FIFTH PERCENTILE FEMALE HYBRID III AND THOR-FLX PERFORMANCE IN SLED TESTS WITH TOEPAN INTRUSION

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Paper Number 491

ABSTRACT

The 5th percentile (American) female version of the newly-developed Thor-Lx dummy lower extremity, denoted Thor-FLx, was fitted to a 5th percentile female Hybrid III dummy for a series of frontal sled tests with toepan intrusion. The objectives of the study were to compare the Thor-FLx response with that of the Hybrid III/Denton leg, evaluate the effects, if any, on upper-body responses, and evaluate the repeatability and durability of the new leg design. The 56 km/h tests replicated a 40% offset deformable barrier test producing 16 cm of toepan intrusion with peak toepan accelerations of 80 g's. Tests were performed with a standard three-point belt, depowered driver's airbag and a simulated knee bolster. Identical test configurations were used for tests with Thor-FLx limbs and Hybrid III/Denton limbs attached to the same above-knee Hybrid III dummy. Important Thor-FLx design aspects found to influence the response include the tibia axial compliance, ankle joint-stops, Achilles tendon, and anterior tibia shape. An evaluation of test severity based on each designs' injury criteria produced similar outcomes, with both leg types exceeding injury thresholds. There were no significant differences in any of the upper body responses, and incorporation of the new Thor-FLx did not compromise upper body response repeatability.

INTRODUCTION

The lower limbs are prone to frequent and disabling injuries in automobile crashes (Shams *et al.*, 2002; Kuppa *et al.*, 2001a; Shams *et al*., 1999). In an attempt to improve the research tools available for lower limb injury investigation, the U.S. National Highway Traffic Safety Administration (NHTSA) began an effort to develop an advanced dummy lower extremity that became known as Thor-Lx. The goals of the Thor-Lx project were to produce a more biofidelic dummy limb with expanded measurement capabilities that would provide researchers with a better overall account of lower limb response in a crash. At the time of development, the entire Thor (Test Device for Human Occupant Restraint) advanced frontal dummy was used only as a research tool, so the Thor-Lx leg assembly was designed as a retrofit that could be attached at the knee or hip of the 50th percentile male Hybrid III or Thor dummy, and denoted Thor-Lx/HIIIr.

The 50th percentile male Thor-Lx has been evaluated in a number of test environments, and was found to produce biofidelic responses with sufficient repeatability and ease-of-use. A number of component-tests were performed and compared to similar tests with human volunteers and cadavers, which indicated that Thor-Lx response closely represented the response of the human subjects (Ito *et al.*, 2001; Wheeler *et al.*, 2000; Petit *et al.*, 1999; Rudd *et al.*, 1999). In sled and vehicle tests that subjected the design to a number of severe loading conditions, the Thor-Lx was found to be durable while providing a more thorough account of occupant response due to the expanded instrumentation (Rudd *et al.*, 2003; Ito *et al.*, 2001; Kuppa *et al.*, 2001b; Longhitano and Turley, 2001; Rudd *et al.*, 2001). Sled tests presented by Shaw *et al.* (2002) showed that retrofit of the Thor-Lx onto a Hybrid III dummy had minimal effects on above-knee dummy response compared to identical tests with Hybrid III/Denton legs. Furthermore, encouraged by the favorable test results, the NHTSA developed a set of injury criteria applicable to the new leg design (Kuppa *et al.*, 2001a).

An additional component of the NHTSA advanced frontal crash test dummy program was development of a more biofidelic 5th percentile female dummy leg. At the time, the 5th percentile female Thor dummy did not exist, so the leg was designed from the beginning as a retrofit for the Hybrid III dummy, and called Thor-FLx/HIIIr, hereafter referred to as Thor-FLx (Figures 1-3). Design criteria for the Thor-FLx were scaled from the specifications of the Thor-Lx 50th percentile male dummy leg (Shams *et al.*, 2002). The anthropometry for the 5th percentile female leg was based primarily on work by Robbins (1985). Most of the design elements of the Thor-FLx were carried over from the Thor-Lx, with the exception of the ankle joint-stop design and the knee covers, which were modified based on size requirements and improved functionality (Shams *et al*., 2002).

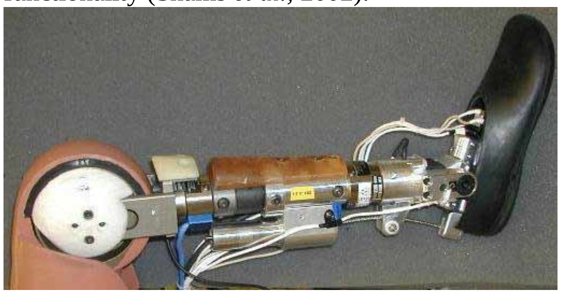

Figure 1. Thor-FLx assembly with flesh removed.

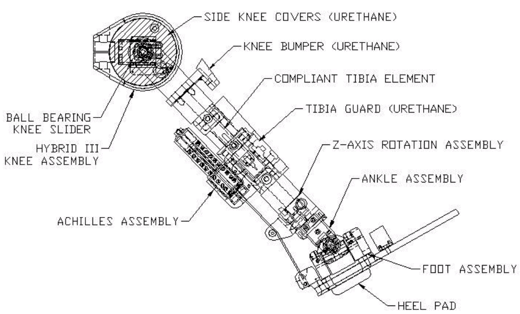

Figure 2. Schematic of Thor-FLx hardware.

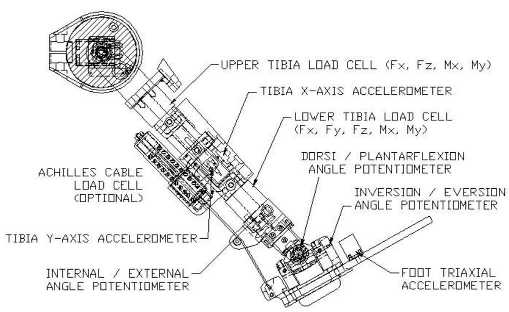

Figure 3. Schematic of Thor-FLx instrumentation.

Because of the more recent introduction, few tests with the female version of the Thor leg have been presented in the literature. Several biofidelity tests were performed by Shams *et al.* (2002), who found that the Thor-FLx response met the design specifications and showed little degradation in response after numerous tests. Vehicle tests with the 5th percentile female Hybrid III/Denton leg (hereafter referred to as Denton) and Thor-FLx were presented by the NHTSA (2002), which also showed the Thor-FLx to be sufficiently durable and able to maintain its calibration responses after repeated tests. In comparing the Denton leg to the Thor-FLx, the NHTSA reported that the Denton leg exhibited stiffer axial load response than the Thor-FLx for inertial loading, a result also seen in comparative testing with the 50th percentile male legs (Ito *et al.*, 2001; Wheeler *et al.*, 2000; Rudd *et al*., 1999). Another conclusion regarding the Thor-FLx in the vehicle tests was that the Achilles tendon played an important role in the distal tibia axial load response following the toepan intrusion. While limited published test results indicate good Thor-FLx performance, further testing was needed in order to support widespread implementation of the new leg design.

One important criterion in retrofitting the Thor-FLx leg onto the Hybrid III dummy is not having the different leg design affect the dummy's upper body responses, from which restraint systems have been designed. Because of the variability associated with vehicle testing, the NHTSA (2002) was unable to assess whether or not upper body responses differed as a function of leg type. An investigation of this type is best performed with sled tests, which can subject the dummy to severe impacts in a repeatable manner. This paper describes a series of sled tests designed to show whether or not retrofit of the Thor-FLx onto the Hybrid III 5th percentile female dummy would produce upper body responses different from those produced by the dummy fitted with the standard Hybrid III/Denton leg. In addition, the tests evaluated the repeatability and durability of the Thor-FLx as well as the lower extremity response differences between the Thor-FLx and Denton legs.

METHODS

A total of six frontal sled tests (Table 1) with a Hybrid III 5th percentile female dummy were performed at the University of Virginia. Three of the tests were performed with Hybrid III/Denton legs and three were performed with the Thor-FLx/HIIIr legs. The crash pulse was representative of a 56 km/h 1998 Dodge Neon offset frontal collision (Figure 4) with 16 cm of longitudinal toepan intrusion. The Neon offset test produced significant toepan intrusion, a challenging environment chosen to evaluate leg durability and repeatability while highlighting the differences in response of the two designs. Intrusion timing and toepan acceleration levels were based on vehicle test data. The amount of translation was chosen to be close to that found in the vehicle tests while exercising the dummy ankles to their design limit.

Table 1.
Test Matrix

Leg Type	**Tests** (numbers in parentheses indicate test ID)
Hybrid III/Denton	3 (690, 691, 692)
Thor-FLx/HIIIr	3 (693, 694, 696)

repeatable constant stroking force (310 kPa crush strength, 2.5 kN theoretical crush force per knee) for the padded knee-contact surfaces. The belt restraint was a standard three-point system used in combination with a depowered, tethered driver-side airbag, deployed 13 ms after T_o.

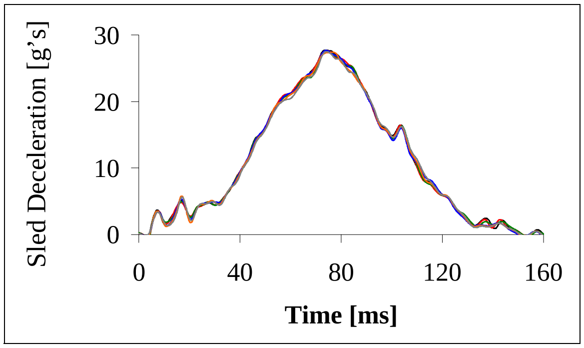

Figure 4. Sled deceleration for six tests.

Equipment

The tests were conducted with a Via Systems Model 713 deceleration sled system, on which a test fixture, or "buck," approximating the interior of a mid-size sedan was mounted. The 56 km/h crash pulse was prescribed with a hydraulic decelerator. Toepan intrusion was produced by a sled-mounted system driven by an independent ground-mounted decelerator (Shaw *et al.*, 2002; Rudd *et al.*, 2001). The aluminum honeycomb-filled intrusion decelerator cylinders were configured to start the intrusion at 71 ms after the initiation of the impact event (T_0) with a peak deceleration of approximately 80 g's (Figure 5) to give approximately 16 cm of translation into the occupant compartment (Figure 6). The toepan angle was fixed at 53° to the horizontal (Figure 7).

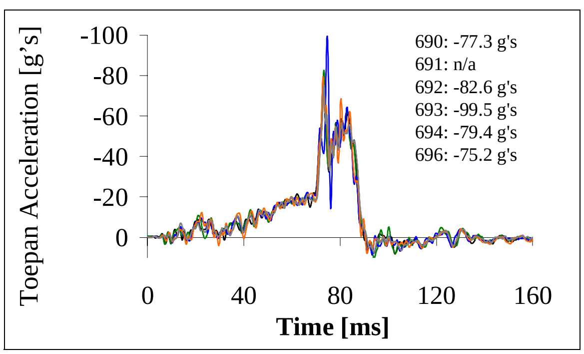

Figure 5. Normal toepan acceleration for five tests (sensor failure on test 691).

The seat was a production bucket seat equipped with an anti-submarining pan integral with the bottom cushion frame. The frame and anti-submarining pan were reinforced to allow multiple uses while ensuring repeatable subject responses. An adjustable knee-bolster device was used to simulate the energy-absorbing characteristics of production instrument panel and dash assemblies. Cylinders filled with aluminum honeycomb provided a

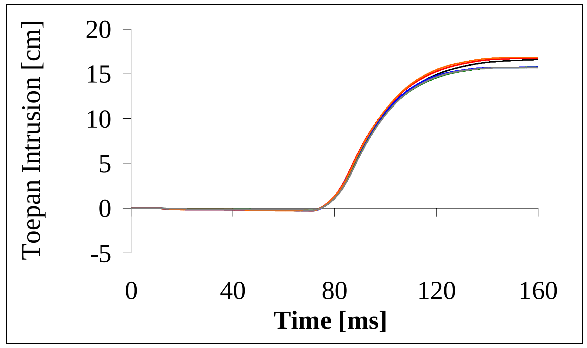

Figure 6. Longitudinal toepan displacement for six tests.

Positioning

Occupant positioning for the 5th percentile female Hybrid III dummy approximated that in a mid-size sedan frontal barrier test, but included a semi-rigid back pad that reduced the seat depth by 9 cm. Moving the dummy forward relative to the seat was necessary to provide sufficient clearance between the calves and the front of the seat cushion following toepan intrusion. Knee-to-bolster and chest-to-wheel distances were similar to those in the frontal barrier tests (Figure 7).

A special seat-pelvis fixture was developed to aid in positioning the dummy (Shaw *et al.*, 2002). The positioning method produced repeatable pre-test dummy position values as determined by low coefficients of variation (CV) (Table 2). The CV is calculated by dividing the standard deviation by the mean within a test group and then multiplying by 100% (Hultman *et al.*, 1991; Maugh, 1983; Foster *et al.*, 1977). For automotive testing, CVs below 10% are generally considered acceptable, and those less than 5% are indicative of low test-to-test variability.

Data Acquisition, Instrumentation and Video

Sensor data from the dummy and buck were recorded at 10 kHz with a 3.3 kHz hardware filter. Raw force and acceleration data were processed by subtracting initial offset values and filtering to SAE J211-prescribed filter classes. Calculation of certain injury criteria required further processing. The data were reported in accordance with the SAE coordinate system (Figure 8).

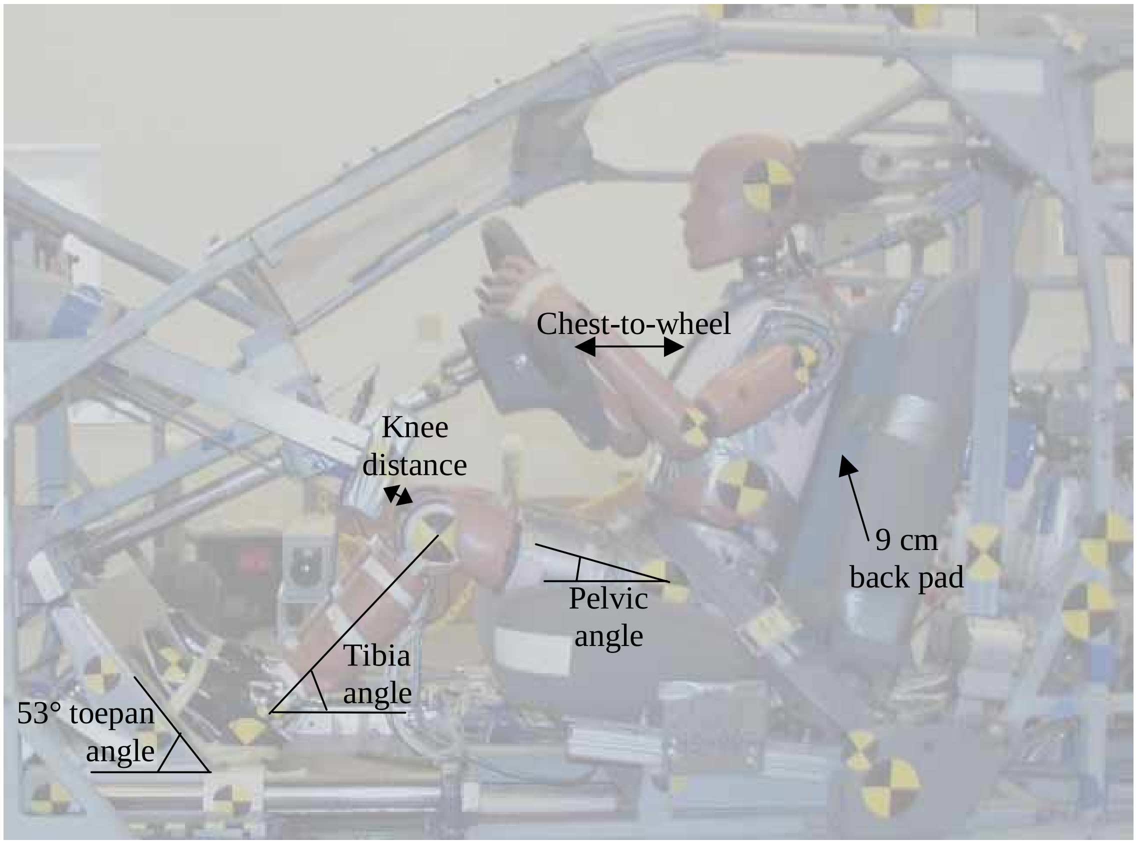

Figure 7. Occupant compartment configuration and initial dummy position.

Table 2.
Initial position measurements

	H-point relative to buck [a]	Left knee distance [b]	Right knee distance	Chest-to-wheel [c]	Head angle [d]	Pelvic angle [d]	Left tibia angle [d]	Right tibia angle [d]
	cm	cm	cm	cm	deg	deg	deg	deg
5th percentile female Hybrid III/Denton								
Mean	0.0	3.4	3.0	21.5	0.2	1.5	43.0	44.8
SD [e]	0.2	0.1	0.1	0.1	0.2	0.2	0.3	0.7
CV % [f]	nc	1.7	1.9	0.3	nc	nc	0.6	1.5
5th percentile female Thor-FLx/HIIIr								
Mean	0.6	3.0	2.7	21.6	0.1	1.4	45.9	45.4
SD [e]	0.1	0.1	0.3	0.1	0.1	0.5	0.8	1.0
CV % [f]	nc	3.3	9.2	0.5	nc	nc	1.7	2.2

a) Horizontal displacement of the h-point relative to an arbitrary origin on the buck
b) Center of anterior knee surface to knee bolster centerline
c) Horizontal distance from the center of the steering wheel (on the airbag module cover) to the dummy chest centerline
d) Angles measured relative to the horizontal
e) SD: standard deviation
f) CV: coefficient of variation = (SD/mean) X 100%
g) nc: not calculated because mean was near zero

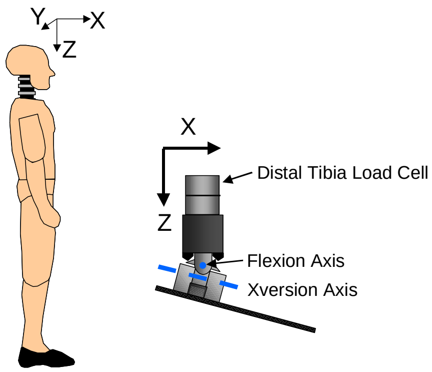

Figure 8. SAE coordinate system with lateral view of ankle on right (positive axes: x forward, y to the right and z down).

Instrumentation common to all tests included sled and buck kinematics, restraint loads and above-knee dummy instrumentation. Above-knee dummy instrumentation included a triaxial accelerometer mounted at the head center of gravity (CG), chest CG, and pelvis CG. Dynamic deformation data for the thorax was measured with the standard Hybrid III chest slider. Upper-neck loads were measured with a triaxial load cell and both femurs were fitted with uniaxial load cells. The same knee assemblies were used for both leg types, and consisted of ball-bearing knee sliders with a string potentiometer to measure shear (x-axis) displacement.

Denton legs were instrumented with four-axis upper and lower tibia load cells (Fx, Fz, Mx, My), x- and z-axis heel accelerometers and z-axis toe accelerometers. Thor-FLx/HIIIr legs included four-axis upper tibia load cells (Fx, Fz, Mx, My), five-axis lower tibia load cells (Fx, Fy, Fz, Mx, My), x- and y-axis mid-shaft tibia accelerometers, a triaxial midfoot accelerometer and rotary potentiometers to measure ankle rotations about all three axes (Figure 3).

High-speed photographic data were recorded by off-board and on-board high-speed digital video cameras arranged to record side views of the crash event for subsequent use in motion analysis. All cameras were operated at 1,000 frames per second.

Data Analysis

This study included evaluations of dummy repeatability and response magnitude. Repeatability was assessed quantitatively by calculating the CV within each group of tests. Qualitative analysis was performed by plotting time-history curves from multiple tests on the same graph. The response obtained with the Hybrid III/Denton legs was considered the "industry standard" for comparison with tests using the Thor-FLx/HIIIr. Differences between peak instrument values were evaluated using a two-sample t-test to indicate statistical significance.

Ankle moments were calculated using distal tibia load cell values and tibia accelerations (when available) as shown in Figure 9 and Equations 1 and 2. Distances and masses used in the calculation are shown in Table 3. The standard Tibia Index formulation was used for both leg types, and the Thor-FLx calculation used modified critical values as presented by Kuppa *et al.* (2001a) and listed in Table 5.

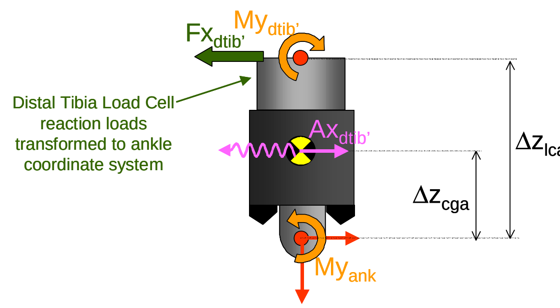

Figure 9. Ankle y-axis moment calculation for Thor-FLx (primed variables indicate values transformed to ankle coordinate system due to ankle z-axis internal/external rotation, which occurs between distal tibia load cell and ankle).

Thor-FLx:

$$My_{ank} = My_{dtib'} - Fx_{dtib'}\Delta z_{lca} - m_{dtib} Ax_{dtib'}\Delta z_{cga} \quad (1).$$

Hybrid III/Denton:

$$My_{ank} = My_{dtib} - Fx_{dtib}\Delta z_{lca} + Fz_{dtib}\Delta x_{lca} \quad (2).$$

Table 3.
Ankle moment calculation values

	Hybrid III/ Denton	**Thor-FLx/ HIIIr**
m_{dtib} [kg]	-	0.536 [a]
Δz_{lca} [m]	0.066	0.089 [a]
Δz_{cga} [m]	-	0.044 [a]
Δx_{lca} [m]	0.014	-
My_{dtib}	y-axis moment at distal load cell	
Fx_{dtib}	x-axis force at distal load cell	
Fz_{dtib}	z-axis force at distal load cell	
Ax_{dtib}	x-axis acceleration of tibia	
My_{ank}	y-axis moment at ankle joint	
a) Source: GESAC, 2001		

Response magnitudes were evaluated with a number of injury criteria from the U.S. Federal Motor Vehicle Standard 208 (FMVSS 208), lower limb performance limits from Mertz (1993), and proposed lower limb injury criteria from Kuppa *et al.* (2001a). Injury criteria for the upper body (above knee) are shown in Table 4, and those for the legs (below knee) are shown in Table 5.

Table 4.
Upper Body Injury Assessment Reference Values (IARV)

Body Region	Hybrid III 5th Percentile Female
Head	*HIC 15*
	700
	HIC 36 [a]
	1000
Neck $N_{ij} = \frac{F_z}{F_c} + \frac{M_{y,oc}}{M_c}$	*Nij* $F_{c,tens} = 4287$ N $F_{c,comp} = -3880$ N $M_{c,flex} = 155$ N-m $M_{c,ext} = -62$ N-m
	1.0
	Upper neck tension [b]
	2620 N
Chest	*Chest deflection*
	52 mm
	Chest acceleration 3ms clip
	60 g's
Femur	*Femur axial load*
	6805 N

a) HIC 36 not specified in FMVSS 208
b) Compression criterion omitted, neck loads tensile only

Table 5.
Proposed Lower Extremity Injury Limits

Body Region	Hybrid III/ Denton Limit	Thor-Lx/HIIIr Limit
Tibia Plateau [b]	*Proximal tibia axial load*	
	5104 N	4000 N
Tibia/Fibula Shaft [b] $TI = \frac{F_z}{F_c} + \frac{\sqrt{M_x^2 + M_y^2}}{M_c}$	*Tibia Index (Hybrid III)* $F_c = -22900$ N $M_c = 115$ N-m	
	1.0	N/A
	Revised Tibia Index (Thor-FLx) $F_c = -8600$ N $M_c = 146$ N-m	
	N/A	0.91
Ankle/ Calcaneus [b]	*Distal tibia axial load*	
	5104 N	3750 N
Ankle/ Malleolus [a]	*Dorsiflexion moment/angle*	
	N/A	37 N-m 35°
	Xversion moment/angle	
	N/A	25 N-m 35°

a) 50% risk of AIS 2+ injuries (Kuppa *et al.*, 2001a)
b) 25% risk of AIS 2+ injuries (Kuppa *et al.*, 2001a)

RESULTS

The Hybrid III dummy and both leg types performed consistently throughout the test series. A few short-duration signal spikes were found in the pelvis during the first test (690), but the dummy was checked for abnormalities and was found to have no problems. The spikes were small in magnitude, did not compromise any results, and diminished in subsequent tests. The upper tibia load cell of the left Thor-FLx limb lost its x-axis moment channel in its first test (693), but was not remedied due to a replacement being unavailable. Aside from this sensor axis failure that affected all of the Thor-FLx tests, the Thor-FLx performed as expected. The sled system produced consistent impact speeds (55.1 – 56.4 km/h) and peak decelerations (27.4 – 27.7 g's; Figure 4). During one test (693), the rubber impact cushion fell out of one of the intrusion decelerators prior to impact, causing a higher initial peak in the toepan normal acceleration (99.5 g's). Although this caused a higher variability among the peak toepan accelerations (75.2 – 99.5 g's; Figure 5), the overall intrusion response and the resulting toepan translation remained fairly consistent (15.7 – 16.8 cm; Figure 6).

A numerical summary is presented in Table 6, which contains dummy responses that met any of the following criteria:

- Average peak response CV greater than or equal to 10%
- Average peak response was at least 80% of IARV or performance limit
- p-value between Hybrid III and Thor response less than 0.05
- Upper body response difference between Denton and Thor-FLx tests greater than 5%
- Lower extremity response difference between Denton and Thor-FLx tests greater than 10%

Any values meeting the above criteria are shown in bold text for clarity. Time-history curves for some of the sensor and calculated data are shown in Figure 10. Corridors (shaded region) have been constructed by averaging the responses in the Hybrid III tests and filling the area between plus/minus one standard deviation. Individual curves plotted on top correspond to the responses from the individual Thor-FLx tests. Ankle moments were calculated according to Equation 1 for Thor-FLx and Equation 2 for Hybrid III. The lack of acceleration data for the Hybrid III precluded inclusion of the inertial component in Equation 2, however, the tibia acceleration (as measured by Thor-FLx) was near zero at the time of peak ankle moment.

Figure 11 shows film analysis results for points relative to their position at T_0 in the sled coordinate frame (x forward, z up). Tibia-foot angle results do not represent the actual ankle flexion angle (as measured by Thor-FLx ankle potentiometers), but show the relative change in angle between the tibia and foot segments as a function of time.

Table 6.
Average peak response values

		Hybrid III/Denton			Comparison		Thor-FLx/HIIIr		
		Average	*% IARV* [a]	*CV* [b]	*Δ* [c]	*p-value* [d]	*Average*	*% IARV* [a]	*CV* [b]
Upper Body	**HIC36**	220	22%	**10%**	**-10%**	0.272	199	20%	9%
	HIC15	128	18%	**17%**	**-13%**	0.332	112	16%	7%
	Nij	0.47	47%	5%	**9%**	0.316	0.51	51%	**11%**
	Chest Deflection	-26.0 mm	50%	7%	**-9%**	0.171	-23.6 mm	45%	7%
	Right Femur Fz	-1831 N	27%	**13%**	**-9%**	0.372	-1674 N	25%	5%
Lower Limb	**Left Upper TI/RTI**	1.06	**106%**	5%	e	e	f	f	f
	Right Upper TI/RTI	1.01	**101%**	3%	e	e	0.58	63%	1%
	Left Upper Tibia Fz	-2701 N	53%	4%	**-11%**	**0.030**	-2401 N	60%	4%
	Right Upper Tibia Fz	-2405 N	47%	2%	**-18%**	**0.001**	-1972 N	49%	3%
	Left Lower Tibia Fz	-2871 N	56%	4%	**14%**	**0.011**	-3263 N	**87%**	3%
	Right Lower Tibia Fz	-2579 N	51%	4%	**10%**	**0.030**	-2843 N	76%	3%
	Left Dorsiflexion	-	-	-	-	-	37.7°	**108%**	1%
	Right Dorsiflexion	-	-	-	-	-	31.1°	**89%**	3%
	Left Ankle My	61.0 N-m	-	3%	**-48%**	**0.000**	31.6 N-m	**85%**	4%
	Right Ankle My	28.5 N-m	-	**31%**	**-24%**	0.315	21.8 N-m	59%	3%

a) % IARV = Mean/IARV X 100%
b) CV: Coefficient of Variation, calculated as CV = Standard Deviation/Mean X 100%
c) Δ: difference between Thor-FLx average and Hybrid III average, positive percentages indicate Thor-FLx produced higher value, calculated as Δ = (Thor – H3)/H3 X 100%
d) p-value calculated from two-sample t-test
e) no direct comparison made for Tibia Index and Revised Tibia Index due to different formulation for Hybrid III/Denton and Thor-FLx/HIIIr
f) Sensor problem for all tests precluded calculation of Revised Tibia Index

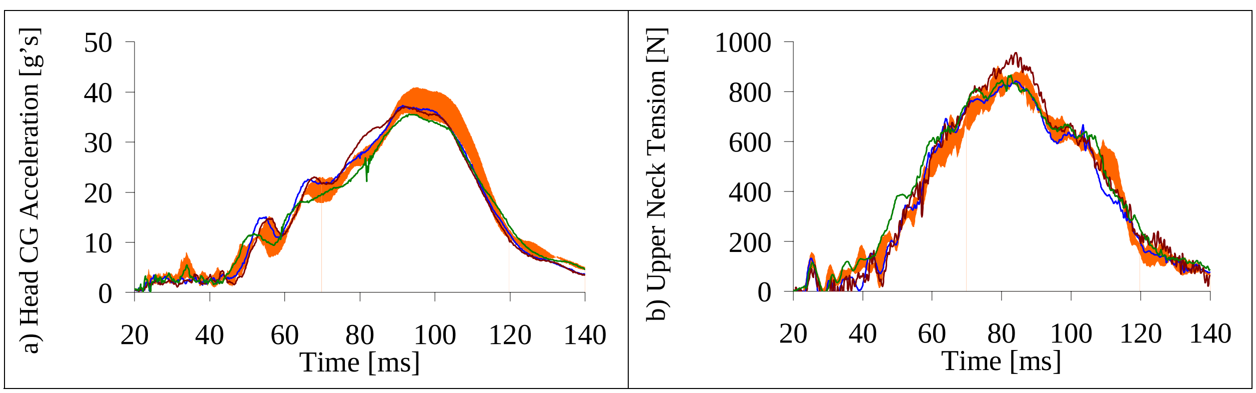

Figure 10. Time-history instrument responses: the Denton leg test results are plotted as an average ± one standard deviation corridor in orange (shaded), and the individual Thor-FLx tests are plotted as lines.

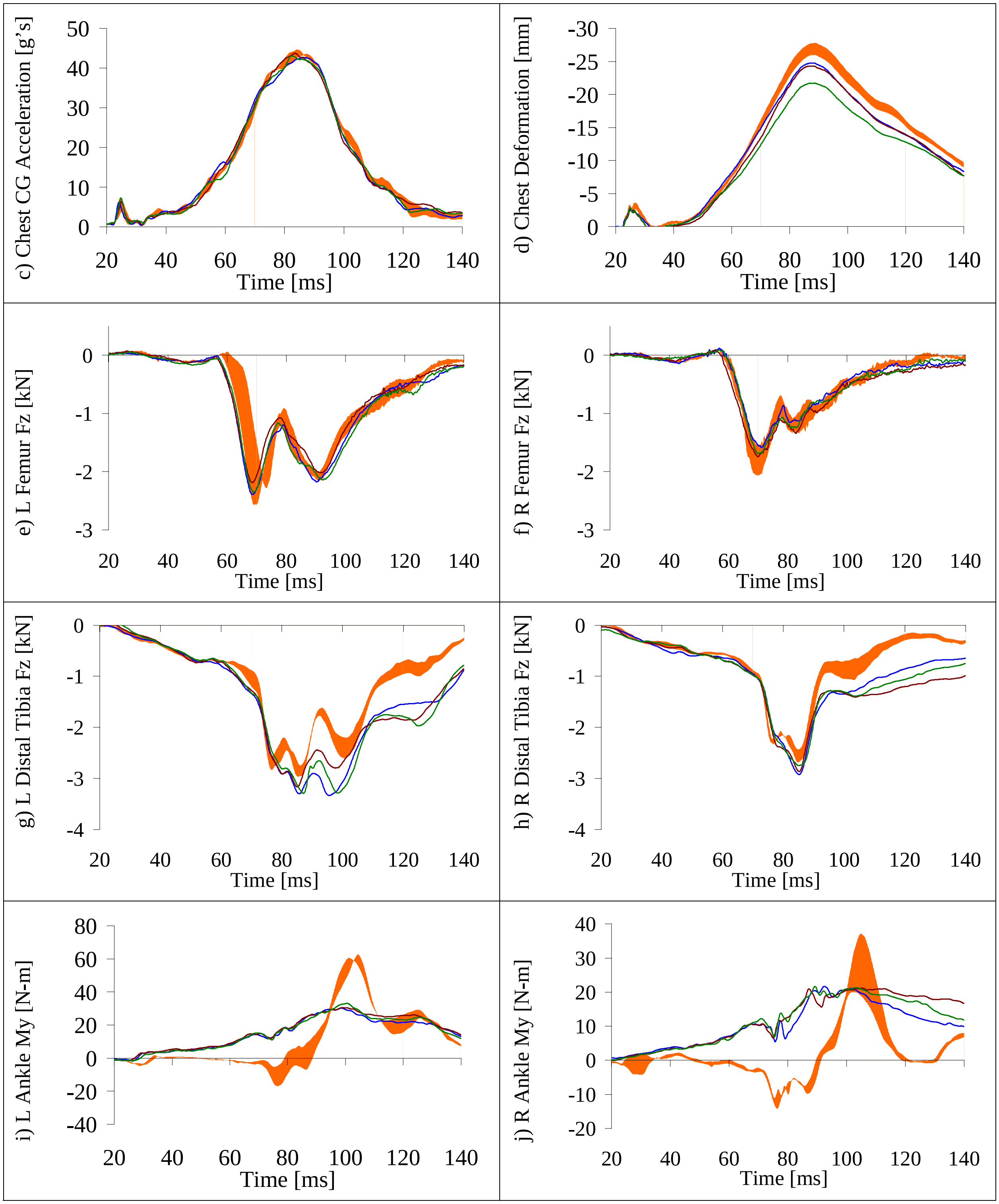

Figure 10 (continued). Time-history instrument responses: the Denton leg test results are plotted as an average ± one standard deviation corridor in orange (shaded), and the individual Thor-FLx tests are plotted as lines.

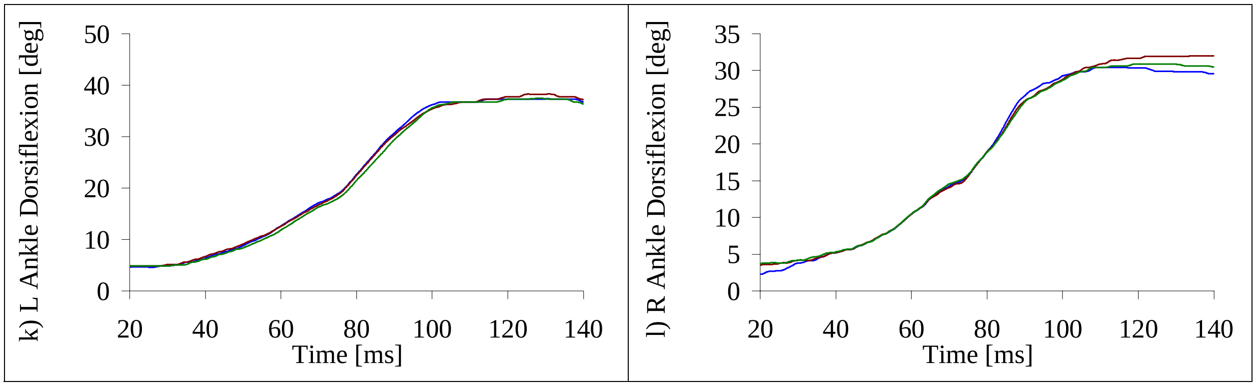

Figure 10 (continued). Time-history instrument responses: the Denton leg test results are plotted as an average ± one standard deviation corridor in orange (shaded), and the individual Thor-FLx tests are plotted as lines.

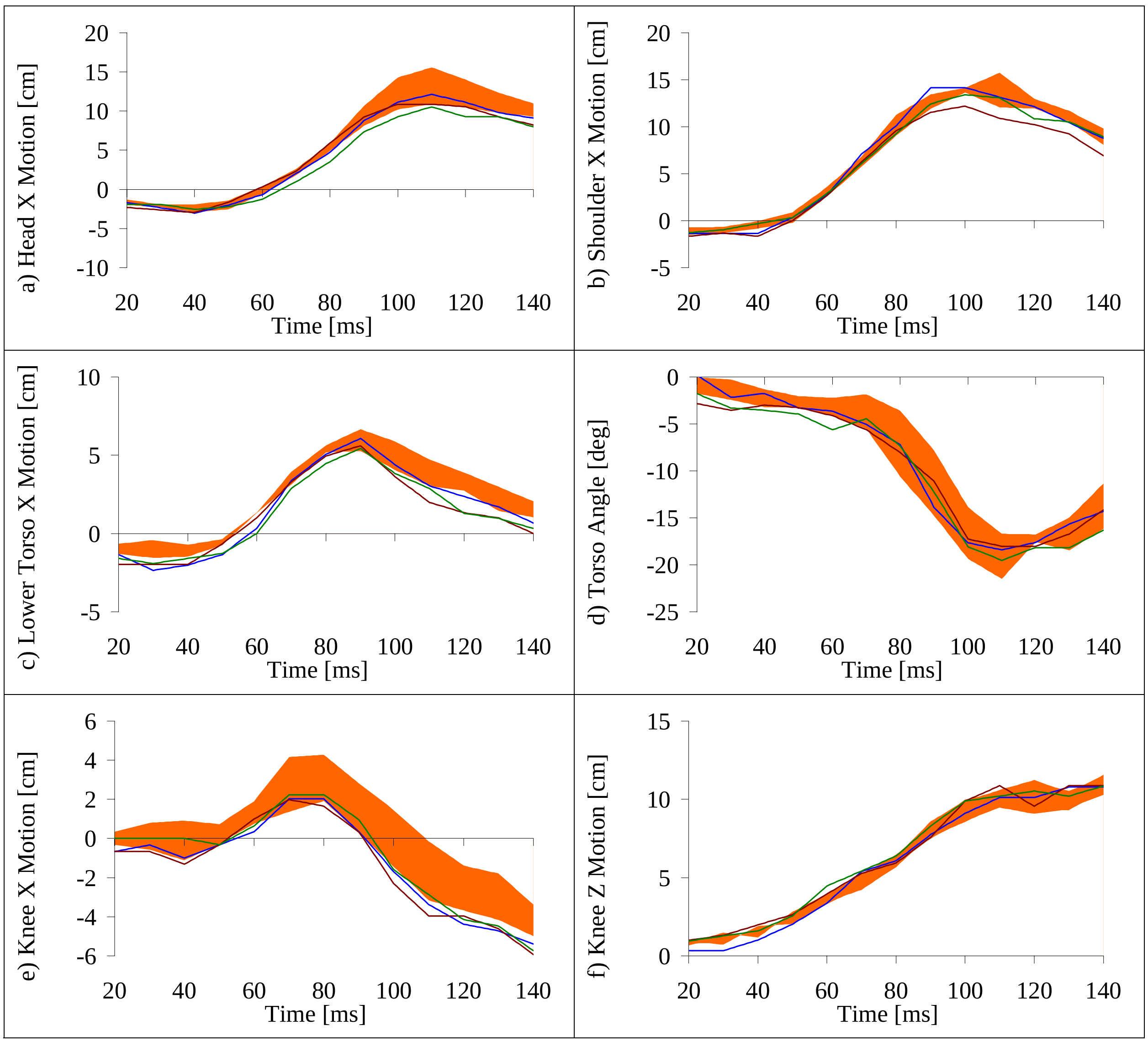

Figure 11. Time-history of film analysis: the Denton leg test results are plotted as an average ± one standard deviation corridor in orange (shaded), and the individual Thor-FLx tests are plotted as lines.

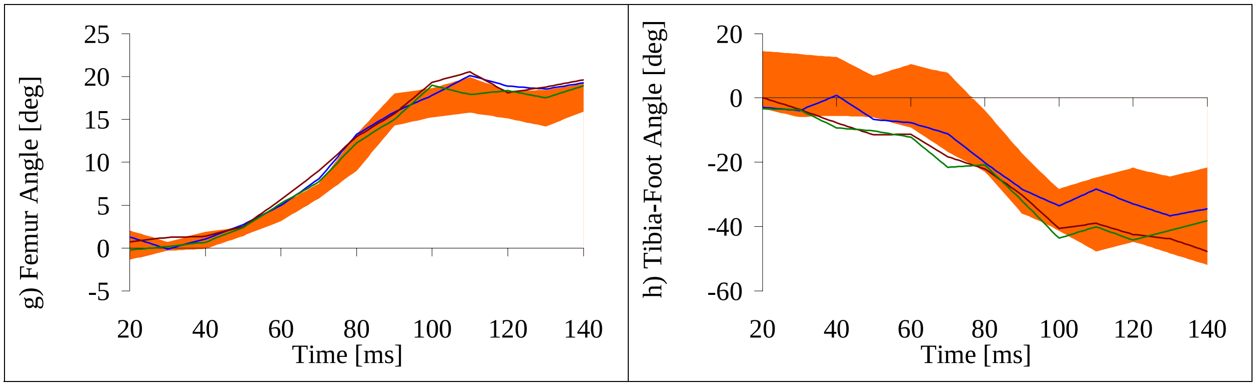

Figure 11 (continued). Time-history of film analysis: the Denton leg test results are plotted as an average ± one standard deviation corridor in orange (shaded), and the individual Thor-FLx tests are plotted as lines.

DISCUSSION

The Hybrid III 5th percentile female dummy with Hybrid III/Denton and Thor-FLx/HIIIr limbs was subjected to a series of frontal sled tests without incurring any structural failures. The toepan intrusion provided a challenging environment for comparison of the lower limb designs, while the repeatability of the sled environment enabled direct comparison of upper body responses.

Upper Body (Above Knee)

Repeatability of Upper Body Responses Most of the CVs for the upper body responses were below ten percent for tests with both leg designs (Table 6), indicating that the test-to-test variability was normal across the board. In the Denton leg tests, the HIC36, HIC15, and right femur axial load had a higher variability as indicated by CVs of 10%, 17%, and 13%, respectively. Due to the restraint conditions and softer vehicle pulse used for these tests, the head accelerations were low and the resulting HIC values were less than 22% of their respective IARVs. One of the Denton leg tests (691) had a peak head CG acceleration a few g's higher than the other two, possibly the result of different head contact with the airbag. Because of this and the low overall value, the slightly higher CVs did not raise any concerns. Thor-FLx tests produced HIC36 and HIC15 CVs of 9% and 7%, respectively. The Denton test right femur axial load value was 27% of its IARV, and the higher variability in this case was believed to be a result of the restraint condition on the dummy's right side (intersection of lap and shoulder belt) and more sensitive knee bolster interaction (13% CV for right knee bolster load). During these tests and other sled tests with toepan intrusion, there has been a tendency for higher variability in knee bolster contact, since the intrusion loads drive the knees up and back at the same time as the upper body is decelerating into the bolster (Rudd *et al.*, 2001; Shaw *et al.*, 2002). Small differences in initial position can lead to noticeable response changes under these circumstances. The CV for the right femur axial load in the Thor-FLx tests was 5%.

In the tests with the Thor-FLx limbs, the neck injury criteria (Nij) had a CV of 11%. The neck tension was fairly consistent from test-to-test (7% CV), but the occipital condyle y-axis moment (15% CV) varied enough to push the CV for Nij to 11%. The neck variation, which was not accompanied by large variability in head or chest measures, was likely the result of slightly different neck interaction with the airbag. Nij values in the Denton leg tests were less variable with a CV of 5%.

Analysis of the time-history motion plots (Figure 11) shows that the tests with the Thor-FLx exhibited about the same overall variability in upper body dummy kinematics as tests with the Hybrid III/Denton leg. In some cases (head x-axis motion and torso angle), the tests with the Thor-FLx limbs produced motions that were more similar to one another than tests with Hybrid III/Denton limbs, but it is important to consider that these differences are not much larger than the expected error inherent in film analysis. Overall, with Denton leg tests producing an average upper body CV of 7.25% and Thor-FLx tests at 6.5%, the upper body repeatability was equivalent and within the normal expected range for both leg designs.

Upper Body Response Trends There were no statistically significant differences between peak upper body responses with the Denton and Thor-FLx legs (Table 6). Upper body kinematics, as measured with film analysis, were qualitatively similar for both leg types as well (Figure 11). After the toepan intrusion began at 71 ms, the Thor-FLx tests exhibited slightly less forward (x-axis) head and torso excursion, but the average differences were less than two centimeters and not much greater than the expected test-to-test range of variation in film analysis. The trend of Thor-FLx tests undergoing slightly less upper body forward motion was likely a result of minimized pelvic excursion from altered knee bolster interaction, which occurred as a result of differences in anterior tibia and knee geometry.

Based on the plots in Figure 10, the upper body responses for Denton and Thor-FLx tests were almost indistinguishable from one another, with the exception of the chest deformation. The peak chest deformation was, on average, 9% lower in tests with the Thor-FLx legs compared to those with the Denton legs. The upper shoulder belt loads were nearly identical for all of the tests (Denton average 4472 N with 2% CV and Thor-FLx average 4471 N with 4% CV), the torso angles were similar (Figure 11d), and there was only a 2% difference in average chest acceleration 3 ms clip.

HIC36 and HIC15 values also decreased for Thor-FLx tests, by 10% and 13%, respectively. One of the Denton leg tests (691) had slightly higher head CG accelerations (peak resultant of 41 g's versus 36 and 38 g's), which was the cause of the increased HIC average over the Thor-FLx tests. This difference was not statistically significant, and relatively minor considering HIC values were less than 22% of their respective IARVs.

Because of their proximity to the legs, differences in femur response would be expected in this type of test, however, the femur axial loads were remarkably similar for Denton and Thor-FLx tests. The time-history plots of femur axial load were very similar (Figure 10e & 10f), and the difference was only noticeable in the peak values (Table 6). On average, the right femur axial load was 9% lower for the Thor-FLx tests than for the Denton tests. This finding was similar to that in the 50th percentile male tests, with Denton leg tests sustaining higher femur loads, especially on the right side because of less bolster contact (Shaw *et al.*, 2002).

The upper body and femur injury prediction measures relative to their IARVs are shown in Figure 12. Most of the measures were well below their threshold value, with the exception of the chest acceleration 3 ms clip, which was just over 70% of the IARV. The column charts in Figure 12 show the differences in response from Denton tests to Thor-FLx tests, as well as the relative response magnitude and variability. Not only did inclusion of the Thor-FLx have little or no effect on relative response magnitude, but the variability in these tests did not compromise the predictive ability of the Hybrid III dummy.

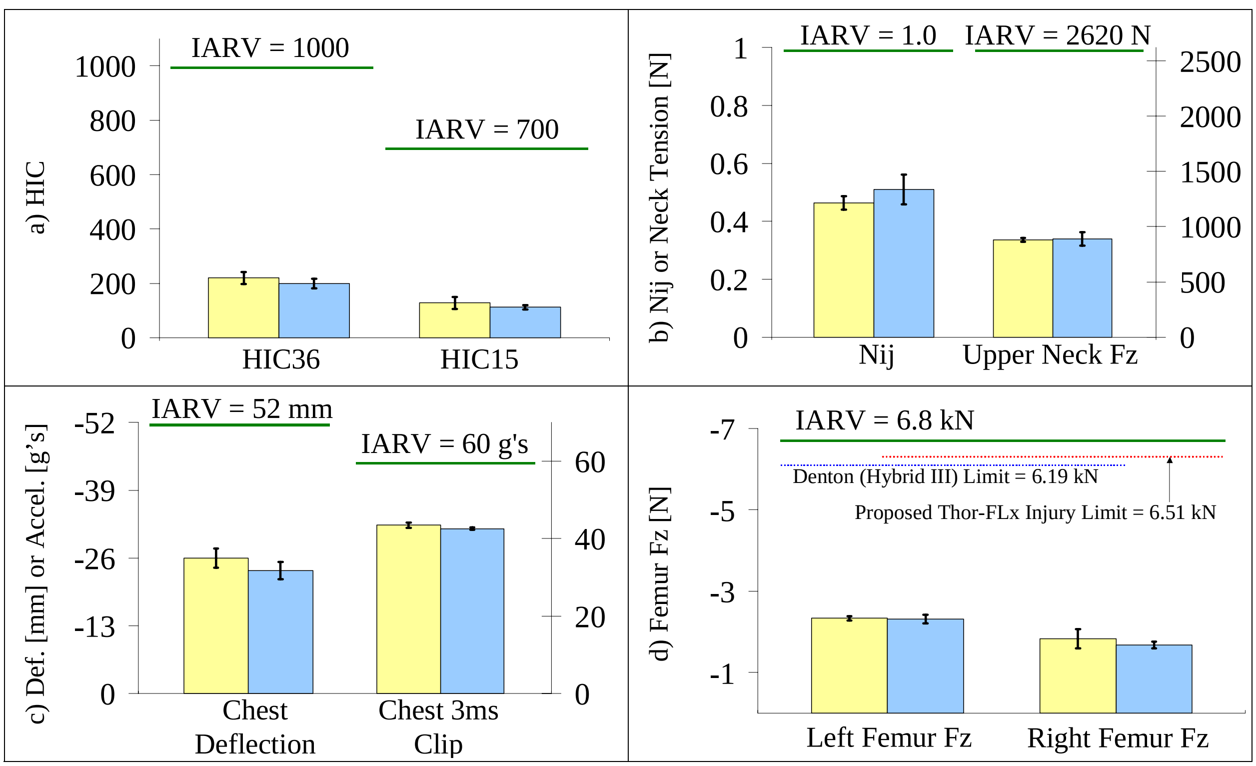

Figure 12. Peak values by leg type relative to IARV: for each value, the lighter bar on the left represents the Denton leg test value and the darker bar on the right represents the Thor-FLx leg test value; the error bars represent ± one standard deviation within each test set; the IARVs correspond to FMVSS 208 criteria, while the proposed femur limits are taken from Kuppa *et al.*, (2001a).

Overall, the upper body response differences were minor and could be attributed to normal test-to-test variation. The relatively small number of replicate tests may not provide the most comprehensive evaluation of repeatability and response difference, but these tests in conjunction with the 50th percentile male tests (Shaw *et al.*, 2002) indicate that retrofit of the Thor leg designs is unlikely to change Hybrid III dummy upper body response.

Lower Limb

Repeatability and Durability of Lower Limb Neither of the leg designs sustained any structural damage during this test series, and neither required any special maintenance to ensure proper working order. The Thor-FLx left upper tibia load cell did partially fail during the first test, but the failure only affected the x-axis moment channel. At the time, a replacement load cell was unavailable, so the testing proceeded despite the lost channel. This loss was considered minor and was believed to be the result of a pre-existing problem with the sensor axis.

All of the lower limb responses, except for the Hybrid III/Denton right ankle y-axis moment, had CVs of 5% or less. During these tests, there was sufficient ankle flexion to engage the soft joint-stop of the Hybrid III/Denton ankle. At this point, the soft joint-stop engages such that small increases in rotation angle are accompanied by large increases in moment. Because of the more variable interaction of the right knee with the knee bolster and a slight variation in total intrusion displacement among the three tests, there was a greater variation in the maximum flexion angle of the right ankle that caused the calculated moment to have a CV of 31%. This variation was not considered to compromise the results, but was indicative of a design limitation with the Hybrid III/Denton ankle joint that was also evident in tests with the 50th percentile male (Rudd *et al.*, 2003). The Thor-FLx, with its continuous ankle joint-stop design, produced CVs of 4% and 3% for its left and right ankles, respectively.

Lower Limb Response Differences The differences between Hybrid III/Denton and Thor-FLx leg responses in this test condition were not as distinct as those seen with the 50th percentile male dummy (Rudd *et al.*, 2003). While all of the responses were statistically significantly different, the ankle y-axis moments were the only dummy responses that reflected the design differences between the Denton and Thor-FLx limbs with a substantially different time-history response.

Tibia axial loads, as listed in Table 6, were significantly different at the 0.05 level. Proximal (upper) tibia axial loads were on average 11% and 18% lower with the Thor-FLx for the left and right leg, respectively. Loads in the Thor-FLx were likely lower because of the compliant element incorporated into the tibia shaft to reduce its stiffness in comparison to the Denton design. On the other hand, distal (lower) tibia peak loads were higher with the Thor-FLx because of the superimposed axial load in the distal load cell from the Achilles tendon with increasing dorsiflexion. The Thor-FLx left tibia peak load was 14% higher and the right was 10% higher, which occurred with approximately 26° of dorsiflexion in the left ankle and 22° in the right. The peaks in distal tibia axial load were dominated by inertial loading from the intrusion, but there was sufficient Achilles loading in the Thor-FLx at that moment to produce higher loads even though the Denton leg has been shown to have a stiffer inertial response.

The most notable difference in lower limb response was at the ankle joints, where the Thor-FLx ankle y-axis moment time-history had a clearly different behavior than the Hybrid III/Denton ankle (Figure 10i & 10j). As soon as the occupant began to move forward under inertial loading (about 20 ms after T_0), the Thor-FLx ankle potentiometers registered increasing dorsiflexion, which corresponded with an increase in the calculated ankle moment for the Thor-FLx. During the same period of time in the Denton tests, the ankle moment remained near zero. After the toepan intrusion began at 71 ms, the Thor-FLx ankles continued to develop a larger ankle moment, although at a faster rate, until the peak was reached between 90 ms and 100 ms. After the toepan intrusion began, the Denton ankle y-axis moment rose quickly starting from 90 ms to its peak at around 100 ms. The left ankle flexion moment was 48% lower in the Thor-FLx than in the Denton, and the right ankle flexion moment was 24% lower. Based on the film analysis of tibia-foot angle (Figure 11h), both Thor-FLx and Denton ankles rotated the same amount during the tests.

Injury Prediction Based on injury criteria available for both leg designs (Mertz, 1993; Kuppa *et al.*, 2001a), this test condition produced lower limb measures above proposed injury thresholds for the Hybrid III/Denton and Thor-FLx (Table 6, Figure 13). The left and right Hybrid III/Denton legs had upper Tibia Indices of 1.06 and 1.01, respectively, indicating high risk of tibia mid-shaft fracture. The Revised Tibia Index, which was applied to the Thor-FLx data, did not exceed its proposed limit of 0.91 in any location.

The Thor-FLx exceeded its dorsiflexion limit at the left ankle, with an average angle of 37.7° which was 8% higher than the proposed value of 35°

(Figure 13b), indicating the risk of an ankle injury. The corresponding left ankle moment, however, did not exceed its proposed limit of 37 N-m. The right ankle rotation was 89% of the proposed limit. Because of the large amount of toepan intrusion present in this test condition, it was expected that an occupant in a similar vehicle crash would be at increased risk of ankle injuries caused by over-rotation.

Based on the proposed injury criteria, the two dummy legs predicted two different injury mechanisms in this same test condition. In this setting, the ankle injury would be more likely to occur than the mid-shaft tibia fracture, indicating that the Thor-FLx has a more realistic injury predictive ability than the Hybrid III/Denton leg.

The Tibia Index, used to predict mid-shaft tibia fractures, accounts for combined loading in the tibia. Kuppa *et al.* (2001a) suggested modified critical values for use with the Thor-Lx and Thor-FLx based on results from a number of whole leg tests. The Revised Tibia Index consists of a higher critical moment and a lower critical axial load compared to the original Tibia Index formulation (146 N-m vs. 115 N-m and –8600 N vs. –22900 N). Tibia Index (for Hybrid III/Denton) and Revised Tibia Index (for Thor-FLx) components at the left distal tibia are shown in Figure 14 for comparison. Because of the canted tibia shaft design in the Denton, axial load-induced moments developed at the load cell locations. The higher measured moment and lower critical moment combined with a high critical force value, led to a moment-dominated Tibia Index. The different critical values for the Revised Tibia Index and the absence of axial load-induced tibia moments in the Thor-FLx resulted in more equal contributions from axial load and moment in the Revised Tibia Index calculation.

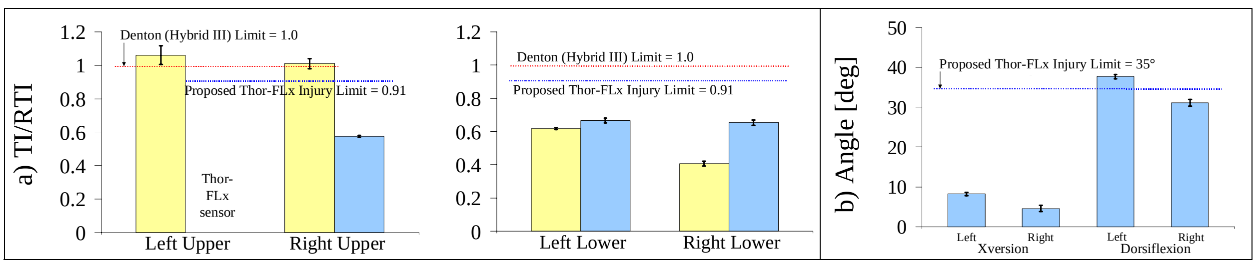

Figure 13. Peak values by leg type relative to proposed injury limit: for each value, the lighter bar on the left represents the Denton leg test value and the darker bar on the right represents the Thor-FLx leg test value; the error bars represent ± on standard deviation within each test set; proposed limits are taken from Kuppa *et al.*, (2001a). TI = Tibia Index, RTI = Revised Tibia Index.

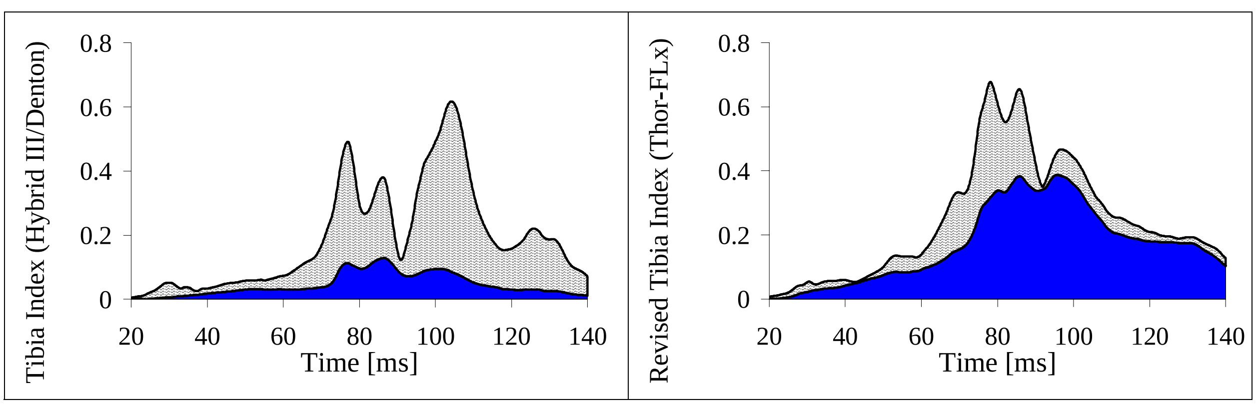

Figure 14. Left distal Tibia Index (left plot) and Revised Tibia Index (right plot) components (solid area represents axial load contribution and hatched area represents moment contribution).

CONCLUSIONS

The repeatability of the sled test methodology provided a test environment conducive to studying the effects of leg type on overall dummy response. Similar studies with the 50th percentile male indicated that the Thor-Lx design was repeatable and durable in the sled test setting, and that retrofit onto the Hybrid III dummy at the knee did not change upper body responses with respect to the dummy with Denton legs (Rudd *et al.*, 2003; Shaw *et al.*, 2002). Both dummy limbs performed as designed during this test series, but the enhanced design and instrumentation of the Thor-FLx gave a more thorough assessment of injury risk. The results suggested the following conclusions:

- Upper body repeatability was acceptable for both leg types. Incorporation of the new leg design did not introduce variability beyond what was expected. Most coefficients of variation were below 10%, which was considered acceptable.
- Similar upper body injury severity was predicted with both leg types. Overall response magnitude relative to IARV was independent of which leg was used.
- Repeatability and durability of Thor-FLx design was good. Aside from one load cell losing an axis, there were no failures of the dummy leg.
- Improved biofidelity and increased measurement capability of Thor-FLx were advantageous over Hybrid III/Denton. During this test series, the most notable design difference was the ankle joint-stop, which, in the Thor-FLx, produced a continuously increasing resistance to dorsiflexion as opposed to the sudden increase near the soft bumper in the Hybrid III. Trends in tibia axial loads were also different as a result of the compliant tibia element and Achilles tendon in the Thor-FLx. The additional sensors of the Thor-FLx provided a more comprehensive account of the lower limb responses.
- Proposed lower limb injury criteria provided meaningful interpretation of Thor-FLx instrument data. The predicted injury risk from the Thor-FLx was similar to what would be expected from a case with significant toepan intrusion.
- The single test condition and relatively small number of replicate tests may preclude broad application of conclusions.

ACKNOWLEDGEMENTS

The authors acknowledge the support and guidance of Nopporn Khaewpong, Mark Haffner, Rolf H. Eppinger, and Shashi Kuppa of the NTBRC of the National Highway Traffic Safety Administration (NHTSA), U. S. Department of Transportation. This study was supported in part by DOT NHTSA Grant DTNH22-93Y-07028. All findings and views reported in this manuscript are based on the opinions of the authors and do not necessarily represent the consensus or views of the funding organization. David Beach and Tariq Shams of GESAC Inc. provided technical support for the Thor-Lx/HIIIr legs.

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