CADAVER LOWER LIMB DYNAMIC RESPONSE IN INVERSION-EVERSION

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ABSTRACT

The aim of this study was to determine the subtalar joint dynamic behaviour in inversion-eversion. A purpose-built test rig was developed to impose the foot rotation along the xversion axis. Six inversion tests and six eversion tests were performed on six pairs of human cadaver legs. Accelerations, angular velocities, forces and moments were measured on the forefoot, calcaneus and leg in order to assess the force balance acting at the subtalar joint.

The fibula contribution and the relative motion between the forefoot and the calcaneus were determined. The subtalar joint moment was evaluated with respect to the xversion angle of the forefoot and of the calcaneus.

BIOMECHANICS, CADAVERS, DYNAMICS, FOOT, LEG

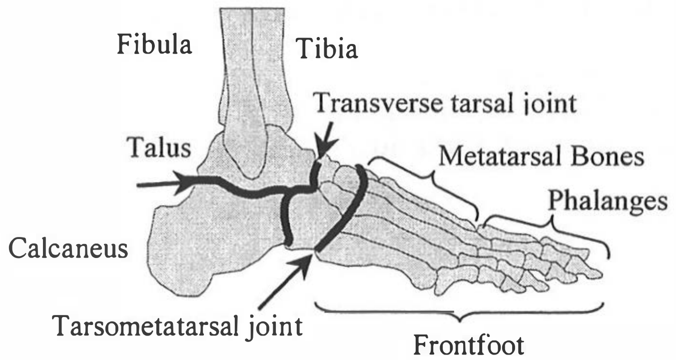
LOWER EXTREMITY INJURIES are frequent and while they are not life threatening they can cause permanent disability. Morgan et al (1991) reported that lower extremities were the second most common site of AIS2+ injuries for belted occupants. According to Lestina et al (1992) inversion-eversion is the most frequent mechanism that causes lower limb injuries in frontal impacts.

In order to reduce the number and the severity of these injuries ankle/foot numerical models and dummy lower limbs are developed and improved. Therefore a good comprehension of the foot and the leg joint kinematics and internal loading is needed.

Several cadaver studies on lower limbs have been published. Dynamic dorsiflexion tests were conducted by Begeman et al (1990) and Portier et al (1997). Static dorsiflexion and static xversion tests were conducted by Parenteau et al (1995) and Petit et al (1996). Cadaver lower limb dynamic response to inversion and eversion was studied only by Begeman at al (1993). Parenteau and Petit (1998) reported a static failure moment of 34.1±14.5Nm in inversion and of 48.1±12.2Nm in eversion. The failure angle was 34.3±7.5 degrees in inversion and 32.4±7.3 degrees in eversion. Begeman calculated the moment in the ankle joint and reported a failure angle in inversion and eversion of 60 degrees (±6). This angle appeared to be a better threshold for injury than the moment calculated in the ankle. Indeed forces and moments in the ankle were not well correlated with injury or angular deflection. In order to further document the relationship between moment and angle, we designed a purpose-built test rig for achieving xversion dynamic tests.

Tests consisted of applying the type of dynamic loading to the foot that might occur in vehicle crashes and that creates xversion, and assessment of foot and leg internal loads in these conditions. The goal was to produce pure inversion without axial loading. The first aim was to determine the relative motion between the forefoot and the calcaneus in the xversion. The forefoot includes the metatarsal bones and the phalanges (Figure 1). The second aim was to determine the dynamic moment--calcaneus angle response curves and dynamic moment-forefoot angle response curves in inversion and eversion before failure. Accelerations, angular velocities, forces and moments were measured on the forefoot, the calcaneus and the leg.

Figure 1 – Anatomy of the foot



METHODOLOGY

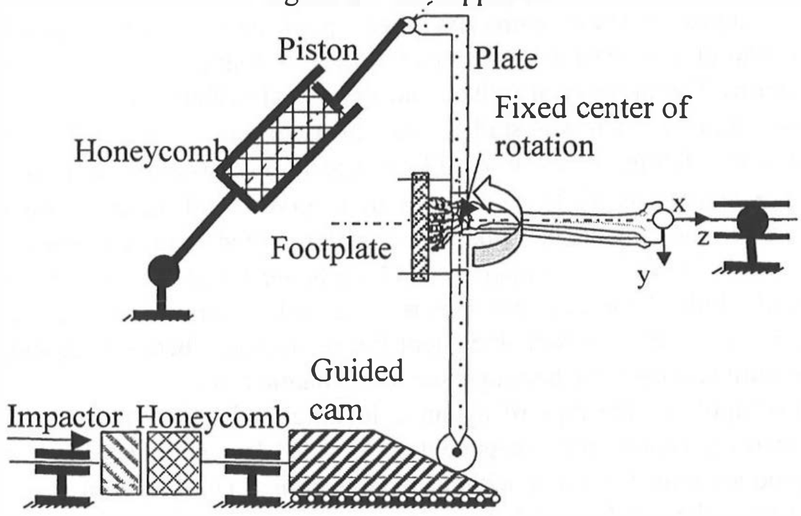
SPECIMEN DATA: The tests were conducted on six pairs of thawed fresh frozen human cadaver lower limbs. Both male and female specimens were tested and ranged in age from 73 to 90. Cadaver information is presented in Table 1.

Table 1 – Cadaver data

Subject	522		523		524		525		526		527	
Sex	M		F		M		M		M		F	
Age	85		86		73		87		89		90	
Weight (kg)of	Right	Left	Right	Left	Right	Left	Right	Left	Right	Left	Right	Left
Lower limb	3.31	3.18	3.36	3.40	4.04	3.79	3.26	3.19	3.29	3.28	2.04	2.27

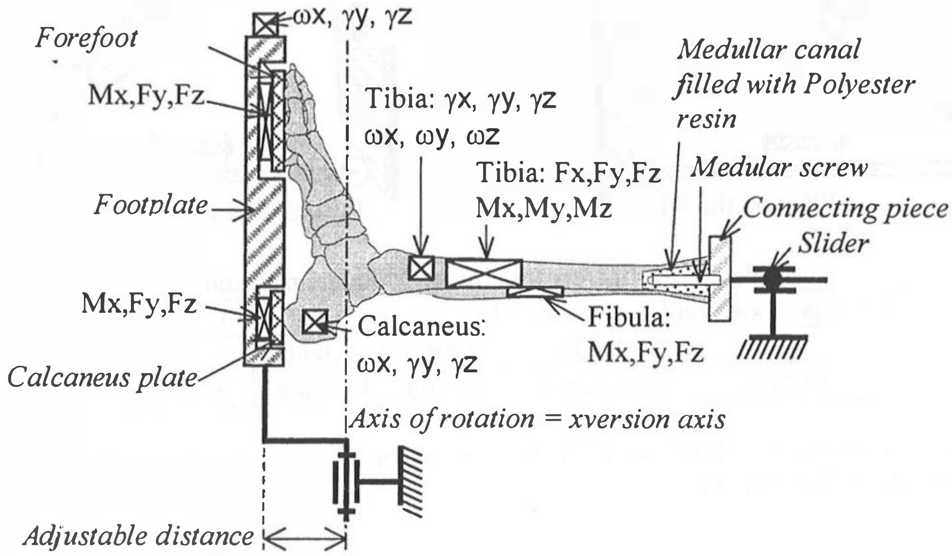
TEST SET-UP: The test apparatus (Figure 2) consisted of a plate free to rotate about a fixed vertical axis and of a footplate mounted to the plate and adjustable in the z axis. The plate, on the one side was forced to rotate through 40 degrees via a guided cam impacted by an impactor, and on the other side activated a piston which crushed a honeycomb. The continuous contact between the cam and the plate was assured by the crush of the honeycomb.

Figure 2 – Test apparatus



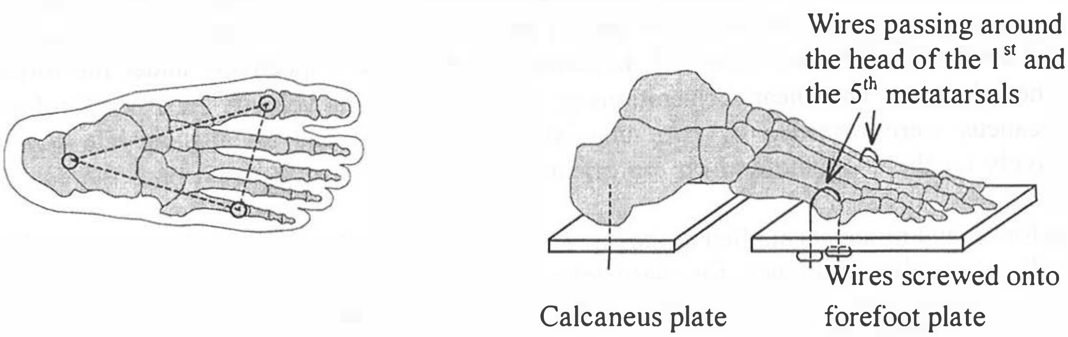
The leg, amputated just under the knee at the tibial plateau, and with all musculature preserved was mounted horizontally to the test apparatus. The medullar canal was cleaned and filled with polyester resin. A connecting piece secured the tibial plateau to a slider via a screw inserted in the medullar canal resin. The ligaments and the tendons were attached to the connecting piece. The foot positioned vertically was fixed to the footplate. For each foot an adjustment of the footplate in relation to the plate in z axis allowed the plate rotation axis to be superimposed on the xversion axis (Figure 3) previously defined on Xrays according to the results reported by Parenteau (1995).

Figure 3 – Lower limb position and instrumentation



In half of the tests only the forefoot was fixed to the plate in order to determine the relative motion between the forefoot and the calcaneus, and to determine the subtalar joint moment when only the forefoot is forced to rotate. In the other half of the tests both the forefoot and the calcaneus were fixed in order to determine the subtalar joint moment when both the forefoot and the calcaneus are forced to rotate. In both cases fixation respected the anatomic support points of the foot defined by previous Xrays (Figure 4). In both cases subtalar joint moment could be determined thanks to the load cells implanted under the forefoot and under the calcaneus.

Figure 4 – Foot support points and foot fixing



The foot was fixed to the footplate by a forefoot fixing on a forefoot plate and a calcaneus fixing on the calcaneus plate. The forefoot was fixed to the forefoot plate by metal wires passing around the head of the first and the fifth metatarsals, and screwed under the forefoot plate. The calcaneus was fixed to the plate by a screw into the calcaneus. The forefoot rotation was assumed to be the same asthe plate rotation and the calcaneus rotation was expected to be lower. That is why the angle of 40 degrees was chosen for the plate rotation, which is lower than the plate rotation applied in the Begeman et al (1993) dynamic tests which produced severe injuries, and higher than the calcaneus angle applied in the Parenteau and Petit (1998) static tests.

The plate and the piston were able to be mounted on the right or on the left side of the impactor in order to create inversion and eversion for a right and a left foot (Figure 5). The motion created by the footplate position and the tested foot are explained in Table 2.

Figure 5 – Footplate position toward the impactor

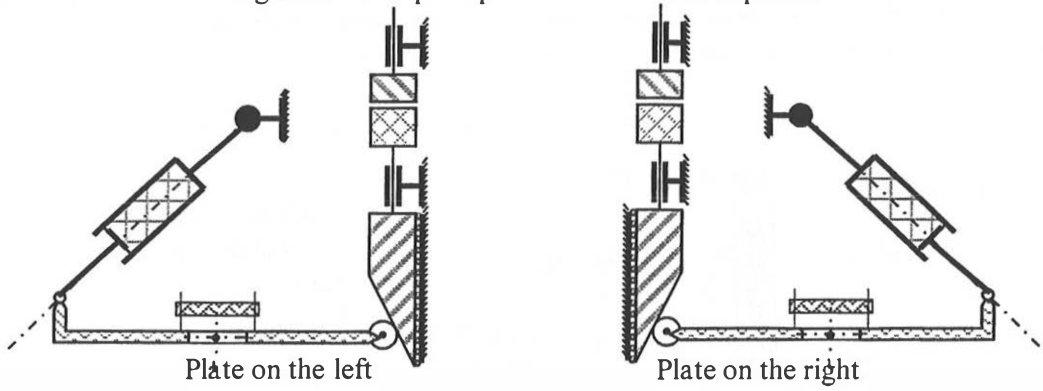


Table 2 – Motion created by the footplate position

Footplate position	Right		Left	
Foot	Right	Left	Right	Left
Motion	Inversion	Eversion	Eversion	Inversion

Six tests were performed with the plate on the right of the impactor and six tests were performed with the plate on the left (Table 3).

Table 3 – Test matrix

Test	29	30	31	32	33	34	38	39	40	41	42	43
Footplate position	R	R	R	R	R	R	L	L	L	L	L	L
Cadaver	522	522	523	523	524	525	524	525	526	526	527	527
Foot	R	L	R	L	R	L	L	R	R	L	R	L
Calcaneus	free	free	free	free	free	free	fixed	fixed	fixed	fixed	fixed	fixed
Motion	Inv	Ev	Inv	Ev	Inv	Ev	Inv	Ev	Ev	Inv	Ev	Inv

INSTRUMENTATION: Accelerations, angular velocities, forces and moments were measured on the forefoot, the calcaneus, and the tibia. On the fibula only forces and moments were measured.

The forces Fy, Fz and moment Mx acting on the forefoot and acting on the calcaneus were recorded with two 3-channel load cells implanted on the plate respectively under the forefoot and under the calcaneus. The linear accelerations γy, γz and the angular velocity ωx of the forefoot and of the calcaneus were recorded by two uniaxial accelerometers and an angular rate sensor fixed respectively on the footplate and on the calcaneus. The sensors were fixed onto the calcaneus by screws.

The forces and moments applied to the leg were recorded by a load cell implanted in the tibia and a load cell, especially developed for these tests, implanted in the fibula. It seemed interesting to determine accurately the load supported by the fibula in inversion and eversion motions. The tibia load cell and the mounting procedures were the same as those used by Portier et al (1997) in dynamic dorsiflexion tests. The fibula load cell was designed and mounted in the same manner as the tibia load cell taking into account fibula dimensions. The motion of the leg was measured with accelerometers mounted to a triaxial angular rate sensor. The sensor was fixed with metal wire to the tibia.

ANALYSIS:

Inversion-eversion: Kapandji (1989) determined that the xversion natural range of motion principally takes place in the subtalar joint but also in the transverse tarsal joint. The measurement of the forefoot, calcaneus and leg angular velocities relative to the fixed laboratory coordinate system allowed the determination of the rotations of the calcaneus relative to the leg in the subtalar joint and of the forefoot relative to the calcaneus in the different midfoot joints, theoretically in the transverse tarsal joint but it was not demonstrated in this study.

According to Parenteau et al (1998) the xversion center of rotation was assumed to be fixed at the subtalar joint. The center of rotation was determined for each limb with Xrays prior to testing.

Force and moment: Xversion forces and moments were evaluated at the subtalar joint center of rotation. Forces and moments were calculated on the one side with the leg test data and on the other side with the foot test data as:

$$\begin{aligned} MOx_{foot>leg} = {} & Ix_{leg} \bullet \omega' x_{leg} + m_{leg} \bullet (OG_{leg} y \bullet \gamma z_{Gleg} - OG_{leg} z \bullet \gamma y_{Gleg}) \\ & - Mx_{tibia} - OTy \bullet Fz_{tibia} + OTz \bullet Fy_{tibia} \\ & - Mx_{fibula} - OBy \bullet Fz_{fibula} + OBz \bullet Fy_{fibula} \end{aligned} \qquad (1)$$

$$Fy_{foot>leg} = m_{leg} \bullet \gamma y_{Gleg} - Fy_{tibia} - Fy_{fibula} \qquad (2)$$

$$Fz_{foot>leg} = m_{leg} \bullet \gamma z_{Gleg} - Fz_{tibia} - Fz_{fibula} \qquad (3)$$

$$\begin{aligned} MOx_{leg>foot} = {} & Ix_{foot} \bullet \omega' x_{foot} + m_{foot} \bullet (OG_{foot} y \bullet \gamma z_{Gfoot} - OG_{foot} z \bullet \gamma y_{Gfoot}) \\ & - Mx_{forefoot} - ORy \bullet Fz_{foreoot} + ORz \bullet Fy_{forefoot} \\ & - Mx_{calcaneus} - OHy \bullet Fz_{calcaneus} + OHz \bullet Fy_{calcaneus} \end{aligned} \qquad (4)$$

$$Fy_{leg>foot} = m_{foot} \bullet \gamma y_{Gfoot} - Fy_{forefoot} - Fy_{calcaneus} \qquad (5)$$

$$Fz_{leg>foot} = m_{foot} \bullet \gamma z_{Gfoot} - Fz_{forefoot} - Fz_{calcaneus} \qquad (6)$$

Where O is the center of rotation, G is the center of gravity, T, B ,R H are respectively the tibia, the fibula, the forefoot and the calcaneus load cells, m is the mass, I is the moment of inertia, ω' is the angular acceleration, γ is the linear acceleration, M is the moment, F is the force, x is the postero-anterior axis of the tibia, y is the transverse axis of the tibia, z is the axis along the tibia.

For the calculation the distal part of the leg is considered. This is defined as starting from the middle of the fibula and tibia load cells and extending to the talus, the foot included the entire foot with its sensors and without the talus.

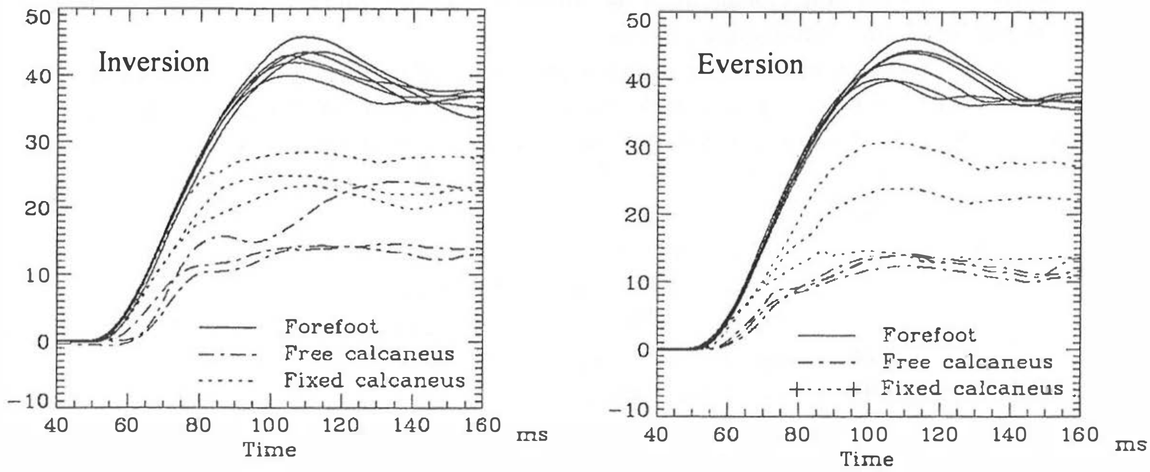
The mass and the moments of inertia used in the calculation were measured for each foot and each leg after testing. The moments of inertia were measured at the center of gravity from free oscillation of an oscillating plate.

RESULTS

AUTOPSY: After the tests a post-experimental dissection was performed on each limb. No injury was observed.

INVERSION-EVERSION: Forefoot and calcaneus rotations were calculated relative to the leg, and forefoot rotation was determined relative to the calcaneus. In all the tests the calcaneus rotation was inferior to the forefoot rotation imposed by the plate (Figure 6). In inversion the calcaneus angle ranged from 14.5 to 28.5 degrees, forefoot angle ranged from 40 to 46 degrees, forefoot rotation relative to the calcaneus ranged from 11 to 32 degrees. In eversion calcaneus angle ranged from 12.5 to 30.5 degrees, forefoot angle ranged from 40 to 46 degrees, forefoot rotation relative to the calcaneus ranged from 12 to 32 degrees. Therefore in inversion and in eversion angles were similar, and in both motions the rotation of the forefoot relative to the calcaneus was considerable. The different joints between the transverse tarsal joint and the tarsometatarsal joint play an important role in the xversion motion however as the joints were not isolated the contribution of each joint in the overall xversion kinematics was not assessed.

Figure 6 – Forefoot and calcaneus inversion and eversion rotations (degrees)



CENTER OF ROTATION: The center of rotation was 63±4mm from the sole of the foot. This distance is compared in table 4 to the distances reported by Petit et al (1996) and Crandall et al (1996).

Table 4 – Center of rotation position relative to the sole of the foot (mm)

Current study	Petit et al (1996)	Crandall et al (1996)
63±4	85±12	71±12

FORCES AND MOMENTS:

Foot measurements: Generally moments applied to the foot were higher in eversion than in inversion, in particular when the calcaneus was fixed (Table 5). When the calcaneus was fixed the force applied to the calcaneus was higher than the force applied to the forefoot in inversion and lower in eversion. The midfoot joints stiffness seemed to be higher in eversion.

Table 5 – Moments measured under the forefoot and the calcaneus (Nm)

		Inversion			Eversion		
Free foot	Forefoot	18	8	27	29	24	39
	Calcaneus	2	2	5	2	2	3
Fixed foot	Forefoot	17	5	14	55	45	20
	Calcaneus	26	31	19	43	32	20

Leg measurements: The tibia and the fibula were more stressed axially than laterally. Tibia axial force was about five times the lateral force in inversion and four times as high in eversion. Fibula axial force was about four times as high as the lateral force in inversion and seven times as high in eversion.

Peak axial forces measured on the tibia for the inversion ranged from 130N to 340N and for the eversion ranged from 130N to 400N. For the fibula the peak axial forces for the inversion ranged from 30N to 90N and for the eversion ranged from 20N to 350N. Peak inversion moments measured on the tibia ranged from 6Nm to 16Nm and peak eversion moments ranged from 1Nm to 4Nm. Average forces and moments were higher for the eversion than for the inversion. And when the calcaneus was fixed tibia and fibula loads were higher than when the calcaneus was free. Average loads measured on the leg are summarized in Table 6.

Table 6 – Loads measured on tibia and fibula for all tests

		Tibia			Fibula		
Motion	Calcaneus	Mx (Nm)	Fy (N)	Fz (N)	Mx (Nm)	Fy (N)	Fz (N)
Inversion	Fixed	17; 11; 13	65; 48; 75	219;336;163	2;1 ; 1	25;21;13	67; 63; 58
	Free	6; 7; 11	29; 23; 50	128;141;127	1; 1; 1	5; 8; 11	41; 10; 23
Eversion	Fixed	28; 25;17	159; 104;98	396;116;195	4; 2; 2	27;31;10	352;188;139
	Free	15; 12; 15	42 ;43; 68	139;128;130	1; 1; 1	8; 8; 19	42; 23; 103

The lateral force measured on the fibula was approximately 14 to 29% in inversion and 13 to 22% in eversion of the total lateral leg force. The axial force measured on the fibula was approximately 13 to 26% in inversion and 13 to 50% in eversion of the total axial leg force. The inversion moment measured on the fibula was approximately 4 to 14% and the eversion moment was 3 to 12% of the total leg moment.

Calculated forces and moments at center of rotation: The subtalar forces and moments were calculated at the fixed center of rotation using equations 1, 2, 3, 4, 5 and 6.

Foot measurements allowed the calculation of an inversion moment of between 13Nm and 31Nm and an eversion moment of between 20Nm and 66 Nm. Leg measurements allowed the calculation of an inversion moment of between 13Nm and 40Nm and an eversion moment of between 24Nm and 71Nm. In both cases the average eversion moment was higher than the inversion moment.

DISCUSSION

Inversion-eversion: The rotation in the midtarsal joint was considerable. In the tests where only the forefoot was fixed to the plate the proportion of the forefoot rotation relative to the calcaneus ranged from 44% to 72% in relation to the forefoot rotation relative to the leg. Therefore it is important to specify when speaking about xversion if the rotation is the forefoot or the calcaneus rotation

Calcaneus rotation was compared to the failure angles determined by Parenteau and Petit (1998) in static tests. In Begeman et al (1993) dynamic tests the xversion angle was measured on the footplate, as was measured the forefoot rotation in this study, therefore the forefoot rotation was compared to the failure angle determined by Begeman (Table 7).

Table 7 – Measured xversion angles compared to failure xversion angles (degrees)

	Calcaneus		Forefoot	Parenteau and Petit (1998)	Begeman (1993)
	free	fixed			
Inversion	19±5	26±3	43±3	34±8	60±6
Eversion	13±1	22.5±8	43±3	32±7	60±6

Angles measured in this study were lower than the failure angles, which is in agreement with the fact that no injury was observed. Further research will be conducted to determine an injury threshold in dynamic xversion. Even in the tests where the calcaneus was fixed the calcaneus rotation was lower than the footplate rotation. Fixing the calcaneus by a screw did not allow the footplate rotation to be imposed on the calcaneus. Therefore in order to impose a calcaneus rotation up to 40 degrees, which is higher than the static failure angle reported by Parenteau and Petit the calcaneus fixation will be changed in further research.

Leg measurements: Leg axial measurements were low because of the translation of the proximal tibia respect to the knee slider. The source of the forces measured by the tibia and fibula load cells is the leg inertia and muscle and ligament tension. In inversion the tibia was compressed and pressed laterally by the talus, the fibula was sometimes compressed and sometimes in tension, and it was pulled laterally by the ligaments and tendons (Figure 7). In eversion the tibia was sometimes compressed and sometimes in tension and it was pulled laterally by the ligaments and tendons, the fibula was compressed and pressed laterally by the talus (Figure 7). Some rebounds of the heel on the footplate, due to the soft tissues under the calcaneus, probably caused the tensions and compressions of the tibia and of the fibula respectively in eversion and inversion. These rebounds can explain the noise in the measures. The axial forces measured on the tibia and fibula in an inversion test and in an eversion test are shown in figure 8 and 9.

Figure 7 – Compressions and tensions of the tibia and fibula in inversion and eversion

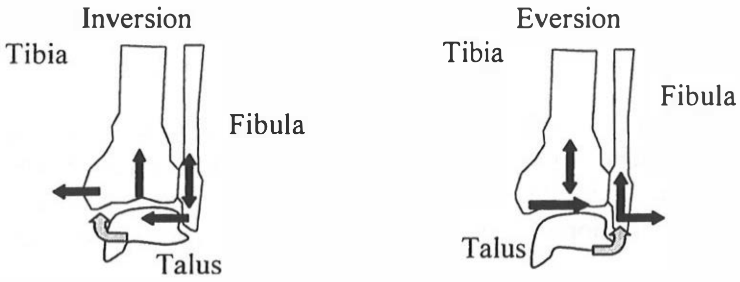


Figure 8 – Fz forces (daN) measured on the fibula and the tibia in eversion, calcaneus fixed on the footplate (test 39)

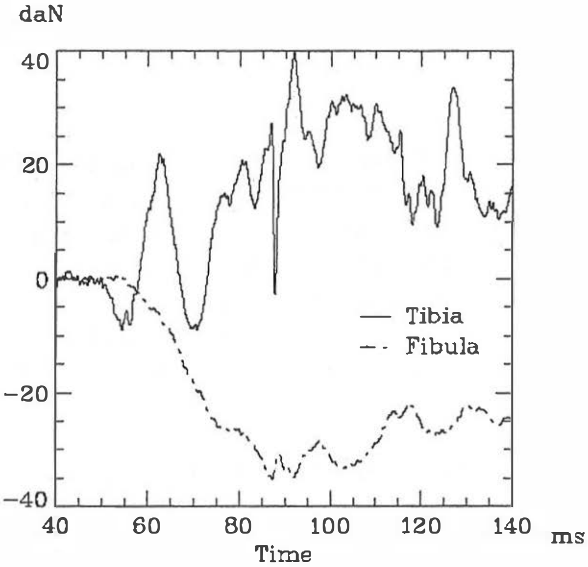
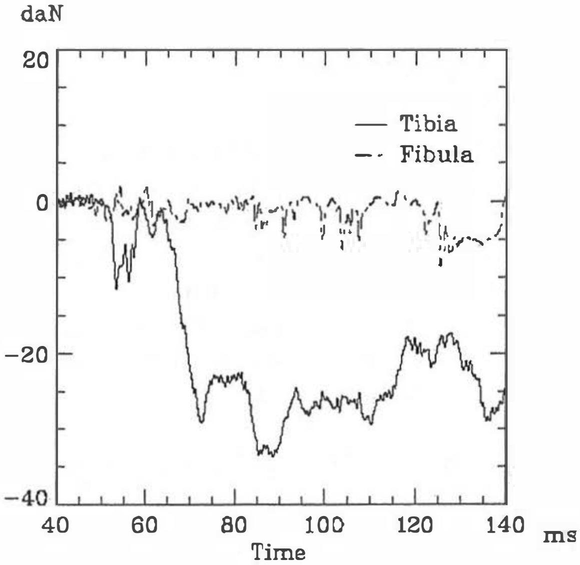


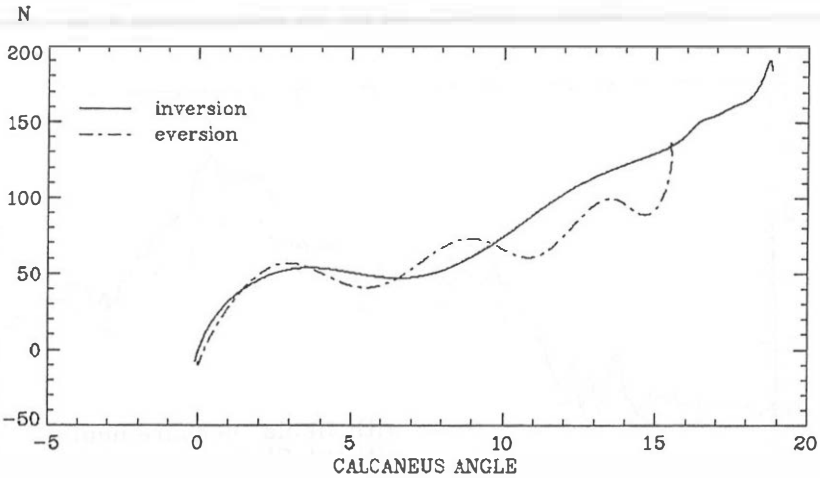
Figure 9 – Fz forces (daN) measured on the fibula and the tibia in inversion, calcaneus fixed on the footplate (test 41)



The proportion of the load sustained by the fibula was considerable. The fibula axial force was up to 50% of the total axial force measured on the leg. This is much higher than the proportion reported by Crandall et al (1996) who found that fibula sustains 7 to 12% of the total applied load with the foot in the neutral position.

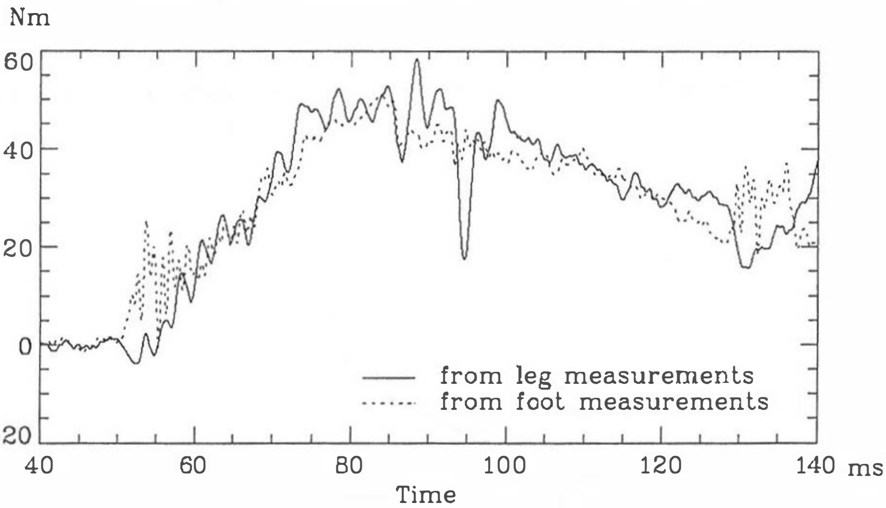
Calculated forces and moments at center of rotation: Loads in the subtalar joint were from leg measurements and also from foot measurements. A difference was observed between the axial force estimated from the leg and that from the foot. The load calculated from the leg measurements was due to bone contact and ligament tensions. Whereas the load calculated from the foot measurements was due to bone contact, to ligament tensions and to surrounding tibia and fibula musculature. Therefore the difference in the axial forces was supposed to be the passive muscle force as it was observed in dorsiflexion motion (Portier 1997). This force seemed to be linear as a function of xversion angle. The peak force estimated up to 190N in xversion was much lower than the force estimated up to 1900N in dorsiflexion, but in this study the rotation stopped before failure. The average passive musculature forces in inversion and in eversion were similar (Figure 10).

Figure 10 – Average passive muscle axial force (N) as a function of inversion and eversion angle (degrees)



Contrary to the dorsiflexion tests there was no significant difference in the joint moment (Figure 11). The moment arm of the muscle force in relation to the subtalar joint center of rotation was low enough not to create a resistance moment.

Figure 11 – Subtalar joint moments (Nm) calculated from foot measurements and from leg measurements for the eversion test n°40



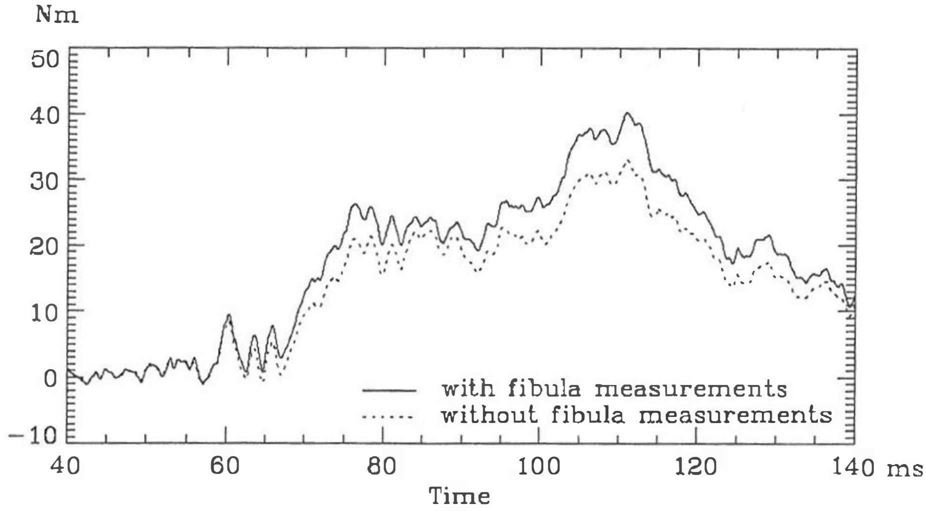
The subtalar joint peak moments were approximately in the range of failure moments reported by Begeman (1993) for dynamic xversion with no dorsiflexion, and by Parenteau and Petit (1998) for static xversion, whereas no injury was observed (Table 8).

Table 8 – Calculated xversion moments compared to failure moments (Nm)

Moment determined:	from foot measurements	from leg measurements	by Parenteau and Petit (1998)	by Begeman (1993)
Inversion	13 to 31	13 to 40	18 to 59	34 to 38
Eversion	20 to 66	24 to 71	29 to 66	18 to 55

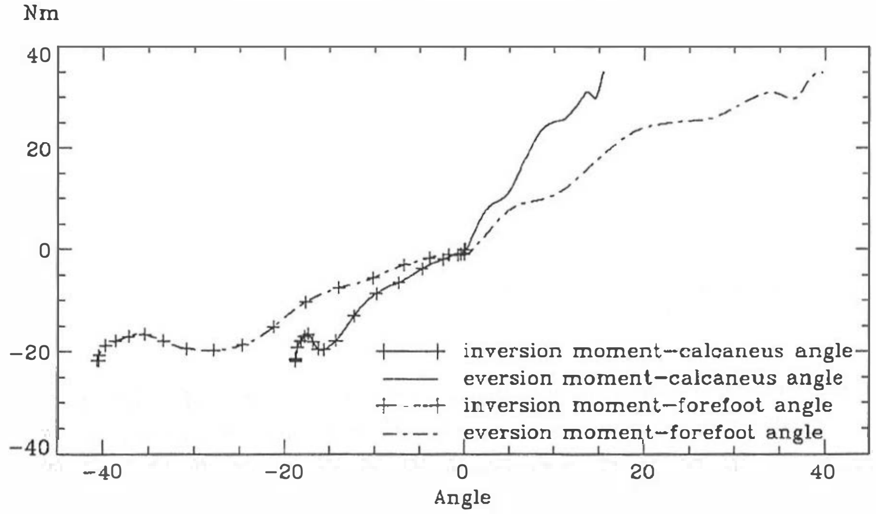
The moment calculated from leg measurements was also calculated without taking into account the fibula measurements in order to determine the contribution of the fibula to the subtalar joint behaviour (Figure 12). The moment was decreased from 8% to 17.5% when the fibula measurements were not taken into account. The contribution of the fibula forces was of 12% in average of the total calculated moment.

Figure 12 - Subtalar joint moments (Nm) calculated with fibula measurements and without fibula measurements for the inversion test n°38



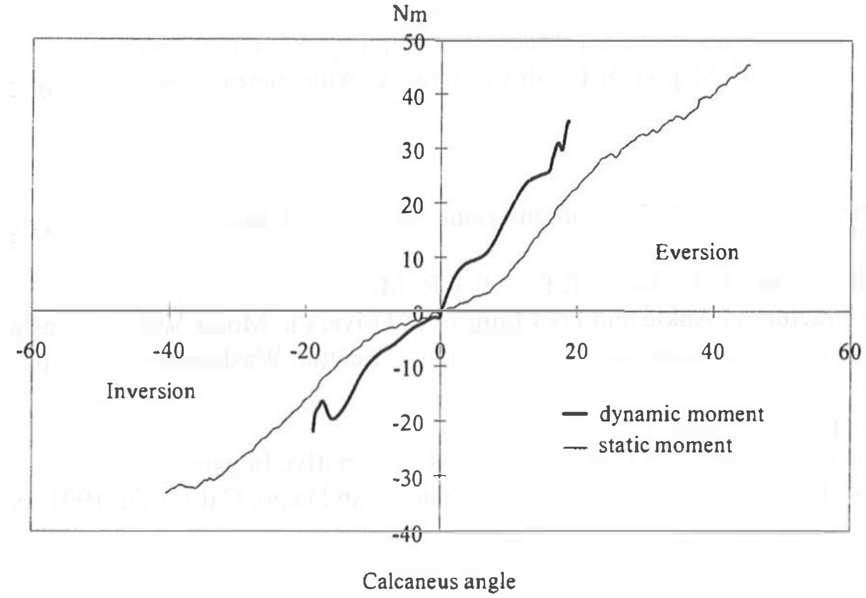
Moment and inversion-eversion angle time histories were combined to evaluate subtalar joint moment as a function of inversion-eversion angle. Figure 13 shows the average moment-angle responses for calcaneus and forefoot rotation. In inversion the average moment was maximum at 22Nm, at a calcaneus angle of 19 degrees and at a forefoot angle of 41 degrees. In eversion the moment was maximum at 35Nm, at a calcaneus angle of 16 degrees and at a forefoot angle of 40 degrees.

Figure 13 – Average moment–angle (Nm/degrees) responses in inversion and eversion for calcaneus and forefoot rotation



A comparison of the xversion dynamic tests and static tests (Petit 1996) is presented in Figure 14. The moment shown is a function of the calcaneus angle. The subtalar joint dynamic stiffness was about twice as high as the static stiffness. The stiffness estimated from the forefoot rotation was of about 0.5Nm/deg in inversion and 0.9Nm/deg in eversion, the stiffness reported by Begeman was of 0.5Nm/deg.

Figure 14 – Average dynamic (current study) and static (Petit 1996) moment responses (Nm/degrees) at the center of rotation in inversion and eversion



CONCLUSION

This study focused on inversion and eversion dynamic motions. It provided new knowledge of the foot/ankle complex behaviour, necessary to develop and improve numerical models and dummies.

We first of all quantified the forefoot contribution in the global xversion motion. Up to 72% of the forefoot xversion could take place in the midtarsal joint. Therefore the midfoot kinematics joint should be taken into account in numerical models and in dummy design.

An original methodology was developed in order to measure the loads supported by the fibula in inversion and eversion motions. Thus we determined that in eversion the fibula load could be equal to the load supported by the tibia and that the fibula contribution was up to 17.5% of the total moment in the subtalar joint, which indicates a major contribution of the fibula to the subtalar joint behaviour in xversion.

We also estimated the axial force due to passive muscle in inversion and eversion. It was linear as a function of xversion angle.

Finally we evaluated the subtalar joint moment at a fixed center of rotation, as a function of inversion and eversion angle before failure.

Further research will be conducted, the 40 degrees rotation will be imposed to the calcaneus in order to determine an injury threshold.

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