QUASISTATIC CHARACTERIZATION OF THE HUMAN FOOT-ANKLE JOINTS IN A SIMULATED TENSED STATE AND UPDATED ACCIDENTOLOGICAL DATA.

Philippe PETIT**, Laurent PORTIER**, Jean-Yves FORET-BRUNO*, Xavier TROSSEILLE*, Chantal PARENTEAU***, Jean-Claude COLTAT****, Claude TARRIERE*, Jean-Pierre LASSAU*****

* Biomedical Research Department - RENAULT S.A
Nanterre - FRANCE.
** Ecole Nationale Supérieure d'Arts et Métiers,
Paris - FRANCE.
*** Department of Injury Prevention,
Chalmers University of Technology, Gothenburg - SWEDEN.
**** Hôpital Intercommunal de Poissy,
Poissy - FRANCE.
***** Institut d'Anatomie de l'UFR Biomédicale des Sts Pères
Paris V - FRANCE

ABSTRACT :

EPIDEMIOLOGY - The magnitude and the type of lower leg injuries observed in real-world frontal accidents were investigated from the updated APR database. No significant difference of the injury risk was observed in the foot and ankle area neither between the right and left driver feet, nor between drivers and passengers. Although the foot-ankle injury risk linearly increased with footwell intrusion, 28% of the total number of injuries was observed to occur with a footwell intrusion smaller than 50 mm.

BIOMECHANICS - A total sample of 25 fresh amputated human legs were quasistatically tested in inversion, eversion and dorsiflexion in a simulated tensed state. Muscle tension was simulated by applying a constant tensile force in the Achilles tendon. The calcaneus was forced to rotate either in the sagittal or in the frontal plane. The average injury thresholds, the biomechanical responses and the positions of the joint centers of rotation were determined for the ankle and subtalar joints in inversion, eversion and dorsiflexion.
Additive tests were performed to assess the midfoot compliance.

ACCIDENTOLOGY

An investigation into the APR (Association Peugeot Renault) accident database has already been carried out in 1992 (Portier *et al.* 1993) to examine the magnitude and the type of lower leg injuries observed in real-world accidents. This investigation has been performed again from the updated data (early 1996).

Three characteristics were used to select 2553 occupants involved in a frontal car crash out of the database : 1- they were submitted to a single frontal collision with delta-V and acceleration known, 2- the cars involved were first registered after 1972, 3- the non-ejected front-seat occupants were restrained and their ages were known. Among the 2553, 238 front-seat occupants sustained at least either a sprain, a laceration into joint, a dislocation or fracture to the lower leg. Table 1 gives the injury typology of the sample.

It must be noted that the purpose was to count the occupants and not the injuries. In this way an occupant who sustained several injuries of the same type (for example 3 metatarsal fractures) was counted only once.

Table 1 : *Number of BELTED DRIVERS or PASSENGERS for each type of injury. Sample extracted from the APR database (1996).*

Tibia & fibula	46	Proximal epiphysis fracture	10	Tibial plateau fracture	6
				Fibula head or upper fibula fracture	6
		Diaphysis fractures	25	Tibial & fibula diaphysis fractures	10
				Tibial diaphysis fracture	6
				"Lower leg fracture"	2
				Fibula fracture	8
		Distal epiphysis fracture	16	Pilon tibial	7
				Tibia & fibula fracture, (distal part)	3
				Tibia fracture, (distal part)	3
				"Lower leg fracture" (distal part)	1
				Fibula fracture (distal part)	2
Ankle/ subtalar joints	**105**	**Malleolar fractures**	**48**	Medial malleolus fracture	17
				Lateral malleolus fracture	10
				Bilateral malleolus fracture	11
				Ankle fracture	9
				"Malleolus fractures"	2
		Ankle/subtalar sprains or dislocations	**65**	"Ankle sprain"	48
				Calcaneal-fibular sprain	10
				Deltoid ligament sprain	3
				"Ankle dislocation"	3
				Subtalar dislocation	9
Foot	**123**	Calcaneal fracture	18	Calcaneal fracture	17
				Achilles tendon tear	1
		Tarsal bone (except talus and calcaneus) fractures	**48**	Talar fracture	23
				Scaphoid fracture	12
				Cuboid fracture	11
				Cuneiform fracture	5
				"Foot fracture"	5
		Tarsal interosseous ligament tears	10	Tarsal bone dislocations	6
				Lisfranc-line sprain	3
				"Foot sprain"	1
		Metatarsal bone fractures	46	Metatarsal fractures	46
		Metatarsal sprains or disloc.	2	Metatarsal dislocations	2
		Toe fractures	14	Toe fracture	14
		Toe sprains or dislocations	14	Toe dislocation	13
				Toe sprain	1

The most prominent injuries were **ankle sprains** (65 cases), **malleolar fractures** (48 cases), **tarsal bone fractures** (talus and calcaneus excluded) (48 cases), and **metatarsal bone fractures** (46 cases).

The distribution of the right, left and bilateral injuries were investigated as a function of the occupant seat and the footwell intrusion (Table 2).

Table 2 : *Right and Left injury distribution for Drivers and Passenger as a function of Injury type and Footwell intrusion. Note : Bi. means bilateral injury and ? means unknown.*

Type of Injury	Footwell intrusion (mm)	168 BELTED INJURED DRIVERS (1713 involved)					70 BELTED INJURED PASSENGERS (840 involved)				
		RIGHT	**LEFT**	Bi.	?	Involved	**RIGHT**	**LEFT**	Bi.	?	Involved
Tibia	< 50	**3**	**5**	0	1	1250	**1**	**2**	0	0	704
+	50 - 150	**0**	**1**	0	0	200	**0**	**0**	0	0	64
fibula	> 150	**15**	**8**	1	0	263	**4**	**3**	2	0	72
Foot	< 50	**20**	**13**	1	1	1250	**9**	**13**	0	1	704
&	50 - 150	**12**	**11**	2	1	200	**4**	**2**	1	1	64
Ankle	> 150	**36**	**36**	9	1	263	**9**	**15**	6	1	72

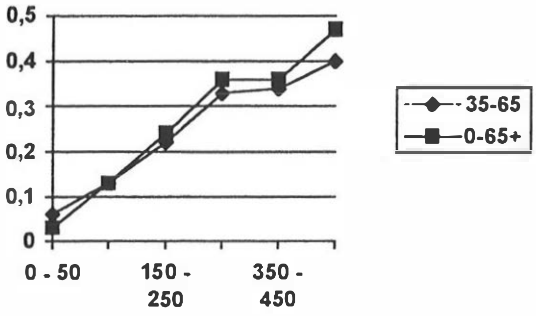
Whatever the intrusion class, Table 2 shows that no significant difference of injury risk was observed in the Ankle-foot area neither between drivers and passengers (χ^2=0,17 and 1,41 depending on the class of Delta-V) nor between the right and left feet of the drivers (χ^2=0,04).

Table 3 : *Number of Drivers or Passengers injured at the Foot or Ankle area as a function of Footwell Intrusion (mm) and Delta-V (km/h)*

Delta-V / Intrusion	DRIVERS and PASSENGERS (BELTED) 205 INJURED (at the FOOT or ANKLE area) / 2553 INVOLVED													
	0 - 50 mm		50 - 150 mm		150 - 250 mm		250 - 350 mm		350 - 450 mm		450+ mm		Total	
0 - 25	10	*717*	0	*1*	0	*0*	0	*1*	0	*0*	0	*0*	10	*719*
25 - 35	11	*590*	5	*42*	2	*10*	2	*4*	0	*0*	0	*2*	20	*648*
35 - 45	21	*374*	12	*113*	10	*45*	5	*14*	4	*11*	1	*5*	53	*562*
45 - 55	9	*170*	15	*81*	9	*48*	5	*29*	8	*22*	13	*23*	59	*373*
55 - 65	6	*68*	1	*19*	5	*15*	13	*26*	8	*25*	8	*27*	41	*180*
65+	1	*35*	1	*8*	3	*5*	2	*2*	4	*8*	11	*13*	22	*71*
Total	**58**	***1954***	**34**	***264***	**29**	***123***	**27**	***76***	**24**	***66***	**33**	***70***	**205**	***2553***
	Inju-red	*Invol-ved*	Inju-red	*Invol-ved*	Inju-red	*Invol-ved*	Inju-red	*Invol-ved*	Inju-red	*Invol-ved*	Inju-red	*Invol-ved*	Inju-red	*Invol-ved*

Table 3 gives the number of drivers or passengers injured at the foot or ankle area as a function of footwell intrusion and Delta-V. It clearly appears that the Ankle-Foot injury risk, defined as the ratio between the people injured and the people involved in the same conditions of Delta-V and intrusion, is linearly increasing with the footwell intrusion (Figure 1). The risk is ranging between approximately 5% and 45%. However, it must be noted that 28% of the total number of Ankle-Foot injuries occurred for footwell intrusion smaller than 50 mm. This ratio is 23% when calculated from the Ankle-Foot injuries which occurred at Delta-V ranging from 35 to 65 km/h.

Figure 1 : *Ankle-Foot Injury RISK as a function of Footwell Intrusion for the 35-65 Delta-V class and the whole sample.*



The results of this investigation somewhat differ from those reported by Portier (Portier *et al.* 1993). This is entirely due to the database update since the analysis methodology was strictly identical. It must be emphasized that the belted injured occupants were approximately twice as numerous in the updated database.

BIOMECHANICS

MATERIAL AND METHOD

Specimen data - A sample of 25 fresh amputated human legs was provided by the Anatomy Laboratory of the Saints Pères University (Paris). The height of each specimen was calculated as a function of the tibia length, sex and age using Equation 1 (Lentner,1991). The tibia length was measured on the X-rays taken prior to the tests. Table 4 gives the average age and height for the different tests, namely : inversion, eversion, dorsiflexion and midfoot flexion.

Equation 1

$$height(mm) = 786.2 + 2.52 \times tibia\ length(mm) - 0.6 \times [age(mm) - 30]: \textit{for males}$$

$$height(mm) = 615.3 + 2.90 \times tibia\ length(mm) - 0.6 \times [age(mm) - 30]: \textit{for females}$$

Table 4 : *mean age and mean height and number of specimen for the different types of tests.*

	Inversion	*Eversion*	*Dorsiflexion*	*Midfoot flexion*
Mean age (years)	78.3±10.9	75.6±11.6	77.0±10.9	81.1±9.2
Mean height (m)	1.63±0.09	1.68±0.15	1.63±0.08	1.63±0.11
Sample size (legs)	8	8	7	12

Specimen preparation - The specimens were preserved in a freezer at -30°C. They were thawed at room temperature 12 hours before testing.

The Achilles tendon was isolated over a length of about 20 cm from the calcaneus. The leg was amputated 15 cm above the malleolus, and soft tissues were removed over a length of about 5 cm from the proximal end of the tibia and fibula. The tendon was knotted tightly and then sewn to prevent the knot from sliding.

The proximal end of the leg was placed in an aluminum cup and fixed by 2 Steinmann pins inserted through both the tibia and the fibula. The cup was then filled with cement.

Once the cement was solidified, the heel was placed in a heel fixation cup and fixed by 3 pins of 3 mm in diameter inserted through the calcaneus. The gap between the heel and the box

was then filled with cement. As far as possible, the 3 pins were drilled according to the same template for each specimen, in order to obtain three reference holes on the X-rays.
X-rays were taken prior to and after the tests for each specimen. An autopsy was finally carried out for each specimen.

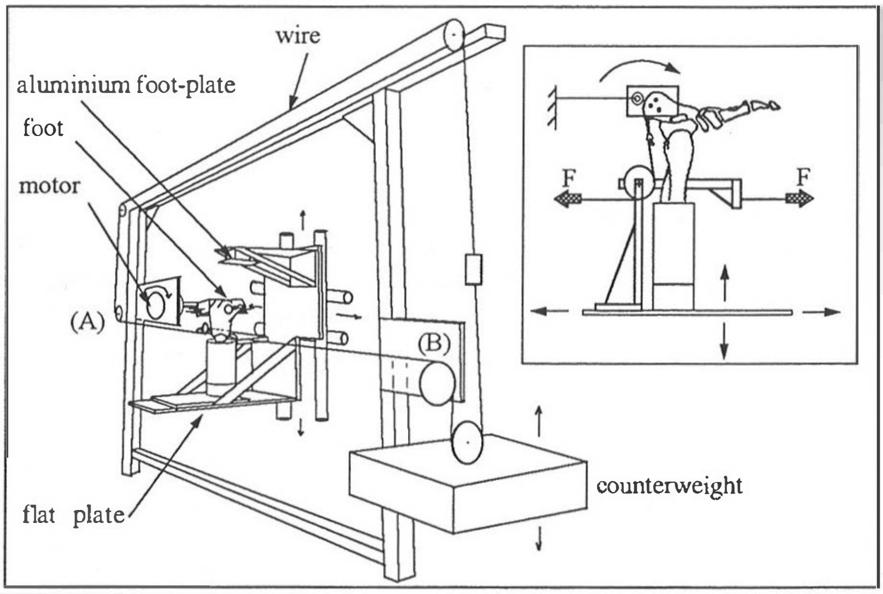
Experimental set-up - The first aim of the experiments was to obtain load/displacement characteristics and tolerance limits of the ankle-subtalar joints in a state of muscular contraction corresponding to an emergency braking. The second goal of the study was to investigate the ankle-subtalar joint kinematics. The last objective was the assessment of the midfoot compliance.

To compare directly the results obtained in this study with previous mechanical properties on the ankle-subtalar joints tested without muscle tension (Parenteau *et al.* 1995), the experimental set up was kept the same, except for the addition of a muscle tension simulating device.

The test set up was composed of two separated apparatus. A movement monitoring device was used to apply a linear increase of rotation on the calcaneus, as previously described by Parenteau (Parenteau *et al.* 1995), and the other apparatus applied a constant force on the Achilles tendon, simulating muscle tension.

The movement monitoring device was composed of an electronically controlled motor, a gear box, a frame and a flat plate. The flat plate was mobile in X and Z directions by means of two orthogonal low friction linear bearings. The tibia fixating cup of the specimen was secured on the flat plate through a 3 axis load cell. The weight of the instrumented specimen was compensated by an adjustable counterweight. The motor shaft was oriented in the Y direction and was connected to the heel fixation of the specimen through a torque transducer. The motor applied an angular movement to the calcaneus both in dorsiflexion and inversion/eversion tests.

Figure 2 : *Test set-up.*



The muscle tension simulation device was composed of a frame, 5 pulleys, a 4 mm in diameter kevlar wire and a counterweight. The counterweight was suspended onto a loop of the wire through a pulley, in order to insure the same constant tensile force in the two strands. One extremity of the wire was knotted to the Achilles tendon and the other to the flat plate of the test rig. The pulleys (A) and (B) were adjusted in the Z direction in order to align the two strands of the wire connected to the leg fixture (top right corner of Figure 2). The distance strands of the wire connected to the leg fixture (top right corner of Figure 2). The distance between (A) and (B) was chosen such that the ankle loading due to the variation of the two wire strand directions during the tests was negligible.

The assessment of the midfoot compliance was performed using the movement monitoring device with an aluminum foot-plate secured on the flat plate through a 3-axis load cell and a square.

Measurements - The data acquisition was performed by means of a PC equipped with a data acquisition board. Each measurement was performed at a sample rate of 100 Hz without any analogical filtering.

Two orthogonal forces (Fx and Fz) and one moment (My) acting at the distal end of the leg were measured by a strain gage socket sensor inserted between the distal fixing cup and the flat plate of the test rig. The X and Z linear displacements of the flat plate were recorded by two potentiometers. The angular displacement of the heel fixing cup (around the Y axis) was calculated from the linear displacement of a wire wrapped several times around the motor shaft. The torque (My) exerted by the motor shaft onto the heel cup was measured with a strain gage socket torque sensor. The Achilles tensile force was recorded by a strain gage transducer inserted in a strand of the counterweight wire. The vertical displacement of the counterweight was measured by a linear potentiometer.

The temperature of the specimens was measured prior to the tests.

Protocol - Two series of tests were performed : one in dorsiflexion, where a 900 N force was applied to the Achilles tendon, and one in inversion-eversion where the Achilles force was 400 N.

Once the specimen was instrumented, the proximal fixing cup was screwed onto the flat plate of the test rig, and the motor shaft was connected to the heel cup. The axis of the foot was either situated in the X or Y direction, depending on the type of test, respectively inversion/eversion or dorsiflexion.

Five complete cyclic movements (i.e. inversion and eversion, or dorsiflexion and plantar flexion) were imposed within the natural range of motion (15° inversion, 15° eversion, 25° dorsiflexion, and 35° plantar flexion).

The foot was repositioned at an angle of 90° relative to the tibia and the wire was attached to the Achilles tendon. As the data acquisition commenced, the counterweight was gradually suspended. It was taking about 5 s to obtain the proper tensile force in the tendon (900 N in dorsiflexion tests, 400 N in inversion/eversion tests).

A movement was imposed to the calcaneus at a constant velocity of 0.123 rad/s until the chosen angular limit had been reached (45° in inversion/eversion, 75° in plantar flexion, and 60° in dorsiflexion). The angular limits were supposed to systematically lead to failure (failure was defined as the first significant drop in moment which could be observed on the plots). Once the angle was decreased to 0 the data acquisition was stopped and the wire was disconnected from the tendon.

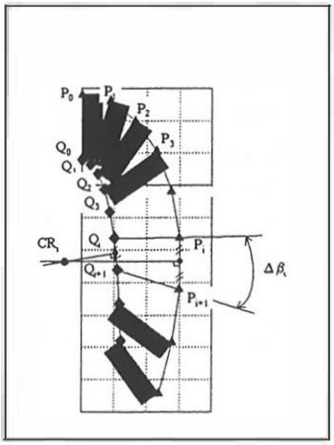
In some cases the specimen was also submitted to a midfoot compliance test. The leg was positioned as in dorsiflexion tests but the Achilles tendon was not loaded. An aluminum plate, fixed to the flat plate of the test rig through a 3 axis load cell, was placed in contact with the sole of the forefoot (from the head of the metatarsals to the toes). The calcaneus was then forced to rotate in the sagittal plane such that the forefoot was pressed onto the aluminum plate. The test was stopped as soon as an audible crack occurred.

The last task was the extraction of a transversal cylinder of cancellous bone from the calcaneus to assess the bone mineral content. It was performed by means of a template and a drill. The point of measurement of the calcaneus mineral content was situated 36 mm from the end of the heel and 40 mm from the sole of the foot.

ANALYSIS

Location of the joint centers of rotation in inversion, eversion, dorsiflexion and midfoot flexion - The determination of the joint centers of rotation was limited to a 2D problem since the movement of the calcaneus relative to the tibia was imposed in the XOZ plane by the motor shaft of the test rig.

Figure 3 : *Determination of the instantaneous centers of rotation. Note : β is the calcaneal angle. It was measured at the test rig motor shaft.*



For each test, the X and Z linear displacements of the flat plate were approximated by 2 third degree polynomial functions of the calcaneus angle. The coefficients of the functions were calculated using the least square method.

The positions $P_0, P_1, \ldots, P_n$ and $Q_0, Q_1, \ldots, Q_n$ of two points P and Q attached to the calcaneus were determined every 1 degree position of the calcaneus using the two approximated linear displacements of the flat plate and the angular displacement of the calcaneus. The instantaneous centers of rotation were defined as the intersection of the mid-perpendiculars of respectively the $[P_iP_{i+1}]$ and $[Q_iQ_{i+1}]$ segments (Figure 3). An average center of rotation (CR) was finally defined as the center of gravity of the succession of instantaneous centers of rotation.

Figure 4 : *Measurements in the frontal plane*

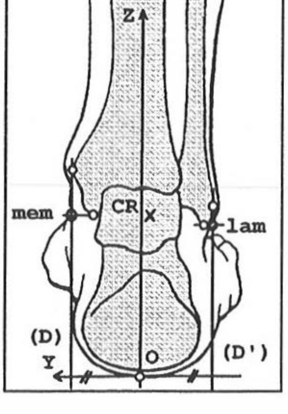
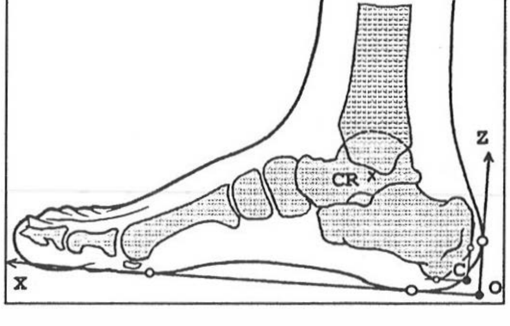


Figure 5 : *Measurements in the sagittal plane*



Once the CR was determined, it was manually reported on the X-rays taken after the tests. The block of cement previously used for the fixation of the proximal end of the tibia and fibula was taken as a reference (Figure 6,

Figure 7). The coordinates of the CR, the medial and lateral malleoli and the most posterior and distal point of the calcaneus were then noted in a coordinate system attached to the foot (Figure 4, Figure 5). In the frontal plane, the coordinates of the malleoli were defined as those of the intersection of a straight line tangent to the malleolus and parallel to the Z axis with a straight line tangent to the malleolus and parallel to the Y axis. The Z axis was defined as the axis parallel to the leg axis and equidistant to the 2 malleoli.

Ankle-subtalar joint responses in dorsiflexion and inversion-eversion in a simulated tensed state - For each specimen, the ankle moment was defined as the moment acting in the joint. It was calculated at the CR using both distances measured either on the specimens prior to the test or on the X-rays and the data recorded by the computer.

When existing, a failure point was defined on the ankle moment versus calcaneus angle plot as the last point before the first significant drop of moment (approximately 10 Nm). The failure points and the maxima reached by the calcaneal angle and the ankle moment were noted for each test. The ankle moments of the specimens tested in the same conditions were then averaged and plotted. Corridors were defined by the average±standard deviation curves.

Note: it sometimes happened that a slight lack of accuracy in the distance measurements provoked an offset in the ankle moment due to the high importance of the Achilles force in the calculation. In that case the offset was removed by a translation of the ankle moment plot in order to have it equal to zero at a calcaneal angle of zero. Those slight modifications were reported in the failure point and maxima values.

Figure 6 : *Free body diagram of the leg in dorsiflexion*

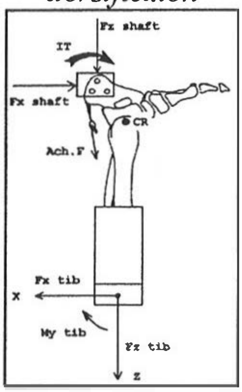
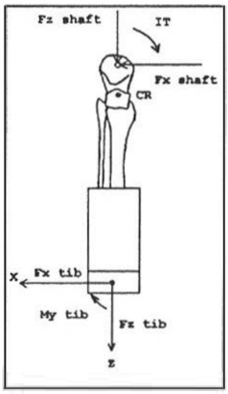


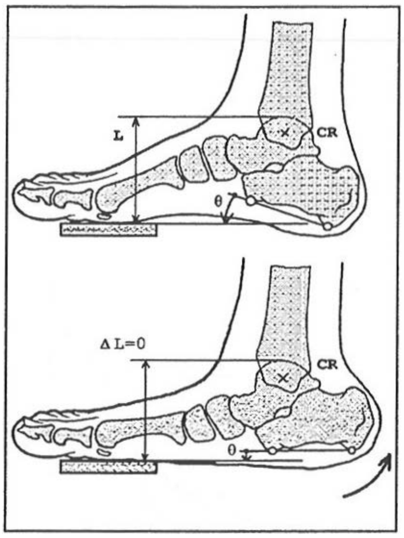
Figure 7 : *Free body diagram of the leg in inversion-eversion*



Midfoot compliance - The midfoot compliance assessment was limited to a 2D problem. The bending moment acting in the midfoot cross sections was calculated at the center of rotation of the ankle joint using the forces acting in the X and Z directions at the center of the aluminum footplate.

The bending moments of every specimen were averaged and reported on a moment at the CR versus the calcaneal angle plot. A corridor was defined by the average ± standard deviation curves.

Figure 8 : *Midfoot compliance test*



RESULTS

Geometrical description - (Figure 4, Figure 5, Table 5) From a sample of 7 legs, the CR was located in dorsiflexion at a distance of 76±8 mm from the sole of the foot and 61±6 mm from the posterior face of the heel.

From another sample of 16 legs, the CR in inversion-eversion was situated at 85±12 mm from the sole of the foot and 3±12 mm from the posterior face of the axis of the leg.

From the whole sample (23 legs tested either in dorsiflexion or inversion-eversion), soft tissues were observed to be respectively 8±4 mm and 17±4 mm in depth at the posterior and distal face of the heel. The medial and lateral malleoli were situated respectively at 83±13 mm and 69±12 mm from the sole of the foot and 34±3 mm transversally from the leg axis.

Table 5: *specimen data for each of the test subsamples. Xc and Zc give the soft tissue thickness; Xcr, Ycr and Zcr are the coordinates of the average calculated center of rotation; Ylam and Zlam are the coordinates of the lateral malleolus; Ymem and Zmem are the coordinates of the medial malleolus; L tibia is the tibia length (from the malleolus to the tibia plateau).Note: all the distances and coordinates are given in mm.*

		Xc	Zc	Xcr	Ycr	Zcr	Ylam	Zlam	Ymem	Zmem	L tibia	age
WHOLE sample (23 legs)	mean	8	17				-34	69	34	83	363	77
	std dev.	4	4				3	12	3	13	35	11
DORSIFLEXION subsample (7 legs)	mean	9	16	61		76	-35	60	35	74	356	77
	std dev.	5	4	6		8	2	16	2	14	24	11
INVERSION-EVERSION subsample (16 legs)	mean	8	17		-3	85	-34	73	34	87	365	77
	std dev.	3	4		12	12	4	7	4	10	40	11

Ankle-subtalar joint responses in dorsiflexion and inversion-eversion in a simulated tensed state - As previously noted, failure was defined as the first significant drop in moment (approximately 10 Nm) observed on the ankle moment versus calcaneal angle plots.

In dorsiflexion, failure was observed at 47±17 Nm and 49±5°.

In inversion failure occurred at 40±26 Nm and 34±8 ° while eversion failure was at 35±9 Nm and 32±7 °.

Figure 9 : *Ankle-subtalar quasistatic response in dorsiflexion in a simulated tensed state*

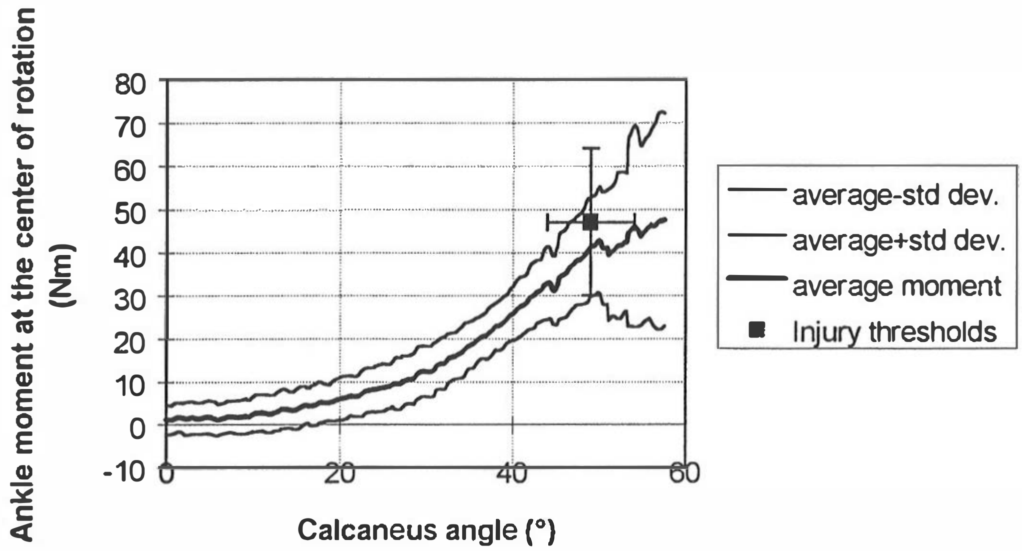


Figure 10 : *Ankle-subtalar quasistatic response in inversion-eversion in a simulated tensed state*

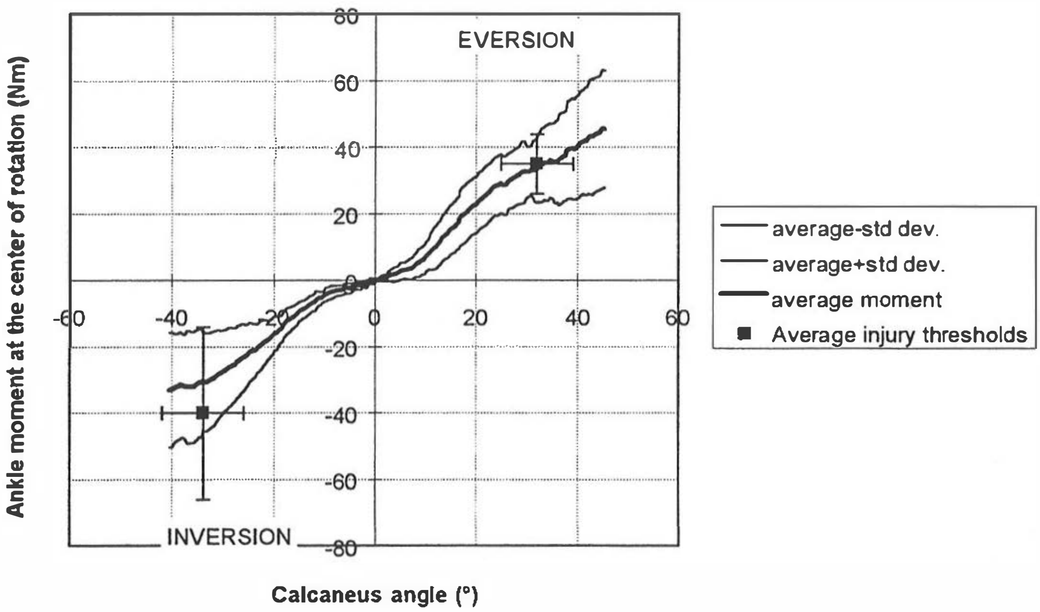
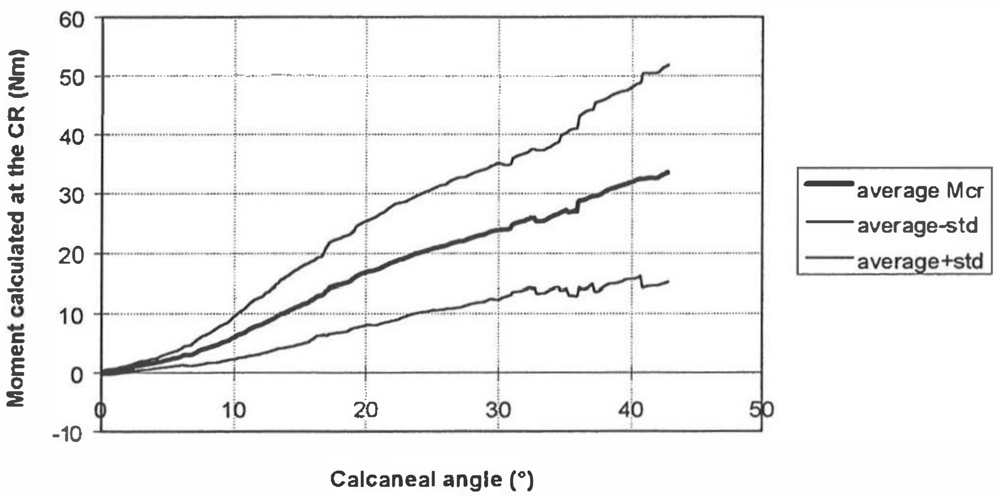


Figure 9 shows the average joint response in dorsiflexion in a simulated tensed state. Figure 10 shows the average responses in inversion and eversion.

The injuries caused by the tests were principally medial malleolus fractures and calcaneofibular ligament tears in dorsiflexion, lateral malleolus fractures and calcaneofibular ligament tears in inversion, and medial malleolus fractures and deltoïd rupture in eversion.

Midfoot compliance - Figure 11 shows the average bending moment acting in a midfoot cross section calculated at the ankle joint CR. The CR was determined from the midfoot bending test data, using the method previously described.

Figure 11 : *Human midfoot average bending moment as a function of the calcaneal angle. A corridor was defined by the average moment ± std dev*



DISCUSSION -The mechanical properties of the braced plantarflexors remain unclear for large range of motion movements, but many authors have studied the maximum allowed stress in the Achilles tendon (Conkrite 1936, Strucke 1950, Yamada 1970, Grafe 1969, Wilhem 1975, Komi 1984). Early investigations strongly differ. However, Grafe examined acrobatic jumps in floor exercises and found that the Achilles tendon could sustain a dynamic load of 5300 N on average.

On the other hand, studies performed on volunteers at Renault showed that 25% of the drivers placed in real conditions of emergency did not exert the 200 N load on the brake pedal that was necessary to obtain the maximum braking power.

For our biomechanical study, the Achilles force was first chosen equal to 900 N in order to correspond approximately to a load of 450 N on the brake pedal. However, it appeared that such a force several times resulted in calcaneus tear or fractures (2 cases out of 7) at the pin insertions (the pins were used for the heel fixation to the motor shaft). In such cases, the records were not used neither to calculate the average response, nor for the injury thresholds. That is the reason why the Achilles force was decreased to 400 N for the inversion-eversion

test series. However, in 1 case in eversion, the calcaneus anchorage provoked a calcaneus fracture and the test was then put aside.
In dorsiflexion tests, the calcaneus was observed to have a plantarflexion movement of approximately 10° prior to the beginning of the motor rotation. This was the result of the Achilles force on the calcaneus fixation. The angle records were corrected to eliminate this artifact.

Table 6 : *Angle and ankle moment injury thresholds observed with and without muscle tension in the Achilles tendon in parallel with the proposal for the dummy foot-ankle joint stop development.*

	Without muscle tension Parenteau *et al.*	With muscle tension Petit *et al*	Proposal for dummy soft joint stops (Viano)
Dorsiflexion	33±17 Nm 44±11 °	47±17 Nm 49±5°	50±10 Nm 45 °
Plantarflexion	43 Nm 72±6 °	-	40±10 Nm 70 °
Inversion	33±8 Nm 32±7 °	40±26 Nm 34±8 °	35±10 Nm 35 °
Eversion	48±12 Nm 30±4°	35±9 Nm 32±7 °	50±10 Nm 30 °

Although the joint average responses with and without muscle tension were very similar (Figure 12, Figure 13) the injury thresholds somehow differed. Parameters such as specimen to specimen variations and the low number of specimens were probably responsible for the main part of those differences. Indeed, since some specimen did not sustain any injury, only 3 specimens were used to calculate the average injury threshold in dorsiflexion, 5 in inversion and 5 in eversion.

Figure 12 : *Human Ankle-subtalar joints tested in inversion and eversion. Comparison of the responses with and without muscle tension.*

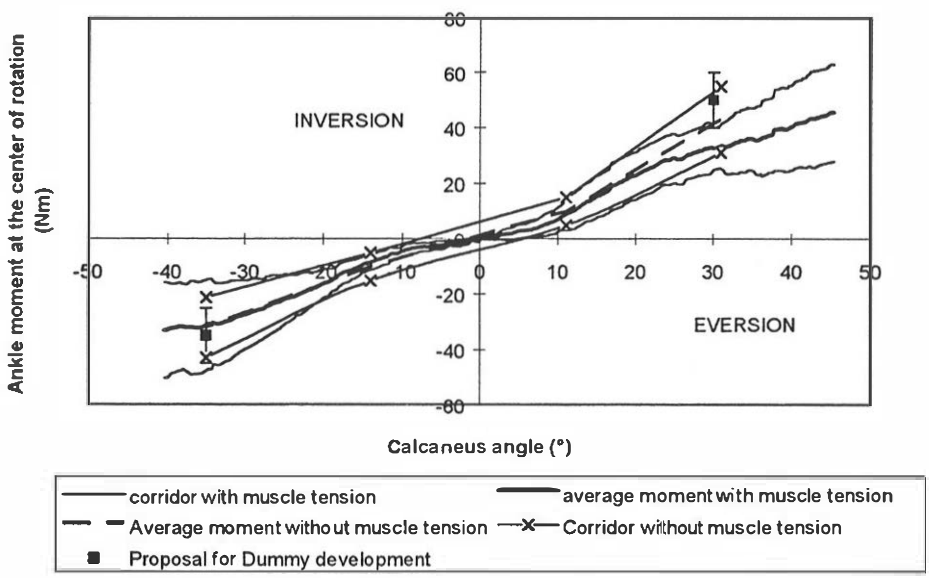


Figure 13 : *Human Ankle-subtalar joints tested in dorsiflexion. Comparison of the responses with and without muscle tension*

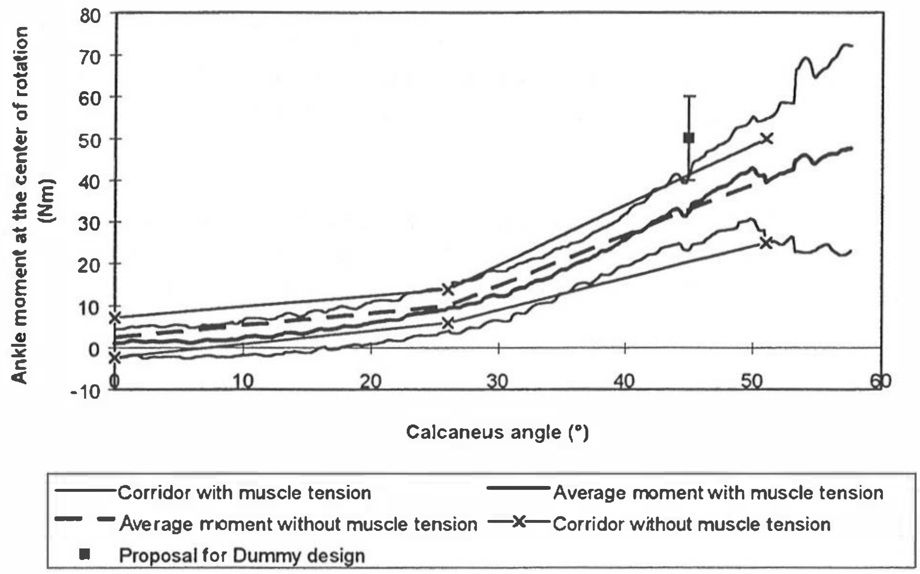


Figure 10, and Figure 11 show the average injury thresholds superimposed on the average joint responses. It must be noted that the average moment responses were calculated from the whole test sample while the injury thresholds were calculated using only the specimens which sustained injuries. That is the reason why the injury thresholds do not necessarily belong to the average response curves.

Several authors (Kapandji 1989, Parenteau 1995) have found that in the natural range of motion, the inversion-eversion movement principally takes place in the subtalar joint, while the dorsiflexion-plantarflexion movement does so in the ankle joint. This description is geometrically supported in this study. Indeed, in the sagittal plane, the trace of the proximal articular surface of the talus is mostly in shape of a circle, the center of which could be approximated by the average CR determined using the test data.

Figure 9 and Figure 10 show that when the calcaneal angle was greater than approximately 40° in dorsiflexion, 30° in eversion and 33° in inversion the corridors defined by the average moment ± standard deviation significantly increased. This was due to the decrease of the number of specimens taken into account. Indeed, most of the specimens were injured at approximately those angular values (3 out of 5 in dorsiflexion, 5 out of 8 in inversion and 5 out of 7 in eversion). The average responses were calculated using only the specimen responses prior to the failure. As a consequence, the accuracy of the average responses clearly decreases for the angular values greater than those limits.

Many low range of motion joints are involved in the midfoot movements. That is the reason why the choice of the point where the bending moment acting in a midfoot cross section is calculated, is of primary importance. This point must be such that its determination either on a cadaver (whatever his size), or on a more or less sophisticated model (physical or mathematical) is repeatable. The joint CR has got all of those characteristics and was already used in the ankle moment calculations.

The boundary conditions of the midfoot compliance tests must be emphasized. As previously described, an angular movement was imposed to the calcaneus in order to force the sole of the forefoot to squeeze an aluminum footplate. The footplate and the proximal end of the tibia were both secured to the flat plate. It is then clear that : 1- the distance in the Z direction between the footplate and the ankle joint articular surface remained constant during the test (Figure 8), 2- the movements taking place in the subtalar joint were included in the angular movement of the calcaneus relative to the foot-plate which was recorded. Although the subtalar joint range of motion was found negligible relative to the ankle joint range of motion in dorsiflexion-plantarflexion by Parenteau, it must be taken into account in the midfoot sagittal motion.

ACKNOWLEDGEMENTS - The authors greatly appreciated the support and enthusiasm of Dr David Viano (General Motors Corporation) for the biomechanical study.

The assistance of Dr François Guillon and Dr Wu is gratefully acknowledged.

REFERENCES :

1. CONKRITE A. (1936), Anat. Rect. 64,173-186.
2. GRAFE H. (1969), « Aspekte zur Ätiologie der subcutanen Achillessehnenruptur » Zentralblatt f. Chirurgie 94; 33, 1073-1082.
3. KAPANDJI I. A. (1989), « Physiologie articulaire Tome 2 : Membres inférieurs ». Malvoine S.A. Editeur.
4. KOMI P. V. (1984), « Biomechanics and Neuromuscular Performance »Med. Sci. Sports Exerc. 16, 26-28.
5. LETNER, C. (1981), « Geigy Scientific Tables », Cibia-Geigy Limited, v. 1, 1981.
6. PARENTEAU C. S., VIANO D. C, LÖVSUND P. (1995), « Foot-Ankle Injury. Epidemiological and Biomechanical Studies ». In proceedings of the Pelvic and Lower Extremity Injuries Conference, Washington DC Dec. 1995.
7. PARENTEAU C. S.and VIANO D. C.(1995), « A new Method to determine the Biomechanical Properties of Human and Dummy Joints ». In proceedings of the IRCOBI conference 1995.
8. PORTIER L., TROSSEILLE X., LE COZ J.Y., LAVASTE F. (1993), « Lower Leg Injuries in Real World Frontal Accidents ». In proceedings of the IRCOBI conference 1993.
9. STRUCKE K. (1950) « Über das elastiche Verhalten der Achillessehne im Belastungsversuch. », Langenbecks Arch. Chir. 265, 579-599.
10. TARRIERE Claude (1995), « Biomechanical Synthesis of New Data on Human Lower Leg Responses and Tolerances in Parallel with Dummy and Injury Criteria ». In proceedings of the Pelvic and Lower Extremity Injuries Conference, Washington DC Dec. 1995.
11. WILHEM H.(1975), « Die subcutane Achillessehnen Ruptur », Unfallheilkunde, 121-330.
12. YAMADA H. (1970), « Strength of Biological Materials. » Strength of Biological Material. Williams & Wilkins, Baltimore.