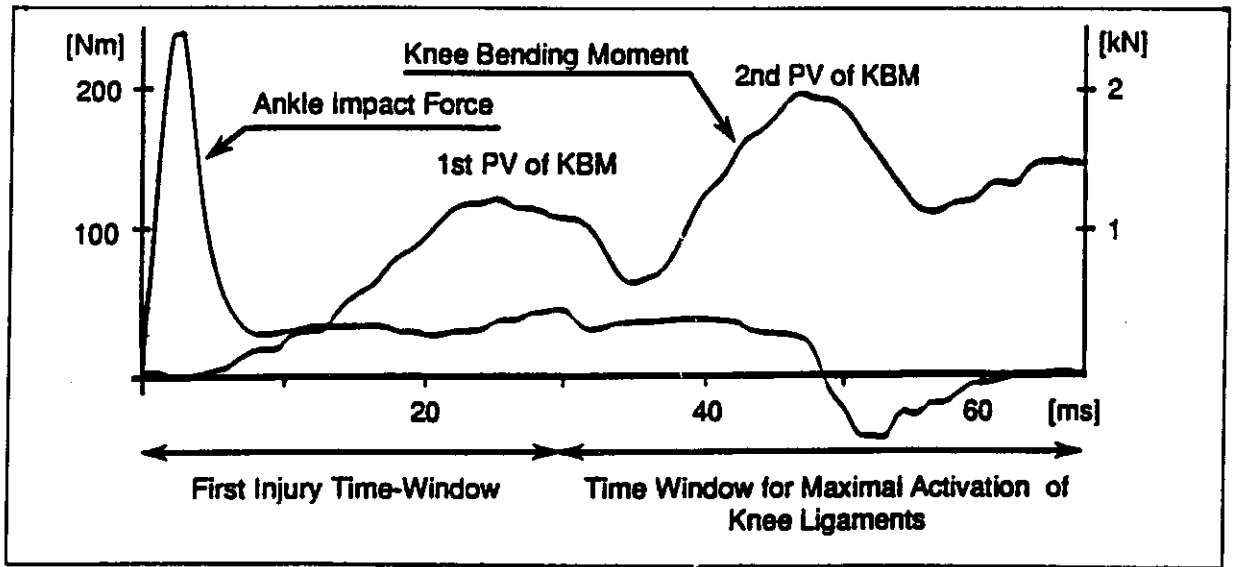


Fig.: 7: Knee bending moment versus time from a typical test. (20 Km/h)

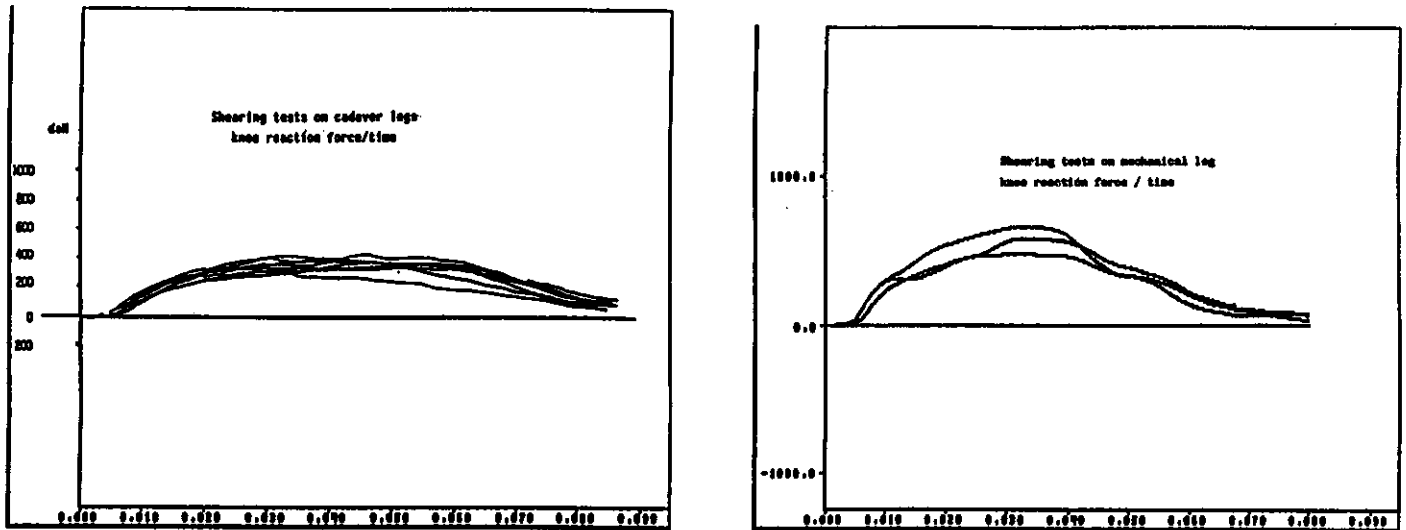


Fig.: 8

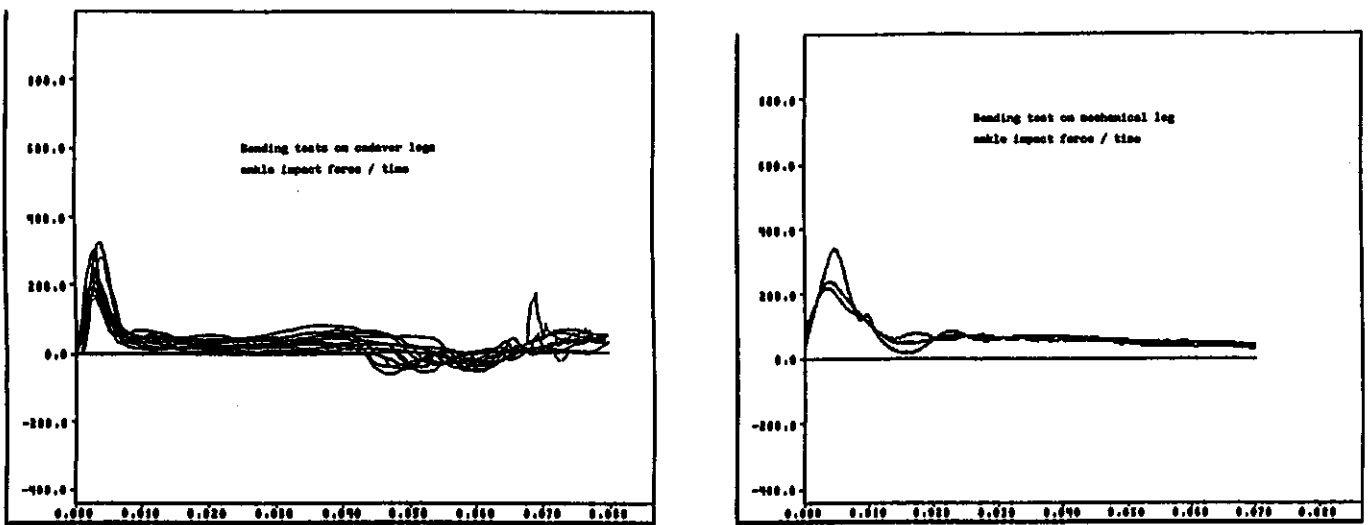


Fig.: 9

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