LOWER EXTREMITY RESPONSE AND TRAUMA ASSESSMENT USING THE THOR-Lx/HIIIr AND THE DENTON LEG IN FRONTAL OFFSET VEHICLE CRASHES

Shashi Kuppa, Mark Haffner, Rolf Eppinger, James Saunders
National Highway Traffic Safety Administration, USA
Paper No. 456

ABSTRACT

NHTSA has recently released the documentation for manufacture and use of the Thor-Lx Hybrid III retrofit (Thor-Lx/HIIIr), an advanced lower extremity device that fits on the Hybrid III 50th percentile male dummy at the distal femur. In order to compare the response of the Thor-Lx/HIIIr and the Denton leg in the vehicle crash environment, NHTSA conducted a series of vehicle crash tests where 40 percent of the vehicle's frontal structure along the driver's side engaged the EU deformable barrier. The test series consisted of 4 pairs of crash tests using a belted Hybrid III 50th percentile adult male dummy in the driver's position. Pairs of tests were conducted under identical crash conditions using the same vehicle make, model, and model year with the Denton legs on the dummy in one test and the Thor-Lx/HIIIr legs on the dummy in the other test. This paper presents a detailed analysis of the responses of the Hybrid III dummy and the two types of legs in the paired crash tests.

Injury assessments for the leg-foot/ankle complex using existing injury criteria for the Denton leg and recently proposed injury criteria for the Thor-Lx/HIIIr are also presented. The predicted injury outcome from each of the leg types is compared to lower extremity trauma in real world crashes.

INTRODUCTION

NHTSA has recently developed the Thor-Lx Hybrid III retrofit (Thor-Lx/HIIIr) **-** an advanced lower extremity test device that fits on to the distal femur of the Hybrid III 50th percentile adult male dummy, and released the documentation for its manufacture and use. Laboratory experiments (Portier, et al. 1997; Rudd, et al., 1999; and Petit, et al. 1999) have demonstrated that, in pendulum impact tests, the force, moment, and foot kinematics responses of the Thor-Lx/HIIIr were more human cadaver-like than the responses of the Denton leg (with 45 degrees ankle and soft joint stop). The laboratory experiments have also demonstrated that the detailed instrumentation and the more human cadaver-like response of the Thor Lx/HIIIr offers more extensive injury assessment capability for the lower limbs than the Denton leg.

In order to compare the response of the Thor-Lx/HIIIr and the Denton leg in the vehicle crash environment, NHTSA conducted a series of vehicle crash tests where 40 percent of the vehicle's frontal structure on the driver's side engaged the EU deformable barrier (40% left offset). The test series consisted of 4 pairs of crash tests at 60 and 64 km/h initial vehicle velocity, using a belted Hybrid III 50th percentile adult male dummy in the driver's position. Each pair of tests were conducted under identical crash conditions using the same vehicle make, model, and model year with the Denton legs on the dummy in one test and the Thor-Lx/HIIIr on the dummy in the other test.

These tests were intended for direct paired comparison of the performance of the Thor-Lx/HIIIr and the Denton legs as well as their influence, if any, on the head, neck, and chest injury measures of the Hybrid III dummy. The durability of the two lower extremity devices was also evaluated. Injury assessment for the lower limbs using existing injury criteria for the Denton leg and recently proposed injury criteria for the Thor-Lx/HIIIr was conducted and the predicted injury outcome was compared to injuries in real world crashes.

DESCRIPTION OF THE THOR-Lx/HIIIr AND THE DENTON LEG

The design and construction of the Thor-Lx/HIIIr is significantly different from the Hybrid III Denton leg (Figure 1). The Thor-Lx/HIIIr design was based on recent biomechanical data which include guidelines for the basic geometric dimensions of the lower extremity, location of the ankle and subtalar joints, inertial properties of the leg and foot (Crandall, et al. 1996), static and dynamic response characteristics due to axial loading at the heel (Kuppa et al., 1998), and the static and dynamic torque-angle characteristics at the dorsiflexion and inversion/ eversion joint centers of rotation (Portier, 1997 and Petit, 1996). In accordance with these guidelines, the Thor-Lx/HIIIr construction includes a compliant element in the leg for biofidelic axial load response, an Achilles tendon to simulate passive resistance of musculature to dorsiflexion, separate location of dorsiflexion and inversion/ eversion joint centers of rotation represented by the ankle and subtalar joints, and continuous torque-angle joint characteristics (Shams, 1999). Internal and external rotation capabilities are also available.

The leg shaft of the Denton leg is offset from the line of action between the knee and ankle joint centers in contrast to the Thor-Lx/HIIIr which has a straight leg shaft (Figure 1). The dorsiflexion and inversion/eversion joint centers in the Denton leg are at the same location and are represented by a single ball joint. The torque-angle characteristics of this joint are discontinuous, with very low resisting torque until the joint stops are engaged at 45º dorsiflexion, after which the moment increases dramatically. Both the Thor-Lx/HIIIr and the Denton leg knee clevis connect to the Hybrid III dummy at the distal femur through a low friction ball bearing knee slider.

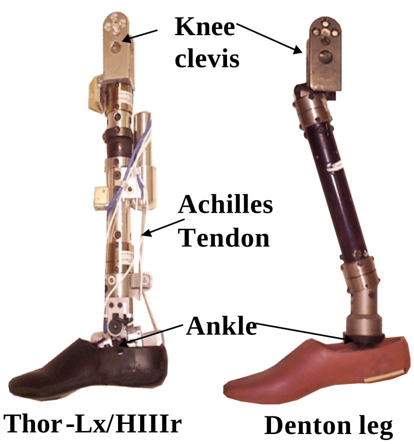


Figure 1. Thor-Lx/HIIIr and the Denton leg.

The instrumentation on the Thor-Lx/HIIIr (Figure 2) consist of a 5-axis lower tibia load cell, a 4-axis upper tibia load cell, triaxial accelerometers at the midfoot and biaxial accelerometers at the tibia, and rotational potentiometers to measure dorsiflexion, inversion/ eversion, and internal/external rotation of the foot.

The Denton leg is instrumented with up to 5-axis upper and lower tibia load cells and biaxial accelerometers near the heel and a uniaxial accelerometer at the toe (Figure 3). The tibia/femur relative translation was measured using a potentiometer connected to the knee slider in the Thor-Lx/HIIIr and the Denton leg.

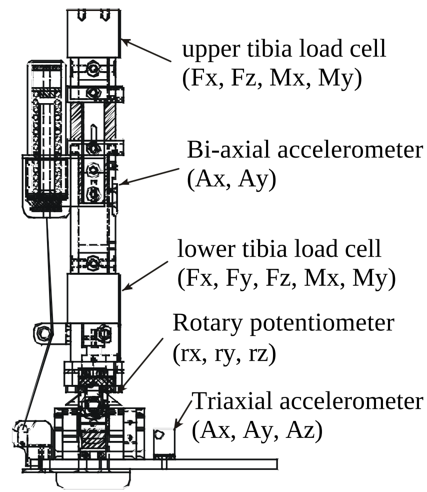


Figure 2. Instrumentation in the Thor-Lx/HIIIr.

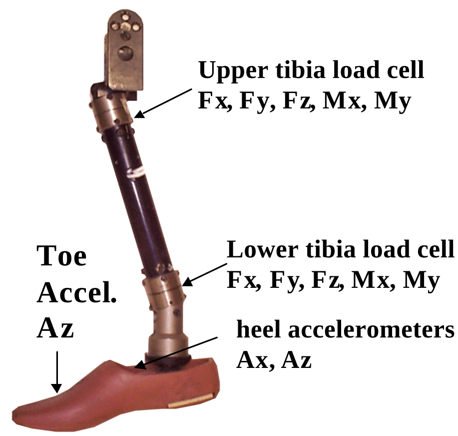


Figure 3. Instrumentation in the Denton leg.

VEHICLE CRASH TESTS

The instrumentation on the vehicles included accelerometers at the rear of vehicle and the toepan. Post-crash static longitudinal vehicle crush and toepan intrusion were measured. The amount of vehicle crush was measured in a similar manner as that in NASS-CDS. The location of longitudinal toepan intrusion measurements are shown in Figure 4. The center toepan location in Figure 4 corresponds to a point on the toepan that is along a longitudinal axis directly behind the brake pedal. The left and right toe pan locations are on either side of the center.

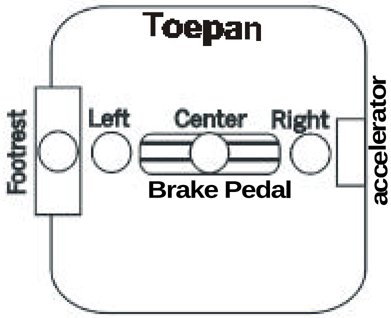


Figure 4. Location of intrusion measurement on the toepan.

The make, model, and model year of the vehicles used in the 40% left offset crash into the EU deformable barrier (40% of the vehicle front along the left aspect engaging the barrier) are presented in Table 1. The measured initial velocity, the percent offset, the peak vehicle deceleration (filtered by SAE Channel Frequency Class 60), measured peak crush of the vehicle front structure, and the peak longitudinal intrusion of the toepan, foot plate and brake pedal for each test are also presented in Table 1.

The maximum vehicle crush measurements are considerably different in the paired crash tests of the Dodge Neon and the Subaru Legacy. Some of the differences in the toepan, footplate, and brake pedal intrusion in the four paired tests may be attributed to differences in measurement location and measurement techniques. The post-crash measured peak left toepan longitudinal intrusion did not correlate to the post-crash measured peak vehicle longitudinal crush (R^2=0.01). For example, the Subaru Legacy in the test with the Thor-Lx/HIIIr had the highest maximum vehicle crush but the lowest measured toepan intrusion, while the Nissan Altima and the Dodge Neon had both high peak vehicle crush and high toepan intrusion.

Table 1. Vehicle crash characteristics of 40% left offset tests into EU deformable barrier using the Denton leg and the Thor-Lx/HIIIr retrofit

vehicle characteristics	Toyota Camry 1996		Nissan Altima 2000		Dodge Neon 1998		Subaru Legacy 2000	
	Denton	Thor-Lx	Denton	Thor-Lx	Denton	Thor-Lx	Denton	Thor-Lx
vehicle speed (kph)	60.8	60.67	63.9	63.6	60.25	60.8	64	64.47
percent offset	41%	41%	41%	40%	40%	39%	40%	41%
peak deceleration (g's)	32.9	26	28.77	26.2	33.9	27.5	35	38.6
max. vehicle crush (mm)	670	680	670	700	835	567	690	742
left toepan intrusion (mm)	123	115	350	276	276	260	90	70
toepan center intrus.(mm)	130	154	330	265	273	217	170	74
right toepan intrus. (mm)	85	147	260	227	207	195	90	33
brake pedal intrusion(mm)	90	102	250	227	323	221	130	159
foot rest intrusion(mm)	105	122	270	263	226	162	70	90

Table 2. Injury measures in paired vehicle offset crash tests and FMVSS 208 allowable limits for the Hybrid III 50th percentile adult male

Injury measures	Allowable limits	Camry		Altima		Neon		Legacy	
		Denton	Thor-Lx	Denton	Thor-Lx	Denton	Thor-Lx	Denton	Thor-Lx
HIC15	700	256	245	307	146	182	271	210	213
Neck Tension (N)	4170	1038	944	1302	1022	1562	1708	2129	1957
Neck Compression (N)	4000	1589	693	160	54	771	442	169	574
Nij	1	0.58	NA	0.26	0.18	0.4	NA	0.43	0.37
chest Acc (gs)	60	33	30.7	37.1	32.1	37.4	38.6	48.5	45.8
chest defl (mm)	63	21.5	24.5	31.6	23.6	30.7	28.9	31.7	26.7
femur Fz left (N)	10000	2276	2227	3510	2701	7266	4611	2507	3264
femur Fz right (N)	10000	2958	2893	2247	2214	3946	3830	2827	3112

HYBRID III DUMMY RESPONSES

The injury measures used in FMVSS 208 (Interim final rule, 5/12/00) - HIC15, peak neck tension and compression, Nij, peak 3-msec clip of chest acceleration, peak chest deflection, and femur forces are presented in Table 2. All the computed injury measures were filtered and processed according to that specified in FMVSS 208. All the available injury measures are well within the injury limits. Some of the differences in the injury measures of the paired tests could be due to the differences in vehicle crash response characteristics and the variability in air bag deployment. The large difference in the peak femur force in the tests with the Dodge Neon maybe due to the larger amount of instrument panel intrusion in the test with the Denton leg than in the test with the Thor-Lx/HIIIr.

In general, the differences in the head and chest injury measures between the paired vehicle tests are within the variability of the vehicle crash response in the paired tests. However, due to the differences in the vehicle crash response characteristics, it is difficult to objectively assess the effect on the head, neck, and chest injury measures by the type of leg used with the Hybrid III dummy. In order to make such an assessment, controlled pairs of sled tests, with repeatable sled deceleration and initial occupant positioning, need to be conducted using the Denton leg and the Thor-Lx/HIIIr.

COMPARISON OF THOR-LX/HIIIr AND DENTON LEG RESPONSES

The forces, moments, and accelerations measured in the Denton leg and Thor-Lx/HIIIr were processed using SAE Channel Frequency Class 600 Butterworth filter. The measured relative femur/tibia displacement at the knee and the ankle rotations were processed using SAE Channel Frequency Class 180 Butterworth filter. The Thor-Lx/HIIIr was fully instrumented in all four tests as shown in Figure 2. However, the Denton leg lacked some measurements in these tests. The upper tibia axial force (Fz) and the upper and lower tibia shear forces (Fx, Fy) was not measured in any of the tests with the Denton leg.

The Thor-Lx/HIIIr and the Denton leg were durable in all four crash tests and in addition, the Thor-Lx/HIIIr calibration responses were unchanged before and after the crash tests. At present, the Agency has not developed calibration corridors for the Denton leg and so an evaluation of its performance pre and post crash tests could not be made.

Tibia Axial Force Response

Under similar impact conditions in laboratory tests, the axial force measured in the Denton leg was higher and with a shorter rise time than that of the human cadaver leg (Kuppa, 1997, Rudd, 1999). On the other hand, the Thor-Lx/HIIIr, with its compliant element, demonstrated human cadaver-like axial force response (Shams, 1999). The paired vehicle crash tests demonstrated similar differences between the Denton leg and Thor-Lx/HIIIr as was observed in the laboratory tests.

In general, the time histories of the Denton leg and the Thor-Lx/HIIIr foot accelerations measured in the paired vehicle crash tests are similar in shape and peak values (Table 3 and Figure 5). This suggests that foot accelerations are primarily influenced by the vehicle crash and intrusion characteristics and not by the type of leg used.

There are, however, several differences in the axial loads measured in the lower and upper tibia of the two types of legs. The axial force measured in the lower tibia of the Denton leg has a similar pattern as the heel accelerations (Figures 5 and 6) while the axial force in the Thor-Lx/HIIIr initially corresponds to the foot accelerations but then peaks at time of maximum foot dorsiflexion. The tensile force in the Achilles tendon of the Thor-Lx/HIIIr increases with increase in dorsiflexion angle. This tensile force combines with the applied force at the plantar surface of the foot resulting in higher total axial force in the Thor-Lx/HIIIr at time of peak dorsiflexion (Figure 5). The Denton leg also demonstrates stiffer axial force response than the Thor-Lx/HIIIr as shown in Figure 6. The rise time in the Denton leg is shorter and the peak force is higher than the response of the Thor-Lx/HIIIr.

Table 3. Resultant foot accelerations (g's) at the heel of the Denton leg and Thor-Lx/HIIIr.

Vehicle	Aspect	Denton	Thor-Lx
Camry	Left	55	54
	Right	90	73
Altima	Left	68	75
	Right	90	83
Neon	Left	105	104
	Right	110	NA
Legacy	Left	102	85
	Right	56	70

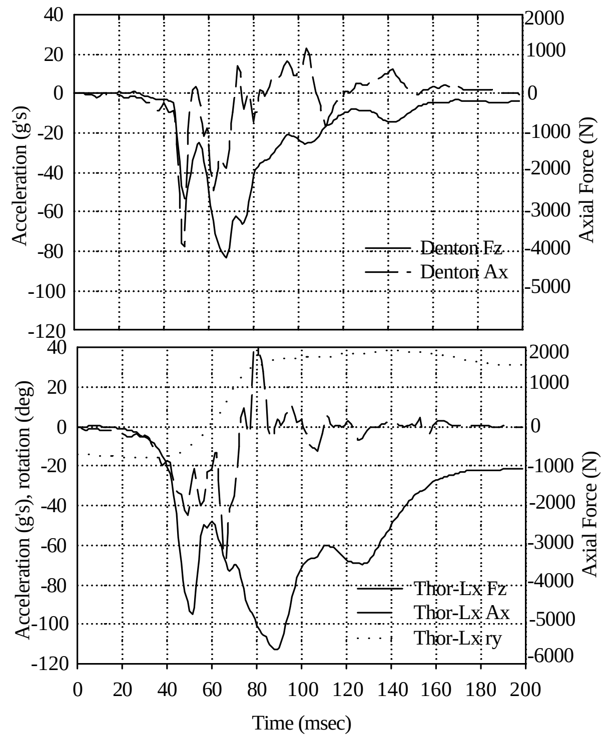


Figure 5. Left lower tibia axial force (Fz), longitudinal foot acceleration (Ax) of the Denton leg and Thor-Lx/HIIIr, and dorsiflexion angle (ry) of the Thor-Lx/HIIIr in the crash tests of the Dodge Neon.

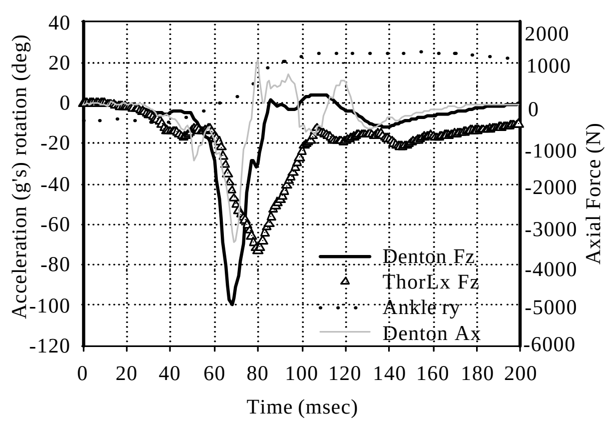


Figure 6. Right lower tibia axial force (Fz) in the Denton leg and Thor-Lx/HIIIr, dorsiflexion (ankle ry) in the Thor-Lx/HIIIr and foot acceleration (Ax) in Denton leg in paired tests of the Nissan Altima.

The difference in the upper and lower tibia axial force in the Denton leg is the inertial term which is small. Therefore, the upper and lower tibia axial forces are very similar in the Denton leg. For this reason, the upper tibia axial force was not measured in the four tests using the Denton leg.

The upper and lower tibia axial forces are significantly different in the Thor-Lx/HIIIr (Figure 7) due to the additional load path of the Achilles tendon. The Achilles tendon attaches to the tibia below the upper tibia load cell and so does not influence the axial force response of the upper tibia as it does to the lower tibia. Therefore, the peak upper tibia axial force occurs at time of peak foot accelerations (first peak of lower tibia axial force). However, at the time of the second peak of the lower tibia axial force, when the dorsiflexion is maximum, the upper tibia axial force is small.

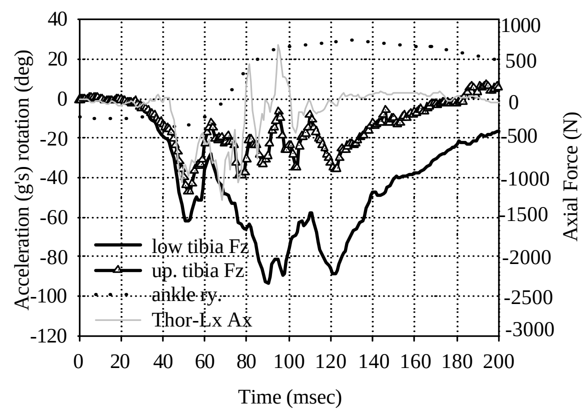


Figure 7. Axial force (Fz) measured in the upper and lower tibia load cell, foot acceleration, and dorsiflexion in the right Thor-Lx/HIIIr leg in the crash test of the Toyota Camry .

Bending Moment in the Leg

Similar to the axial forces measured in the tibia, the moments measured in the upper and lower tibia are significantly different between the two types of legs in the paired vehicle crash tests. The lower tibia moments in the Denton leg are in general higher (Table 4) and with shorter rise time than that of the Thor-Lx/HIIIr (Figure 8).

Table 4. Peak lower tibia dorsiflexion moments (My) in Nm measured in the Denton leg and Thor-Lx/HIIIr.

Vehicle	Aspect	Denton	Thor-Lx
Camry	Left	NA	17.8
	Right	NA	18.8
Altima	Left	143.7	41.8
	Right	40.5	41.7
Neon	Left	413	124
	Right	179.4	57.7
Legacy	Left	93	58
	Right	45	53.3

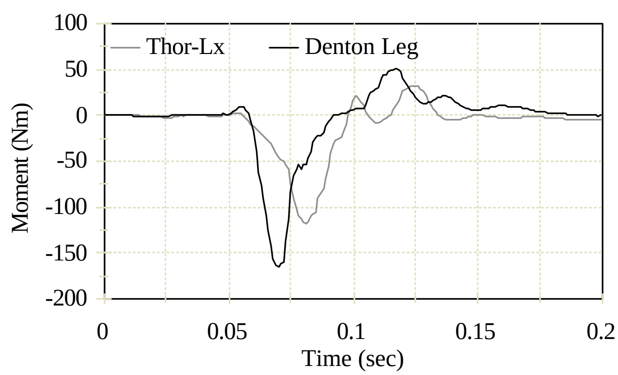


Figure 8. Right lower tibia Mx moments measured in the Denton leg and the Thor-Lx/HIIIr in the crash test of the Nissan Altima.

Welbourne (1998) has demonstrated that due to the offset of the tibia shaft with respect to the joint centers of the knee and ankle in the Denton leg, an upward directed force on the foot can cause significant negative My moments at the upper tibia load cell when no bending forces are being applied to the tibia shaft. In order to compensate this effect, a correction for My for the upper tibia load cell (Equation 1) has been recommended (Welbourne, 1998).

$$\mathbf{My(corr) = My(meas) - 0.028Fz(meas)} \qquad \mathbf{(1)}$$

The moment generated at the ankle joint (M_{y_ankle}) of the Thor-Lx/HIIIr can be computed using the lower tibia load cell measurements and the tibia accelerations using Figure 9 and Equation 2.

$$\mathbf{M_{y_{ankle}} = M_{YL} - F_{XL}D - mA_XD/2} \qquad \mathbf{(2)}$$

where D is the distance and m is the corresponding mass between the ankle joint and the center of the load cell.

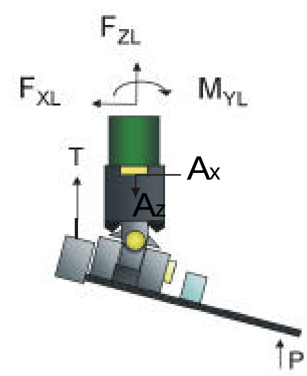


Figure 9. Free body diagram of the foot and lower tibia load cell of the Thor-Lx/HIIIr to axial loading at the ball of foot.

As an example of tibia and ankle moment response of the Thor-Lx/HIIIr, the measured lower tibia moments, shear and inertial contribution, and the computed ankle moment for the left leg in the crash test of the Toyota Camry using the Thor-Lx/HIIIr is presented in Figure 10. The lower tibia moment (My) has an initial negative peak before dorsiflexion commences. This negative peak is compensated by the moment contribution at the ankle from the shear force (FxD) resulting in near zero ankle moment up to 75 msec when foot dorsiflexion starts to occur. The resulting ankle joint moment peaks at time of peak dorsiflexion. The moment at the ankle joint due to inertia (mAxD/2) is relatively small.

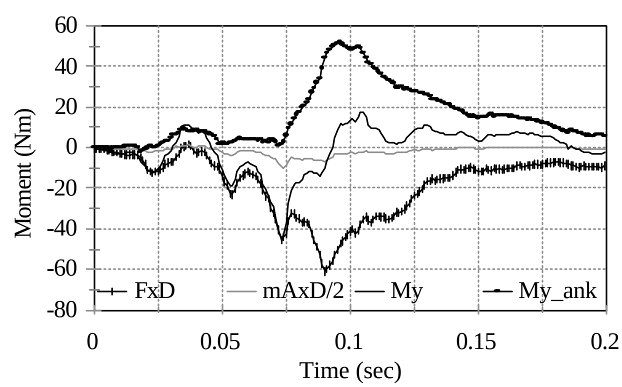


Figure 10. Left lower tibia My moment (My), moment at ankle due to shear force (FxD), moment at ankle due inertial force (mAx D/2), and computed ankle My moment (My_ank) from Equation 2 of the Thor-Lx/HIIIr in crash of the Toyota Camry.

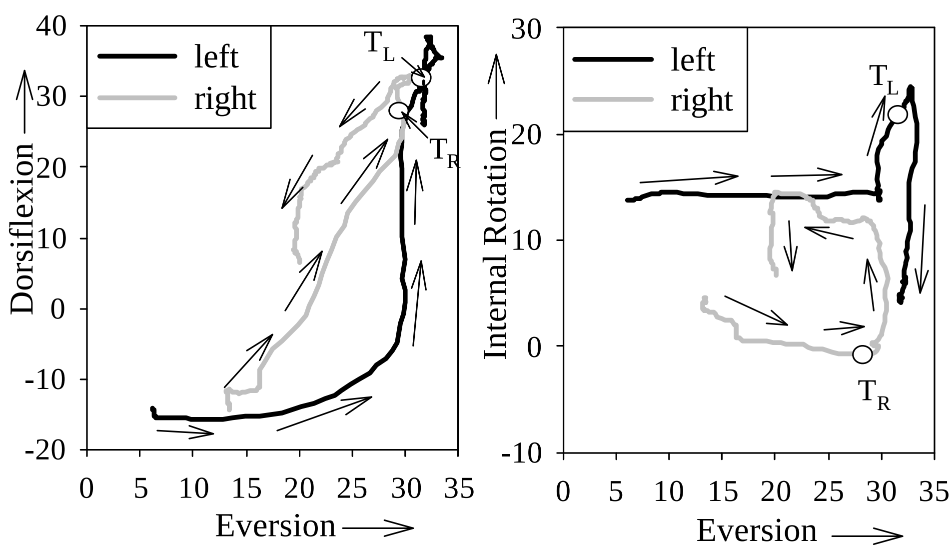
A similar transformation can be applied to compute the Mx moments at the subtalar joint using the lower tibia load cell data of the Thor-Lx/HIIIr. The ankle moments in the Hybrid III Denton leg could not be computed because of insufficient measurements in the lower tibia load cell.

For simplicity in design, the flexion and inversion/ eversion motion of the Thor-Lx/HIIIr are uncoupled. That is, the moment generated at the ankle joint is only a function of the flexion angle and does not depend on the amount of inversion/eversion. Similarly, the moment generated in the subtalar joint is only a function of the inversion/eversion angle and does not depend on the amount of flexion. Therefore, there is a unique relationship between the torque generated at the ankle and the subtalar joint and the flexion and inversion/eversion angle, respectively, which is invariant to loading rates (Shams, et al. 1999). Using this unique relationship between rotation angle and the torque generated, the peak ankle and subtalar moments in the Thor-Lx can be determined from the measured rotational angles.

Foot Rotations

The Thor-Lx/HIIIr has rotational potentiometers to measure flexion, inversion/ eversion, and internal/ external rotation of the foot. As an example of foot kinematics in a frontal offset vehicle crash environment, a plot of the left and right foot rotation of the Thor-Lx/HIIIr in the crash test of the Dodge Neon is presented in Figure 11. The left and right foot are initially plantar flexed and everted. The left foot is also initially internally rotated by 15 degrees. The peak axial force, flexion, and eversion moments are nearly concurrent and occur just before peak dorsiflexion and eversion of the feet. The left foot experiences significant amount of toepan intrusion and as a result first everts considerably (to 30 degrees) before experiencing rapid dorsiflexion and internal rotation. The right foot dorsiflexes and everts at the same time and experiences less peak dorsiflexion, eversion and internal rotation than the left foot. The right foot starts to internally rotate after peak eversion angle is reached.

The accelerometers on the toepan in the vehicle crash tests had undergone rotations during intrusion and so meaningful dynamic intrusion information could not be derived from the measured toepan accelerations. On the other hand, foot rotation measurements such as that in Figure 11 are a reliable source, providing a unique perspective of the interaction of the foot with the intruding toepan and pedals.



T_R,T_L rotation at time of peak axial force and joint moments in left and right leg

Figure 11. Foot rotations of the left and right foot of the Thor-Lx/HIIIr in the crash test of the Dodge Neon.

Femur Axial Force and Tibia-Femur Relative Displacement

The femur and the knee slider mechanism used with the Thor-Lx/HIIIr and the Denton leg are the same. However, there are differences in the measured femur axial force and the tibia-femur relative displacement in the paired test. The large difference in the left femur axial force in the paired crash tests with the Dodge Neon could be attributed to differences in the vehicle crash characteristics resulting in differences in instrument panel intrusion. Otherwise, the axial femur forces in the other paired tests are similar (Table 2).

The knee displacements are consistently higher with the Denton leg than that with the Thor-Lx/HIIIr (Tables 6 and 7). This could be attributed to the alignment of the knee slider in the two leg construction. Due to the offset of the tibia shaft of the Denton leg with the joint centers of the knee and ankle, the knee slider on the Denton leg is mounted at an angle to the axis of the femur, while the knee slider is mounted approximately parallel to the femur axis in the Thor-Lx/HIIIr.

LOWER LIMB INJURY PREDICTION USING THE DENTON LEG AND THE THOR-LX/HIIIr

Kuppa, et al. (2001) synthesized injury criteria for the lower extremities along with relevant injury risk curves from published literature. In addition, the Denton leg has existing performance limits proposed by Mertz (1993). A summary of injury limits at 25% and 50% probability of injury for the 50th percentile male proposed by Kuppa et al. (Kuppa, 2001) and existing performance limits for the 50th percentile male Denton leg proposed by Mertz (1993) are presented in Table 5.

The response of the Denton leg was assessed using the performance limits proposed by Mertz. Injury assessment was made using the corrected upper tibia moments (Equation 1) for the Denton leg.

The injury limits proposed by Kuppa et al. (2001) have been derived from human tolerance data and are applied specifically to the Thor-Lx/HIIIr due to its compliance with human cadaver response data. The response of the Thor-Lx/HIIIr was assessed using the limits at 25% probability of AIS 2+ injury proposed by Kuppa et al. The injury risk curves developed using dorsiflexion moment and inversion/eversion moment had some uncertainty (p=0.093) associated with them due to the small sample size. Therefore, the injury limit for dorsiflexion and inversion/ eversion moment at 50% probability of injury was used in assessing the Thor-Lx/HIIIr responses. Since no injury curve was developed for knee displacement, the performance limit of 15 mm proposed by Mertz was used for the Thor-Lx/HIIIr.

Since the Thor-Lx/HIIIr construction, unlike human foot/ankle response, has uncoupled torque angle characteristics in flexion and inversion/ eversion, the recommended moment threshold levels can be replaced by the corresponding rotation angles. The Thor-Lx is designed to produce an ankle moment of 60 Nm at 35^0 dorsiflexion and a subtalar moment of 40 Nm at 35^0 inversion/eversion. Therefore, while assessing foot and ankle injury using the Thor-Lx/HIIIr, injury limits of 35 degrees dorsiflexion and 35 degrees inversion/eversion were applied. Using limits on angles rather than moments eliminates the need to computationally translate forces, accelerations, and moments measured at the lower tibia load cell to the ankle (Equation 2). Further, this computation may get corrupted by unknown forces impacting the foot/leg between the ankle joint and the lower tibia load cell such as in pedal interaction with the foot.

Table 6 presents the lower limb injury assessment of the Denton leg in the four offset crash tests using the performance limits proposed by Mertz. The lower limb injury assessment of the Thor-Lx/HIIIr in the four crash tests using the injury limits proposed by Kuppa et al. are presented in Table 7. The shaded region are the responses which exceeded the injury and performance limits.

The Denton leg exceeded the left and right upper Tibia Index performance limits proposed by Mertz when the upper tibia moment correction (Equation 1) was applied in the crash test with the Dodge Neon. When the upper tibia moment correction was not applied, the upper Tibia Index of the Denton leg were below the recommended performance limit of 1.0 in all the crashes. The upper tibia moment correction increased the TI in all four vehicle crash tests with the Denton leg except for the right leg in the crash of the Nissan Altima.

Table 5. Injury criteria and limits for the 50th percentile male proposed by Kuppa et al. (2001) and performance limits for the Denton leg proposed by Mertz (1993)

<table>
<tr><td colspan="4">Proposed Injury Criteria and injury limits at 25% and 50% probability of AIS 2+ injury to 50th percentile male (Kuppa, 2001)</td><td colspan="2">Performance limits for the Denton leg (Mertz, 1993)</td></tr>
<tr><td>Body Region</td><td>Injury Criteria</td><td>25% prob</td><td>50% prob.</td><td>Injury Criteria</td><td>threshold</td></tr>
<tr><td>Hip/femur/knee</td><td>axial femur force</td><td>9040N</td><td>11150 N</td><td>axial femur force</td><td>9070 N</td></tr>
<tr><td>Knee ligament</td><td>Tibia/fibula relative translation</td><td>--</td><td>15 mm</td><td>Tibia/fibula relative translation</td><td>15 mm</td></tr>
<tr><td>Tibia Plateau</td><td>Proximal tibia axial force</td><td>5600 N</td><td>7000 N</td><td>tibia axial force</td><td>8000 N</td></tr>
<tr><td>Tibia/fibula shaft</td><td>Revised Tibia Index (RTI) F/12+M/240</td><td>0.91</td><td>1.16</td><td>Tibia Index (TI) F/35.9+M/225</td><td>1.0</td></tr>
<tr><td>ankle+calcaneus</td><td rowspan="2">Distal tibia axial force</td><td rowspan="2">5200 N</td><td rowspan="2">6800 N</td><td rowspan="4">tibia axial force</td><td rowspan="4">8000 N</td></tr>
<tr><td>midfoot</td></tr>
<tr><td rowspan="2">ankle malleolus</td><td>dorsiflexion moment / angle</td><td>--</td><td>60 Nm / 35 deg</td></tr>
<tr><td>inversion/eversion moment / angle</td><td>--</td><td>40 Nm / 35^0</td></tr>
</table>

Table 6. Hybrid III Denton leg responses and injury assessment using limits proposed by Mertz (1993).

	Injury limit	Camry		Altima		Neon		Legacy	
		left	right	left	right	left	right	left	right
Femur Fz (N)	9070 N	2276	2958	3510	2247	7266	3946	2507	2827
Knee Shear (mm)	15 mm			16	10			8	13
Upper TI	1	0.30	0.49	0.65	0.90	0.82	0.97	0.40	0.46
Upper TI (corrected moment)	1	0.33	0.77	0.65	0.59	1.30	1.39	0.58	0.52
Lower TI	1	0.66	0.67	0.68	0.87	1.93	0.93	0.53	0.40
tibia Fz (N)	8000 N	1915	2781	1362	5010	4228	3590	1699	2254
result. foot accel. (g's)		57	63	68	94	114	113	103	62

Table 7. Thor-Lx responses and injury assessment using injury limits proposed by Kuppa (2001)

	Injury Limits	Camry		Altima		Neon		Legacy	
		left	right	left	right	left	right	left	right
Femur Fz (N)	9040 N	2227	2893	2701	2214	4611	3830	3264	3112
Knee Shear (mm)	15 mm	2.2	2.6	11.2	6	4.3	4.1	4.9	10.6
Upper RTI	0.91	0.19	0.38	0.54	0.47	0.71	0.49	0.36	0.44
Upper Tibia Fz (N)	5600 N	771	1206	1915	2486	3916	3401	1650	2269
Lower RTI	0.91	0.3	0.39	0.39	0.8	0.96	0.82	0.55	--
Lower tibia Fz (N)	5200 N	1935	2344	2642	3653	5638	6100	2852	2942
Xversion (deg)	35 deg.	31	15.7	21.1	36	33.4	30.6	36.5	37
Dorsiflexion (deg)	35 deg	30.4	29.5	19.6	25	38.5	33	29	28

Relevance of Injury Assessment Using the Thor-Lx/HIIIr and the Denton Leg to Rear World Lower Limb Injuries

In a detailed analysis of the NASS/CDS data files, Kuppa et al. (2001), noted that the lower extremities are the most frequent AIS 2+ injured body region. Front outboard occupants in air bag equipped vehicles involved in frontal crashes have a 4.5% risk of AIS 2+ lower extremity injuries. The proportion of AIS 2+ lower limb injuries and the associated functional Life-years Lost to Injury (LLI) from this study is presented in Table 8 (Kuppa et al., 2001). This study examined only the maximum AIS level lower extremity injury for each occupant. Injuries regarding the skin, blood vessels or the nerves were not considered in this analysis.

Table 8. Percentage of different AIS 2+ lower extremity injuries and the associated of Life-years Lost to Injury (LLI) among all AIS 2+ lower extremity injuries occurring to front outboard occupants in air bag equipped vehicles involved in frontal crashes.

	Percent AIS 2+ injuries	Associated Percent LLI
knee-thigh-hip	54.70%	41.90%
knee ligament	0.50%	0.80%
tibial plateau	7.10%	8.20%
leg shaft	4.50%	8.10%
ankle-foot	33.20%	41%

The results in Table 8 suggest that the knee-thigh-hip and foot/ankle complexes are the most likely AIS 2+ injured regions of the lower extremities and are also associated with the highest percentage of functional life years lost to injury. The foot and ankle complex account for 74% of below knee injuries (tibia plateau, leg shaft, and ankle/foot) while the tibia plateau and leg shaft account for the remaining 26%.

The axial force measured in the Hybrid III femur with the Thor-Lx/HIIIr and the Denton leg in the 8 crash tests were well below both the injury limits proposed by Kuppa et al. (2001) and Mertz (1993) suggesting a low probability of injuries to the knee-thigh-hip complex for a belted driver involved in a left offset frontal crash. However, according to the study by Kuppa et al., knee-thigh-hip complex account for 55% of all AIS 2+ lower extremity injuries and 42% of associated LLI (Table 8) for front outboard occupants in air bag equipped vehicles involved in frontal crashes. Though belted and unbelted occupants were considered in the study by Kuppa et al., the belt usage rate in this data set was quite high (88%). Therefore the results in (Table 8) essentially represent that of belted front outboard occupants. The predicted frequency of knee-thigh-hip injuries from the eight crash tests is far lower than that observed in real world crashes. This suggests that the Hybrid III hip/femur design, the associated injury criteria, and crash test conditions may need to be revisited.

The Denton leg exceeded the knee displacement performance limit of 15 mm in the Nissan Altima implying possibility of knee ligament injuries. The Denton leg exceeded the upper and lower TI limit of 1.0 in the crash of the Dodge Neon implying possibility of tibia shaft fractures. It did not exceed the tibia axial force limit of 8 kN associated with foot and ankle injuries in any of the crash tests.

In the crash test of the Dodge Neon, the left and right Thor-Lx/HIIIr exceeded the injury limit for lower tibia axial force associated with debilitating calcaneal and pilon fractures. The left leg in this test also exceeded the injury limits for RTI and dorsiflexion angle, which are associated with tibia shaft and malleolar fractures, respectively.

In three of the four vehicle crash tests using the Thor-Lx/HIIIr, the eversion and dorsiflexion injury limits were exceeded. These injury measures are associated with malleolar and ligamentous ankle injuries which are 60% of all field observed AIS 2+ foot and ankle injuries (Kuppa et al., 2001). The Subaru Legacy which had comparatively less post-crash measured toepan intrusion was one of the vehicles where the Thor-Lx/HIIIr exceeded the eversion injury limit. This result suggests that the post-crash intrusion measure is not sufficient to associate severity of the crash event to lower limb injuries. The dynamic intrusion of the toepan involves localized deformations which may not be captured by this post crash measurement. However, the foot rotation measurements of the Thor-Lx/HIIIr are able to capture the interaction of the dynamic toepan and pedal localized deformations with the dummy feet.

The Thor-Lx/HIIIr, with its ankle rotation measurements, predicted a higher incidence of foot and ankle injuries than leg shaft or tibia plateau fractures. The Denton leg predicted leg shaft fractures in one vehicle crash test and knee ligament injuries in another test, but did not exceed its foot and ankle injury limits in any of the four vehicle crash tests. These differences in injury prediction between the Denton leg and Thor-Lx/HIIIr are associated with the differences in their design, instrumentation, and associated injury limits.

CONCLUSIONS

Pairs of same make, model, and model year vehicles were crashed under similar conditions using the Hybrid III 50th percentile adult male dummy in the drivers position equipped with Denton legs in one test and the Thor-Lx/HIIIr in the other test. The crash environment selected was a 40% left offset crash into the EU deformable barrier which generally produces significant intrusion of the toepan. The responses of the Denton leg and the Thor-Lx/HIIIr in the paired crash tests were analyzed and the following observations were made:

1. Both the Denton leg and the Thor-Lx/HIIIr were durable in this crash environment and in addition, the Thor-Lx/HIIIr calibration responses were unchanged before and after the vehicle crash tests. Since no Agency developed corridors exist for the Denton leg, this pre and post crash assessment could not be made for the Denton leg.

2. Objective assessment of the effect of the type of leg used, on the Hybrid III dummy head, neck, chest, and femur injury measures in the paired crash tests could not be made due to variability in vehicle crash response characteristics of the paired tests.

3. The Denton leg exhibits stiffer axial force response than the Thor-Lx/HIIIr as was also observed in previous laboratory tests.

4. The Achilles tendon has considerable influence on the axial force response of the Thor-Lx/HIIIr in this high intrusion environment. The axial force peaks at time of maximum dorsiflexion in the Thor-Lx/HIIIr while it peaks at initial toepan loading in the Denton leg.

5. The foot rotation measurements on the Thor-Lx/HIIIr provide insight into the interaction of the feet with the intruding toepan and pedals. The static post-crash intrusion may not be a sufficient measure of the severity of dynamic toepan and pedal intrusion.

6. The Thor-Lx/HIIIr predicted higher incidence of foot and ankle injuries than leg shaft fractures. The Denton leg did not exceed its foot and ankle injury limits in any of the four crash tests. These differences in injury prediction between the two leg types are associated with the differences in their design, instrumentation, and associated injury limits.

7. Knee-thigh-hip injury prediction from the 8 crash tests with the Denton leg and Thor-Lx/HIIIr was far lower than that observed in real world crashes suggesting that the Hybrid III hip/femur design, associated injury criteria, and crash test conditions may need to be revisited.

ACKNOWLEDGMENTS

The authors would like to thank the staff of the University of Virginia Auto Safety Laboratory for their numerous consultations and Mr. Rodney Rudd for providing images of the Denton leg and the Thor-Lx/HIIIr. Many thanks to the engineers at Veridian Engineering for their timely completion of the vehicle crash tests.

REFERENCES

Crandall, et al., "Biomechanical Response and Physical Properties of the Leg, Foot, and Ankle (962424)," Proceedings of the Fortieth Stapp Car Crash Conference, Albuquerque, New Mexico, November, 1996.

Luchter, S.., "Long Term Consequences of Lower Extremity Injuries," Proceedings of the International Conference on Pelvic and Lower Extremity Injuries, Washington, D.C, December, 1995.

Kuppa, et al., "Axial Impact Characteristics of Dummy and Cadaver Lower Limbs," Sixteenth International Technical Conference on the Enhanced Safety of Vehicles, Windsor, Canada, 1998, Paper No. 98-S7-O-10.

Kuppa, S. et al. "Lower Extremity Injuries and Associated Injury Criteria," Proceedings of the Seventeenth International Technical Conference on the Enhanced Safety of Vehicles, Amsterdam, June, 2001.

Mertz H., "Anthropomorphic Test Devices," Accidental Injury, Biomechanics, and Prevention, edited by Nahum, A., Melvin, J., Springer-Verlag, 1993.

Petit, P., et al., "Quasistatic Characterization of the Human Foot-Ankle Joint in a Simulated Tensed State and Updated Accidentological Data," Proceedings of the IRCOBI Conference, 1996, pp. 363-376.

Petit, P., Trosseille, X., "Comparison of the Thor, Hybrid III, and Cadaver Lower Leg Dynamic Responses in Dorsiflexion," Forty-Third Stapp Car Crash Conference, Paper No. 99SC10, 1999.

Portier, L., et al., "Dynamic Biomechanical Dorsiflexion Responses and Tolerances of the Ankle Joint Complex," Proceedings of the 41st Stapp Car Crash Conference, 1997.

Rudd, R., Crandall, J., Butcher, J., "Biofidelity Evaluation of Dynamic and Static Response Characteristics of the Thor Lx Dummy Lower Extremity," International IRCOBI Conference on the Biomechanics of Impact, Spain, 1999.

Shams et al., "Development and Design of Thor-Lx: The Thor Lower Extremity," Proceedings of the Forty-Third Stapp Car Crash Conference, Paper No. 99SC09, 1999.

Welbourne, E.R., and Shewchenko, N., "Improved Measures of Foot and Ankle Injury Risk from the Hybrid III Tibia, Proceedings of the 16th International Technical Conference on the Enhanced Safety of Vehicles, Paper No. 98-S7-O-11, 1998.