

## **SHEARING AND BENDING HUMAN KNEE JOINT TESTS IN QUASI-STATIC LATERAL LOAD**

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### **ABSTRACT**

Previously a mathematical model of the human leg based on lateral dynamic impact tests was created (Bermond et al, 1994), but it was necessary to carry out additional quasi static lateral tests to fill in gaps in our knowledge. These studies are presented in this paper. This research concerns the protection of the pedestrian against the front of the car, and of the car occupant in case of intrusion inside the compartment.

In this study, shearing and bending tests were carried out with 20 fresh human legs in quasi-static lateral load. These tests were conducted to obtain lesions in the knee joint area and to assess the behaviour law of the whole extended knee joint in quasi-static shearing or bending lateral load.

IN THIS PAPER, STATISTICAL ANALYSIS for lower limb injuries in car/pedestrian accidents and car occupants in case of intrusion inside the compartment, as well as an overview of the functional anatomy of the lower limb, are shown. Then the experimental apparatus to achieve the leg shearing and bending in lateral load, is presented. Finally results of the 20 tests are discussed.

The objective of the study is to increase the understanding of lower limb response when subjected to quasi static lateral loads as a complement to previous dynamic studies (Kajzer et al, 1990, 1993, Levine et al 1984) aimed at integrating it into the human mathematical model. These studies primarily concern the articulation of the knee when the leg is stretched.

### **BACKGROUND**

**STATISTICAL ANALYSIS FOR INJURED TRAFFIC USERS -**  
Pedestrians are an unprotected road user group. They represent the majority of road accident victims ; in 1986 more than 18,000 pedestrians were killed in traffic accidents in the EEC, USA and Japan (Vallée et al, 1989).

Using the following studies (Ramet et al, 1987, Haddak et al 1994), based on clinical data we have shown that lower limb lesions are an important consequence of all road accident categories (tables 1- 2).

Table 1 - Distribution of the injured by user type (Ramet et al, 1987)

<u>Road Users</u>	<u>Accident percentage (%)</u>	<u>Percentage of lower limb lesions by user type all AIS (%)</u>
Pedestrians	8.8	32
Bicycles	5.8	29
Mopeds	16.8	37
Motorbikes	9.4	39
Cars	56.2	19
Lorries	1.7	22
Vans	1.3	22

Table 2 - Pedestrian accident distribution (Haddak et al, 1994)

<u>Age bracket</u>	<u>Accident percentage (%)</u>
< 24 yrs	36%
24 - 54 yrs	28%
> 54 yrs	36%

These accidents often occur in towns at low speeds. The most frequent pedestrian collision is with the front of the vehicle. In this case the lower limb is the first part of the body to be impacted by the bumper.

A clinical study (Patel, 1982) carried out on 215 pedestrians showed 6 knee ligament injuries whereas 76% of the injured had at least one lower limb injury. A thesis by Millet (1994) reviewed the reports on 110 pedestrians. It showed that 91 subjects suffered from lower limb injuries (8 sprains and 56 fractures). A thesis by Escoda (1984), on lower limb injuries during vehicle - pedestrian impacts in a comparative study of 50 experimental reports and 50 clinical reports, showed that bone and ligament injuries during the laboratory experiments were more frequent than in the clinical ones. It should be pointed out however that the impact speed was high (32 km/h).

Studies by Kajzer, (1993) carried out at the Applied Biomechanics Laboratory (LBA) in association with INRETS in Marseille on about 20 anatomical subjects legs showed frequent ligament injuries, which were mainly complex and multiple bone/ligament type injuries.

## **FUNCTIONAL ANATOMY OF THE KNEE**

**Knee Joint** - The knee-joint must be regarded as consisting of three articulations in one: one between each condyle of the femur and the corresponding tuberosity of the tibia, and one between the patella and the femur. The bones entering into the formation of the knee-joint are the condyles of the femur above, the head of the tibia below. The bones are connected together by ligaments, which are placed on the exterior of the joint, while others occupy its interior.

The main ligaments in the knee joint are: the external ligaments, the Lateral Collateral Ligament (LCL) and the Medial Collateral Ligament (MCL); which are stressed when the leg is stretched and relaxed when the knee is flexed; the interior ligaments are the Anterior Crucial Ligament (ACL) and the Posterior Crucial Ligament (PCL); which are always stressed.

**Articulatory Physiology** - The knee is the intermediate articulation of the lower limb: it is primarily an articulation with one degree of freedom, extension flexion, when the body is standing up. In full stretch the knee is transversally stable and has no possibility of axial rotation due to the combined action of the collateral and crossed ligaments. It is only as a secondary consideration that the knee can make rotational movements in the

longitudinal axis of the leg and only when the knee is bent. During lateral traumatism it can be seen in shock on the external face (fibula head and external tibia plateau) : a fracture of the external tibia plateau and/or a rupture of the internal lateral ligament (Medial Collateral ligament) (Kapandji, 1994). It is in extension however that the knee is most vulnerable to articular fractures and ligament ruptures (that is to say for the pedestrian more than for seated users).

## **EXPERIMENT METHODOLOGY**

Ten fresh human cadavers were chosen on the basis of lower limb integrity and corpulence. Before each test, X-ray investigations were performed to verify that knee joint stability was good when the lower limb was stretched .

Six lower limbs were tested when they were integral with the body. The fourteen other lower limbs were isolated at the hip, making sure that the trochanter major and femoral head remained integral with the limb. These legs were tested in accordance with two test protocols : one being a lateral flexion study and the other being a lateral shear study on the extended leg.

To visualize bone movements, two spherical targets were fixed onto the femur and two onto the tibia with long screws. The tibia femur axis normally shows a slight valgus which we did not take into consideration when positioning the 4 sites. The feet were not supported.

The knee joint line position was referenced by an anatomist then marked on the internal face of the knee. This anatomical reference serves to put the leg in position in relation to the supports, then to correctly place the measuring transducers. During the tests, a doctor uses a stethoscope to listen to the sound phenomena produced by the internal stresses: The main sound events were reference marked with an electrical contact combined with the measurement recordings.

### **TEST PROGRAMME**

**Test Apparatus for Bending in Quasi Static Lateral Load** - The experimental set up was designed for both complete bodies and individual limbs. Bending tests were carried out on a horizontal surface. The femur is held firmly in place by compressing the thigh by using a mechanical screw tightening system attached to metallic plates fixed onto the table. The tibia is tightly strapped onto a duralumin section of about 1.5 metre length. In the restraining system, only the knee is free from any restraints for 5 cm on either side of the line separating the tibia from the femur. The duralumin section is mounted on ball bearings to limit the friction loads on the table during displacements.

A force transducer (N° 1 in figure 1) and a displacement transducer (N° 2 in figure 1) are placed 1.5 metre away from the system's presumed rotation point. An operator exerts an external force directly onto the force transducer using a cable, to maintain a slow, uniform displacement.

**Test Apparatus for Shearing in Quasi Static Lateral Load** - The experimental set up was designed for both complete bodies and individual limbs. Shearing tests were carried out on a horizontal surface. The femur is held firmly in place by compressing the thigh by using a mechanical screw tightening system attached to metallic plates fixed onto the table. The lower part of the leg rests on the heel. Any rotation of the tibia is eliminated by a mechanical stop at the level of the foot.

Fig. 1 - Schematic diagram of the quasi-static bending tests

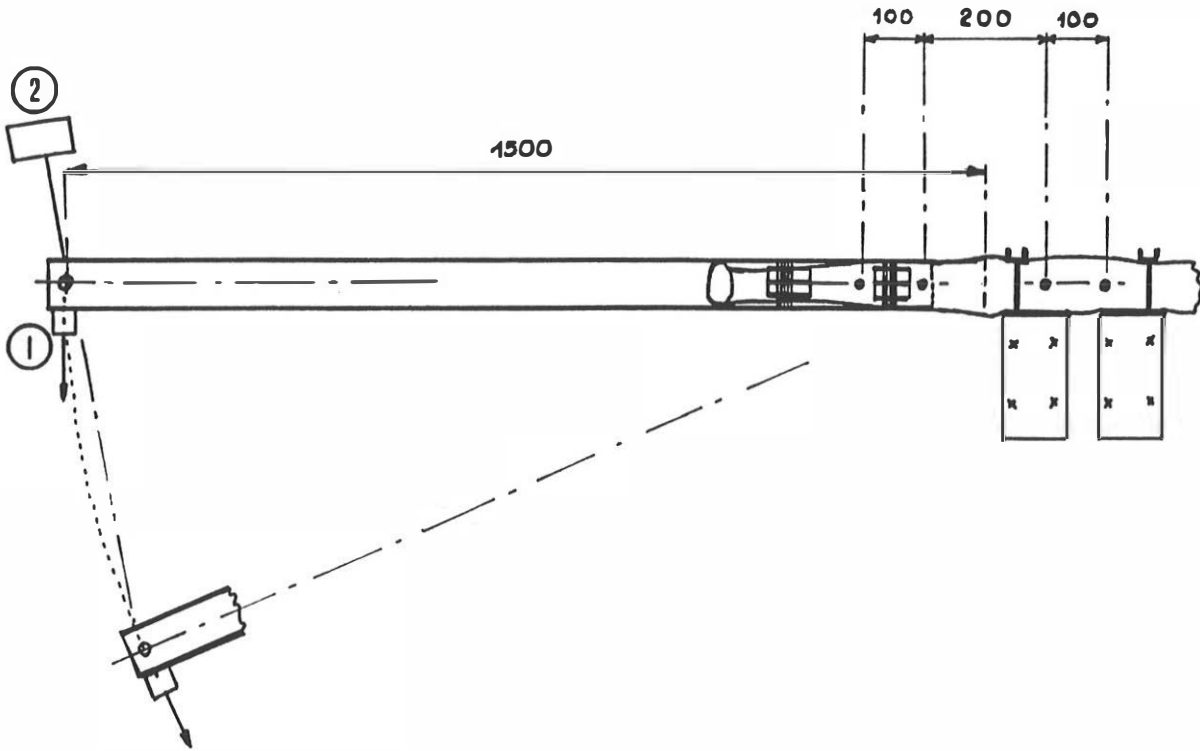
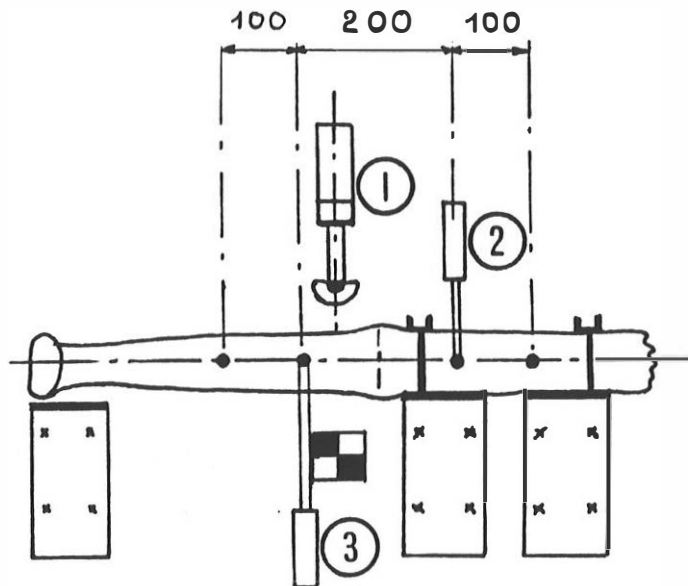


Fig. 2 - Schematic diagram of Quasi Static Shearing Tests



A force transducer (N° 1 of figure 2) was placed at the support point which is 3 cm below the femur - tibia liaison and two displacement transducers (N° 2 & 3 of figure 2) were placed at a distance of 10 cm either side of this reference mark. To have minimal forward displacement, it was necessary to take into account possible crushing of the femur's flesh at the support point ; this is what justified using transducer N° 2. Under these conditions the actual shearing at the femur - tibia interface is the difference between the two displacement measurement values.

## RESULTS ANALYSIS

**RESULTS OF QUASI-STATIC BENDING TESTS** - Of the 10 tests carried out we have 9 recordings and for each test we have two types of recorded data : The force F(N) applied at 1.50 metre from the knee and distance D(m) traced by a point also situated at 1.50 metre from the knee. The bending moment and rotational angle calculations can be deduced from the measurements by using the following relationships :

$$\begin{aligned}\text{Moment (Nm)} &= F(\text{N}) \times 1.50 (\text{m}) \\ \text{Angle (degrees)} &= 2 \times \arcsin (D/3(\text{m}))\end{aligned}$$

Analysis of Quasi-Static Bending Tests - Superposing the bending moment curves (figure 3) as a function of the rotating angle of the tibia relative to the femur gives some interesting phenomena because we have good coherence. Most of the curves follow a regular slope. In addition for each curve, the average slope was calculated by taking the average value of the derivative. The calculation was carried out on the six curves which are entirely within the corridor in figure 4 and over the first 12° of the seventh curve. The average value of these seven slopes gave a coefficient of 6.2. This can be expressed as follows :

$$\text{Bending moment (Nm)} = 6.2 \times \text{rotation angle (degrees)}$$

The results obtained on 3 women's legs as represented by the thicker lines in figure 3 show exactly the same behaviour as that for the men's legs.

The two lower curves change behaviour after an 8° to 10° degree rotation because the femur started to pivot around its axis thus offering less resistance to lateral bending. These two curves were therefore not incorporated in figure 4 which will enable an estimative corridor to be defined. A tolerance of about 25 Nm enables the 7 remaining curves to be integrated (only a part of one curve). Table 3 gives the reference positions necessary to re-plot this corridor.

Only the GPC 22 test seems to acquire greater rigidity after a rotation of about 12°. To understand this phenomena an anatomic analysis has to be envisaged. The bending force applied to the limb primarily puts the internal ligament (MCL) of the knee under tension, however in certain cases, putting the crossed ligaments (ACL, PCL) under tension could increase the rigidity of the whole.

Fig. 3 - Quasi static bending tests (D=right knee : G=left knee)

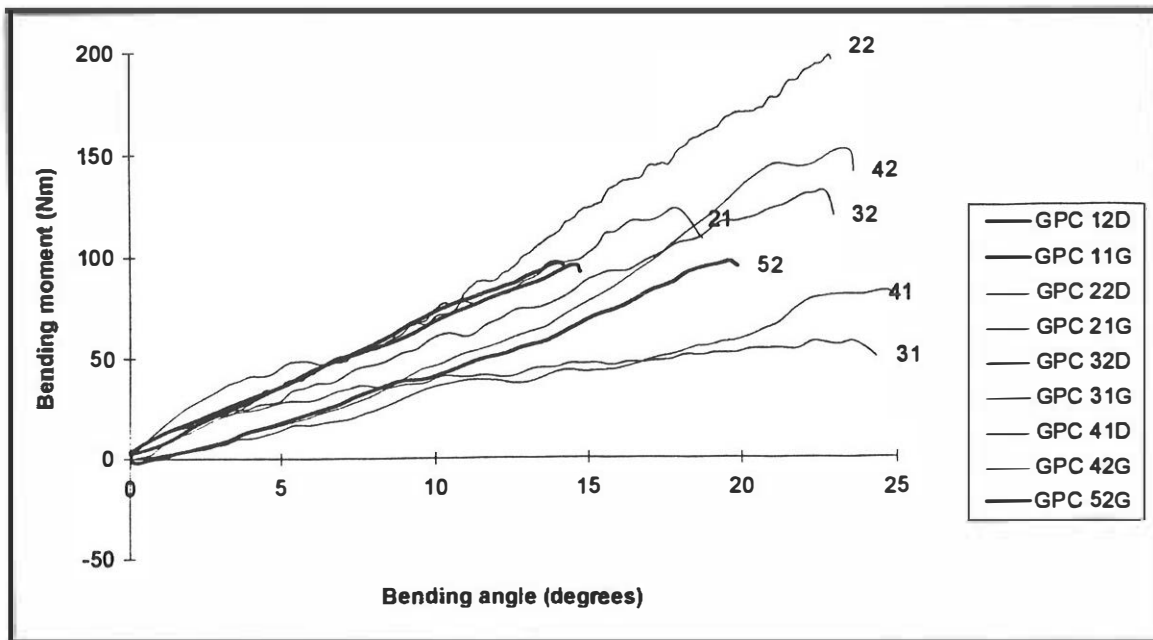


Fig. 4 - Quasi static bending tests with the corridor

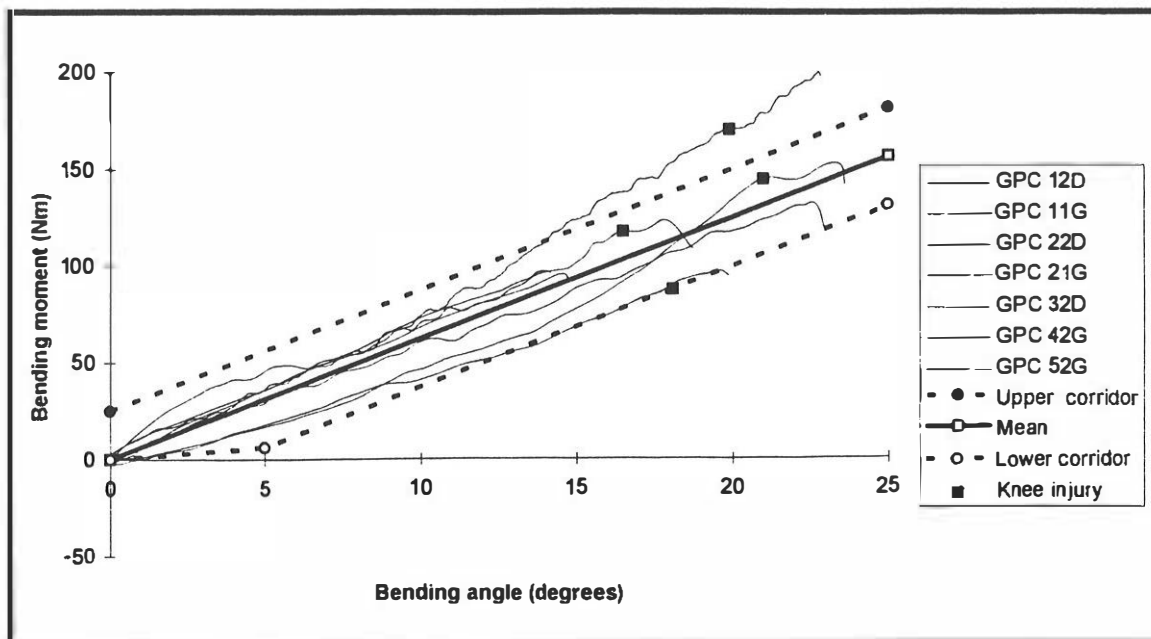


Table 3 - Corridor of quasi-static bending tests

	x (degrees)	y (Nm)
Upper corridor	0	25
	25	180
Average curve	0	0
	25	155
Lower corridor	0	0
	5	6
	25	130

**Tolerance of the Knee in Quasi-static Bending** - Tests were carried out at bending angles of less than 25° to avoid any major destruction to the knee ligament system. Only macroscopic injuries were taken into account during the autopsies carried out on the anatomic parts. The autopsy results are shown in table 4. It should be pointed out that 5 of the 10 legs had no major injury despite the fact that they had been subjected to a rotation of 15°, 22° and 24°. In the other cases the first injuries appeared when the bending angle exceeded 16° and that at the same time the bending moment went through 87 Nm (table 5).

**Table 4 - Clinical data of bending tests**

Test N°	Sex-Age	Cause of death	Weight of Body	Weight of Leg (kg)	Type of Injury
GPC 11	F- 69	Heart attack	59.9		no
GPC 12	F- 69	Heart attack	59.9		no
GPC 21	M- 81	Heart attack	82		Medial Collateral Ligament Rupture Bone Evulsion
GPC 22	M- 81	Heart attack	82		Residual laxity
GPC 31	M- 70	Liver cancer	70		no
GPC 32	M- 70	Liver cancer	70		no
GPC 41	M- 67			8,04	no
GPC 42	M-67			7,94	Partial Posterior Rupture of the MCL
GPC 51	F- 72			8,37	Internal Rupture of the MCL Internal Rupture of Post. Meniscus Ext. Rupture Cornua Ant. Meniscus Cartilage Lesion Lateral Condyle
GPC 52	F- 72			8,64	Internal Rupture of MCL fixation on Internal Meniscus Cartilage Medial Condyle Lesion

**Table 5 - Estimated values representative of the first macroscopic lesions appearing during the quasi-static tests**

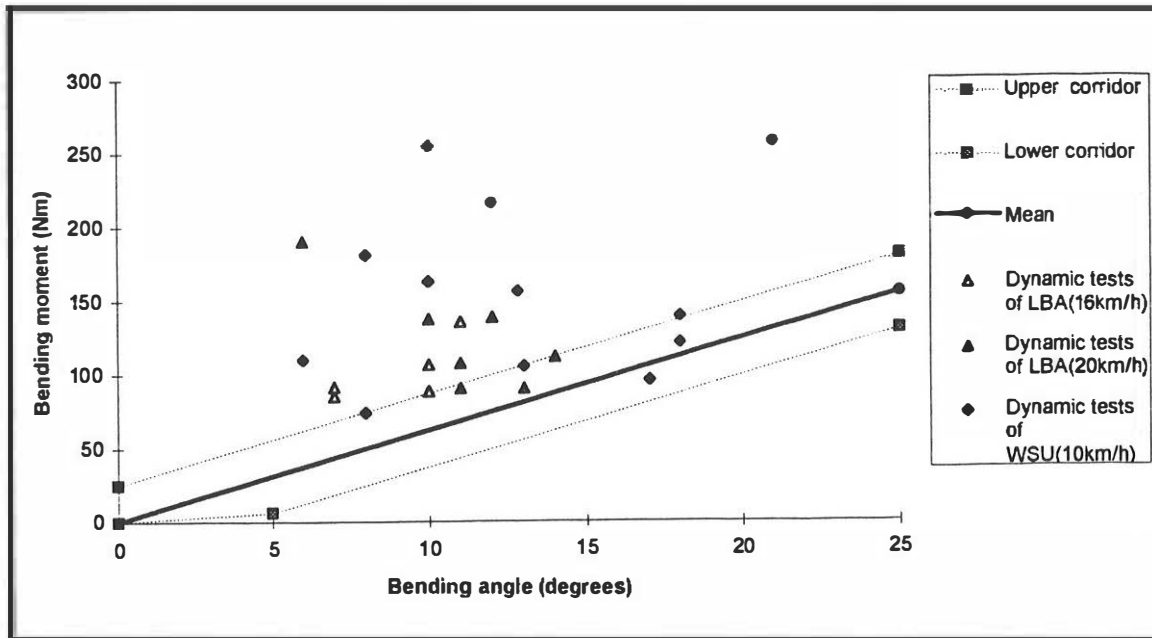
Tests	Angle (degrees)	Moment (N.m)
GPC 21	16.5	117
GPC 22	19.9	169
GPC 42	21.0	144
GPC 52	18.1	87
Average	18.9	129

**Table 6 - Values estimated by the authors as representative of first injuries of the knee**

	LBA Results (Kajzer et al)		WSU Results (Levine et al)	
	Angle (degrees)	Moment (N.m)	Angle (degrees)	Moment (N.m)
Averages	10.2	114	12.8	156
Averages of all dynamic tests	Average Angle = 11.4 °		Average Moment = 134 N.m	

**Comparison of previously published static and dynamic bending tests** - Shock tests using an impactor were carried out at LBA of Marseille and at Wayne State University. The values of the moments and angles published by Kajzer et al (LBA, 1993) and Levine et al (W.S.U., 1984) are, according to their authors, representative of the injury values of the knee ligament system (see table 6). These values were collected and transferred to figure 5 by superposing the corridor of the previously defined static results.

Figure 5 - Comparative bending tests



**Observations** - A concentration of data from the dynamic test results at 10, 16, 20 km/h impact speed, can be observed at bending angle of around 11°; the exact means calculated on the angles and moments are respectively 11.4° and 134 Nm. Compared to the calculated mean values on the four static tests we see that the acceptable average bending moment at the knee increases slightly during dynamic stressing but that the acceptable bending angle at the knee is significantly lower in dynamic than in static conditions (11.4° for 18.9° in static).

**RESULTS OF STATIC SHEARING TESTS** - Of the ten tests carried out we have nine complete recordings and for each test we have recorded three types of information: *the force F(N)* applied below the knee and *the distances D1(cm)* and *D2(cm)* traced by the points located 100 mm either side of the tibia plateau. These points were reference marked outside the leg using screws solidly embedded in the tibia and femur bones. The varus-valgus rotation of the tibia is low because a stop at the ankle eliminates this rotation. Furthermore, we consider that the lateral displacement at the tibia plateau is equal to the difference between the distances measured on the leg during the test. Analysis of films from directly overhead allowed us to verify that this was the case in these tests.

The rotation in flexion (varus-valgus rotation) of the tibia with respect to its initial position was measured during the tests to be between 0.85 and 6.15 degrees with an average of 3.3 degrees for the 10 tests.



The rotation in flexion of the femur with respect to its initial position was measured from the tests to be between 0.81 and 7.4 degrees with an average of 3.6 degrees. This flexion of the femur was possible as the fixing points were on soft tissue on the thighs and not on the bone. Thus it is due to the crushing of the soft tissue at the top of the thigh which allowed this rotation in flexion.

During the GCC 01 and 02 tests, sound phenomena were perceived by the manipulators. It was therefore decided to use a stethoscope to listen to the internal disturbances at the knee during the restraining process. In the GCC 03 test it was verified that several audible events of varying amplitudes were perceived. In addition in tests 04 to 10 the listening technique was complemented by a manual devise enabling the sound signal to be calibrated to the physical measurements. The first signals indicate some internal disturbances which do not have macroscopic systems. We are certainly confronted with a case of elongation of ligaments not detectable at the autopsy. Afterwards a more severe cracking took place and we therefore decided to stop the constraining process.

It was thus possible to superimpose (figure 6) the sound events onto the force curves as a function of displacement. To avoid encumbering the graph, the elements selected were the first sound event and the event which produced the most significant knee injury.

**Analysis of Static Shear Tests** - The superimposition of the shear force curves (figure 6) as a function of the tibia's lateral displacement in relation to the femur reveals some interesting phenomena.

The increase in the force applied can be divided into a number of phases.

- Initially, we observe a non-linear increase as found by Piziali (Piziali et al, 1977) who showed that in small amplitude sollicitation, which is not destructive to the joint, the response can be modeled by a fourth order polynomial.

- After a displacement of about 1.0 to 1.5 cm, the curves straighten out and give the impression of being linear. Physiologically, micro-tears appear to limit the intrinsic characteristics of the ligaments.

- The third phase appears when the internal tearing becomes more significant and here we notice an increase in the length for a constant force which creates a plateau on the curve.

- The end of the experiment occurred when loud internal cracking was heard. Afterwards, the applied force was released slowly.

The creation of a corridor taking in the seven remaining curves could be envisaged (figure 7). To define this, the upper boundary of these curves appears obvious and is a straight line as in :

$$\text{Force (N)} = 1000 \times \text{Displacement (cm)}.$$

The lower boundary can be envisaged as a straight line passing from the point (1,0) and tangent to the curves.

In order to define an average function which would be easy to evaluate and use in our models, a simplification is proposed. The principal aim of the study is to place the global response during the phase of the destruction of the joint. For displacement less than 1 cm, a simple linear function as in :

$$\text{Force (N)} = 500 \times \text{Displacement (cm)} \text{ is proposed.}$$

The average slope of the curves is 970 N/cm.

Fig. 6 - Quasi static shearing tests

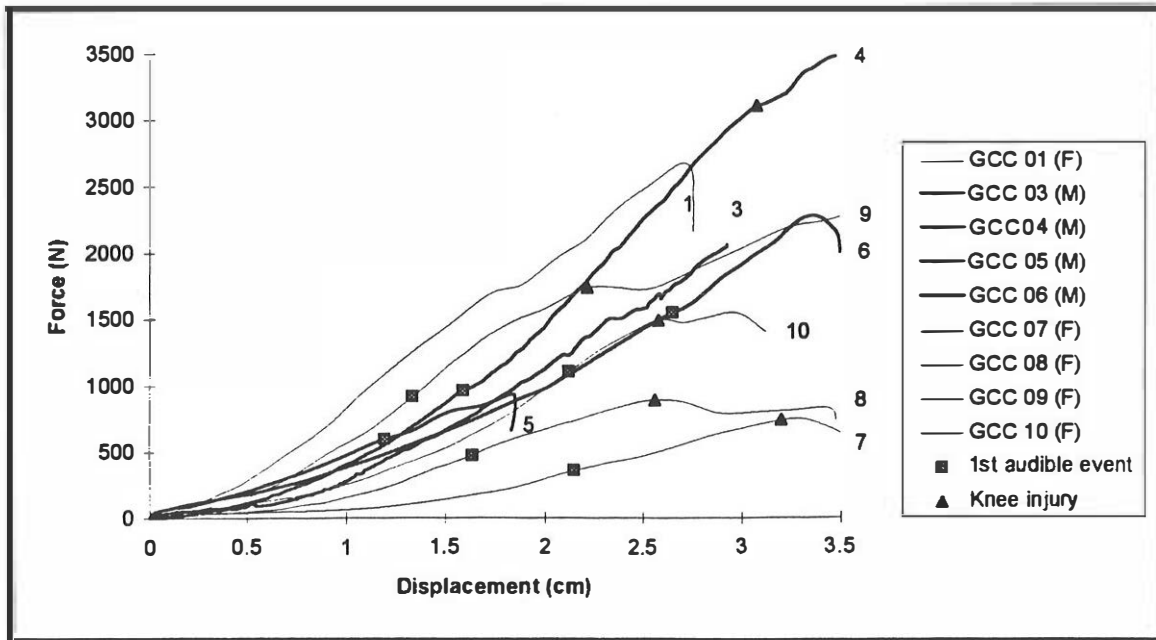


Fig. 7 - Superimposing the three selected functions to represent knee behaviour

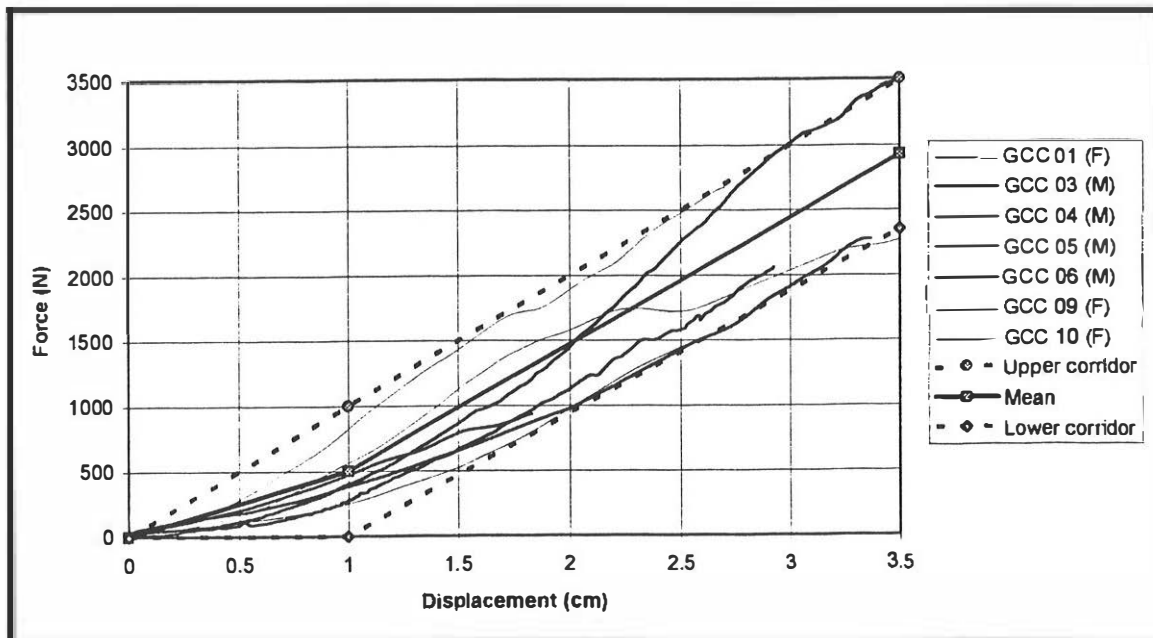


Table 7 - Corridor of quasi static shearing tests

	x(cm)	y(N)
Upper corridor	0	0
	3.5	3000
Average curve	0	0
	1	500
Lower corridor	3.5	2925
	0	0
	1	0
	3.5	2350

The following table gives the coordinates of the points giving the envelope boundary and the line segments representing the average behaviour of a knee in shear.

### Tolerance of the knee in quasi-static shearing tests

The autopsies carried out after the tests enabled the macroscopic injuries to be evaluated (table 8). For two men's legs no injuries of any importance could be detected. However, the other 7 legs which were subjected to a lateral displacement at the articular surfaces of more than 25 mm, showed damage which became more severe, the higher the force to reach these displacement values.

Superposing different parameters (figure 6) provides us with some information.

In particular, the sound recordings carried out during tests 4 to 10 allow us to say that the first internal perturbations happen at a lateral displacement of 12 mm. For the macroscopic lesions found at autopsy, it is possible to place them on the corresponding curve and they only occur after a minimum lateral displacement of 22 mm.

The force levels exerted do not seem a sufficient indicator because the injuries happen at values lying between 0.75 and 3 kN.

Table 8 - Clinical data of shearing tests

Test N°	Sex	Weight of Leg	Type of Injury
GCC01	F	8,79	Rupture Posterior MCL Evulsion Internal Meniscus Rupture ACL Cartilage Lesion condyle
GCC02	F	9,24	Rupture of Internal Meniscus
GCC03	M	8,57	Rupture MCL Evulsion Internal Meniscus
GCC04	M	8,57	Partial Rupture MCL Evulsion Internal Meniscus Cartilage Lesion Medial Condyle
GCC05	M	6,28	no
GCC06	M	6,58	no
GCC07	F	6,66	Partial Rupture MCL Evulsion ant. cornua of internal meniscus
GCC08	F	5,75	Evulsion ant. cornua of external Meniscus
GCC09	F	7,38	Rupture posterior bundle MCL Breakaway Internal Meniscus Evulsion ant. cornua of external Meniscus Partial Rupture ACL
GCC10	F	7,74	Capsular Breakaway of Internal Meniscus

## DISCUSSION

The tests carried out in this study allow us to place the global response of the knee joint with respect to its macroscopic destruction as seen at the autopsies.

**BENDING TESTS** - The overall reaction of knees stressed in lateral bending is sufficiently homogenous to allow a behavioral law to be proposed in the following form : *Bending moment (Nm) = 6.2 Rotation angle (degrees)*

A tolerance corridor of about 25 Nm enables virtually all the experimental responses to be integrated. There is no fundamental difference between the male and female knee reactions.

The macroscopic knee injuries observed during the autopsy occurred at a rotation above 16° and a bending moment above 100 Nm. Comparatively, injuries obtained under dynamic conditions occur at slightly higher moments but at significantly lower rotating angles. Impact speed significantly reduces ligament extension possibilities.

**SHEARING TESTS** - The results of the 7 tests were used for the creation of the corridor in which two successive linear functions give the global behaviour of the knee. Initially, for lateral displacement less than 10 mm and where there is no injury, a simplifying linear function can be used :

$$\text{Force (N)} = 500 \times \text{Displacement (cm)}.$$

From 10 to 35 mm of displacement, the linear function used is an average of the slopes of the curves and can be written as :

$$\text{Force (N)} = 970 \times \text{Displacement (cm)} - 470.$$

There is no significant difference in the response of the knees of men and women. Physiologically, a normal knee has only one degree of freedom, bending and extension. Nevertheless, by using a stethoscope it was possible to account for the first internal disturbances of the knee which happen after a lateral tibia displacement about 12 mm in relation to the femur. The intensity of the sound event made it possible to situate the macroscopic lesions considered to be the most serious. These lesions occur after a lateral displacement of at least 22 mm. Although some minor incidents would certainly have taken place at this level, it can be considered that 20 mm is an acceptable limit value of the knee's resistance to static shear before reaching macroscopic injuries.

Dynamic impactor tests were carried out by LBA of Marseille (Kajzer et al, 1990) to analyse the effect of shear. The lateral displacements at the knee joint were not measured, only the force level associated with injury. The published results were  $2.57 \pm 0.37$  kN at 15 km/h and  $3.22 \pm 0.46$  kN at 20 km/h.

The force level associated with the critical points does not seem to be a pertinent indicator in our experiments because the values obtained were between 0.75 and 3 kN which correspond to a very large behavioural difference of the knee for this type of stress.

## CONCLUSIONS

The experimental tests carried out by the INRETS - LBSU give us the behaviour of the human knee. The proposed corridors reflect the global behaviour of the knee when it is solicited outside its physiological limits. In the case of quasi-static flexion, a linear relationship between the flexion moment and the rotation was proposed. In the case of quasi-static shear, two successive linear rules represent the applied force as a function of the lateral displacement of the tibia, with respect to the femur, in order to model the behaviour of the knee.

These results represent an asset which would be interesting to integrate into certain human mathematical models.

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