APPLICATION AND EVALUATION OF A NOVEL KTH INJURY CRITERION FOR THE HYBRID III DUMMY IN FRONTAL CRASH TEST ENVIRONMENTS

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ABSTRACT

This paper evaluates a recently published comprehensive knee-thigh-hip (KTH) injury criterion through its application to the Hybrid III 50th percentile male (HIII-50M) and 5th percentile female (HIII-5F) dummies in frontal crash tests along with a comparison with real world KTH injury risk in frontal crashes. This criterion, developed by Rupp et al. (2009) (Rupp-KTH criterion), determines risk of injury to the hip, femur, and knee using the peak compressive femur force and impulse.

Femur load cell data from various frontal crash tests were analyzed using the Rupp-KTH criterion. The risk of KTH injuries as calculated with this criterion in the various crash conditions was compared to that observed in real world frontal crashes using the National Automotive Sampling System-Crashworthiness Data Systems (NASS-CDS) data files. The relative proportion of knee, thigh, and hip injuries predicted by the Rupp-KTH criterion was also compared to that observed in real world crashes.

The Rupp-KTH criterion predicts an overall KTH injury risk reflective of real world risk with unbelted Hybrid III dummies, but under-predicts real world injury risk for belted dummies. The proportion of hip injuries among all KTH injuries is predicted reasonably well for unbelted occupants and under-predicted for belted occupants. Dummy interaction with the knee bolster in different restraint conditions likely affects the level of agreement between predicted and observed injury risk.

This study applied injury criteria to Hybrid III dummy responses in specific crash conditions and seating configurations. Injury risk prediction may be improved with other dummy designs or crash environments.

INTRODUCTION

With the increasing use of safety belts and the availability of air bags, more occupants survive serious crashes. However, many people involved in frontal crashes sustain disabling lower extremity injuries (Kuppa et al., 2003). Though lower extremity injuries are not typically life threatening, the physical and psychosocial consequences of lower extremity injuries are often long lasting (Read et al., 2002). Lower extremity injuries require comparatively longer periods of hospitalization and recovery than injuries to other body regions (Read et al., 2004).

Using NASS-CDS data files, Kuppa et al. (2003) concluded that the lower extremity is the most frequently injured body region in frontal crashes accounting for 36% of all AIS 2+ injuries. Approximately half of lower extremity injuries are to the knee-thigh-hip (KTH) complex and the other half are below the knee. A detailed analysis of KTH injuries indicated that 46 percent of all KTH injuries are to the hip. The relatively high frequency of hip/pelvis injuries is of particular concern because hip injuries are generally more difficult to treat than injuries to the either the knee or the thigh.

NHTSA funded a research program to better understand the mechanism of KTH injuries in frontal crashes and to determine the fracture tolerance of the hip relative to that of the knee and thigh for knee impact conditions that are representative of those resulting from frontal impacts of late-model air bag/knee-restraint-equipped vehicles. Results of this program showed that the hip is the weakest part of the KTH complex under these loading conditions and that hip flexion and adduction from a standardized automotive seating posture significantly reduce hip fracture tolerance (Rupp, 2002, 2003a).

NHTSA then funded research to better assess the relationship between cadaveric testing and the Hybrid III dummy responses in crash tests. The research indicated that the knee/femur complex of the Hybrid III dummy is 2 to 16 times stiffer than that of the human (Rupp, 2003b). In addition, knee impact forces in cadavers were significantly lower than those in the Hybrid III dummy under similar impact conditions (Rupp, 2005). Therefore, in order to assess KTH injury risk using the Hybrid III dummy, the forces measured by the Hybrid III femur load cell need to be transformed to represent equivalent forces in a human KTH complex under similar impact conditions.

As part of the NHTSA-funded program, Rupp et al. (2008) conducted symmetric axial knee impacts to human cadavers representing the range of knee impact conditions observed in frontal crashes of recent vehicle models. This test data was used to develop and validate a one-dimensional lumped parameter model of the human midsize-male KTH complex. A similar one-dimensional lumped parameter model was also developed of the Hybrid III dummy KTH complex (Rupp et al., 2009). The simulations with the human model indicated that for long duration impacts (axial knee impact with energy absorbing knee bolster), the risk of hip injury is higher than the risk of knee or distal femur injury while for short duration axial knee impacts (impact with hard rigid surface), the risk of knee/distal femur injury is higher. The cadaver and Hybrid III dummy models were exercised in different knee impact loading conditions (Rupp et al., 2009) to develop a relationship between the measured Hybrid III femur force time history and the risk of hip injury.

This paper applies the KTH injury risk formulations developed by Rupp et al. (2009) for the Hybrid III 50th percentile male dummy (HIII-50M) and the Hybrid III 5th percentile female dummy (HIII-5F) in different frontal crash test modes. Risks predicted by the new formulation are compared to the injury risk observed in real world frontal crashes of comparable crash modes.

Development of KTH Injury Risk Curves for the Hybrid III Dummy

Rupp et al. (2009) has developed a new KTH injury criterion for the Hybrid III dummy that uses both peak compressive femur force, which is measured along the long axis of the femur, and impulse of the force to calculate the risk of injury to the knee, thigh, and hip. This method takes into account both the magnitude and duration of the load to the KTH complex. As discussed in Rupp et al. (2009), the revised injury assessment reference boundaries have an upper force limit that is based on limiting peak Hybrid III femur force so that it does not exceed the force associated with a specified risk of AIS 2+ knee/distal femur fracture, while the lower force limit and the impulse limit are set to correspond to a specified risk of AIS 3+ hip injury. An illustration of the criterion is shown in Figure 1.

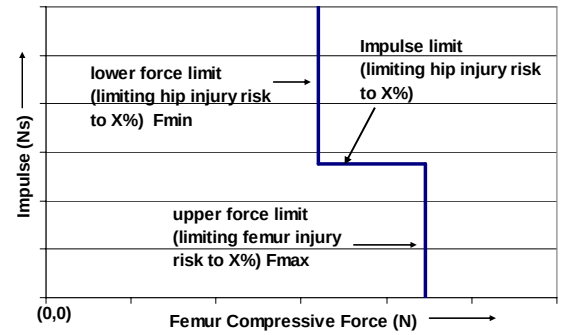

Figure 1. Layout of injury assessment reference boundary represented by the peak compressive femur force and the associated impulse for a specified level of KTH injury risk.

Table 1 lists the HIII-50M lower force limit, the impulse limit, and the upper force limit reported in Rupp et al. (2009) that is associated with injury assessment reference boundaries for 3%, 5%, 10%, 15%, 20%, 25%, 30%, 35%, 40%, 45%, 50%, and 75% risk at a hip posture that is 30˚ flexed and 15˚ abducted (i.e., the typical posture at the time of peak femur force in a FMVSS No. 208 or NCAP test) (Rupp, 2003b). Table 2 lists the lower force limit, impulse limit, and upper force limit as measured in the HIII-5F dummy for risks of KTH injury from 3-75 percent. In Table 1 for 3% risk and in Table 2 for 3 and 5% risk, impulse limits are not provided because the lower force limit is greater than or approximately equal to the upper force limit. In this situation, the impulse limit for hip injury does not apply.

Table 1.
Injury Assessment Reference Boundaries Associated with Risk of KTH Injury from 3% to 75% for the HIII-50M Dummy (Rupp et al., 2009)

Risk %	Lower force limit Fmin	Impulse Limit	Upper Force Limit Fmax
	(kN)	(Ns)	(kN)
3	4.97		4.97
5	5.22	113.5	5.69
10	5.63	121.8	6.87
15	5.92	127.7	7.69
20	6.16	132.7	8.35
25	6.38	137.1	8.92
30	6.59	141.3	9.44
35	6.79	145.5	9.92
40	6.98	149.4	10.37
45	7.18	153.3	10.8
50	7.35	157.2	11.23
75	8.4	180.7	13.45

Table 2.
Injury Assessment Reference Boundaries Associated with Risk of KTH Injury from 3% to 75% for the HIII-5F Dummy (Rupp et al., 2009)

Risk %	Lower force limit Fmin	Impulse Limit	Upper Force Limit Fmax
	(kN)	(Ns)	(kN)
3	3.65		3.37
5	3.82		3.86
10	4.13	70.6	4.66
15	4.33	74.1	5.22
20	4.49	77	5.67
25	4.65	79.5	6.06
30	4.79	81.9	6.41
35	4.91	84.4	6.74
40	5.05	86.6	7.04
45	5.18	88.9	7.34
50	5.33	91.2	7.62
75	6.09	104.8	9.14

The Rupp et al. (2009) KTH injury criterion involves determination of the overall risk of KTH injury by calculating and comparing the risks of injury to the hip and femur in any given test. To do this, it was necessary to develop injury risk curves that could be used to determine the risk of femur or hip injury at any measured force or impulse. The risk of femur injury uses a 2-parameter Weibull as the underlying distribution and assumes that the applied knee force on the cadaver is equivalent to the compressive force measured by the femur load cell in the Hybrid III dummy under similar impact conditions (Rupp et al., 2009). The resulting injury risk curves for the HIII-50M and the HIII-5F are shown in Figure 2 and Equations 1a and 1b.

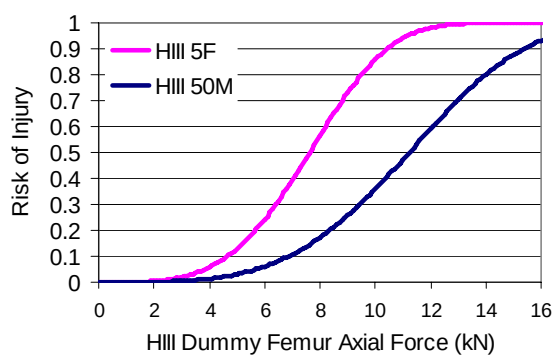

Figure 2. Risk of distal femur / knee injury as a function of peak compressive femur force measured by the HIII-50M and HIII-5F femur load cells.

$HIII-50M$:

$$P(distalfemur/kneeinjury) = 1 - e^{-a} \qquad (1a.)$$

where

$$a = e^{\frac{\ln(F)-2.514}{0.2611}}$$

$HIII-5F$:

$$P(distalfemur/kneeinjury) = 1 - e^{-b} \qquad (1b.)$$

where

$$b = e^{\frac{\ln(F)-2.127}{0.2611}}$$

Where F is the peak compressive force in kN measured in the HIII-50M and HIII-5F dummy femurs.

The risk of hip injury derived from cadaver test data (Rupp et al., 2009) as a function of force at the hip, subject stature, hip flexion, and abduction angle is presented in Equation 2a. For an occupant stature of 178 cm (corresponding to the size of a HIII-50M dummy), seated in normal driving posture (hip flexion =30 degrees and hip abduction=15 degrees), the corresponding hip injury risk is as shown in Equation 2b. Similarly, the hip injury risk for occupant stature of 150 cm, corresponding to the size of a HIII-5F dummy, in normal driving posture is presented in Equation 2c.

$$Risk(hip\ injury) = \Phi\left[\frac{\ln(F)-(-0.2141+0.0114*s)-\ln(1-(f-a)/100)}{0.1991}\right] \qquad (2a.)$$

50th *percentile male* :

$$Risk(hip\ injury) = \Phi\left[\frac{\ln(F)-1.6526}{0.1991}\right] \qquad (2b.)$$

5th *percentile female* :

$$Risk(hip\ injury) = \Phi\left[\frac{\ln(F)-1.3334}{0.1991}\right] \qquad (2c.)$$

Where:
Φ is the cumulative normal distribution;
s is occupant stature, in cm;
f is hip flexion angle, in degrees;
a is hip abduction angle, in degrees; and
F is the peak hip force, in kN.

The hip injury risk curve applicable to the Hybrid III dummy femur force measure was derived by fitting a lognormal distribution to the data in the second column in Table 1. This equation is the same as that presented in Equation 2b for a normally seated 50th percentile male occupant with the force scaled by

0.7126 (Equation 3a and Figure 3). This scale factor represents the transformation of the measured compressive femur force in the HIII-50M dummy to the equivalent hip force in the cadaver in simulations of knee impacts by force limiting knee bolsters. According to Rupp et al. (2009), the risk of injury using the force in the second column in Table 2 was developed by scaling the force in Equation 2c for a 5th percentile normally seated female occupant by 0.7143 (=1/1.4: factor to scale the force at the HIII 5F femur load cell to equivalent force at the cadaver acetabulum in simulation of knee impacts with force limiting knee bolsters). The resulting hip injury risk curve using the force measured at the HIII-5F femur load cell is presented in Equation 3b and Figure 3.

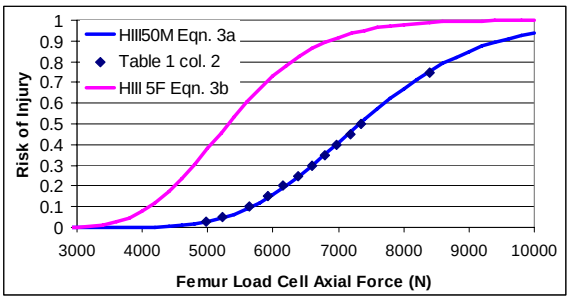

Figure 3. Risk of hip injury as a function of peak compressive femur force in the HIII-50M and HIII-5F dummies.

$HIII-50M$:

$$P_{hip} = \Phi\left(\frac{\ln(0.7126F) - 1.6526}{0.1991}\right) \qquad (3a.)$$

$HIII-5F$:

$$P_{hip} = \Phi\left(\frac{\ln(0.7143F) - 1.3334}{0.1991}\right) \qquad (3b.)$$

Where:
Φ is the cumulative normal distribution; and
F is the compressive force measured on the dummy in kN.

The risk curve for hip injury as a function of impulse of the femur force was obtained by fitting a logistic distribution to the data in column 3 of Table 1. The risk of hip injury for the HIII-50M dummy impulse of the compressive femur force is shown in Figure 4 and Equation 4a. According to Rupp et al. (2009), the risk of hip injury as a function of compressive femur force impulse of the HIII-5F dummy was obtained by scaling the impulse in Equation 4a by a factor of 0.58 as shown in Equation 4b.

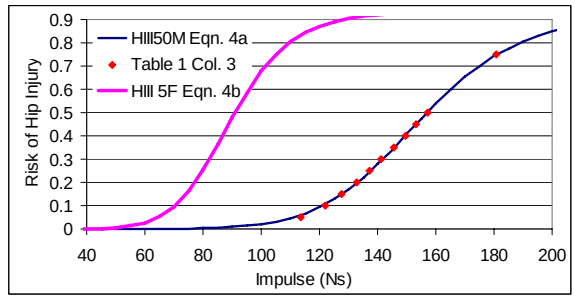

Figure 4. Risk of hip injury as a function of the impulse of the compressive femur force in the HIII-50M and HIII-5F dummies.

$HIII-50M$:

$$P_{hip} = \frac{0.9386}{1+\left(\frac{impulse}{154.5037}\right)^{-8.7288}} \qquad (4a.)$$

$HIII-5F$:

$$P_{hip} = \frac{0.9386}{1+\left(\frac{0.58 * impulse}{154.5037}\right)^{-8.7288}} \qquad (4b.)$$

Where *impulse* is the impulse of the compressive femur force measured on the dummy in Newtons.Seconds.

METHODS

Investigation of KTH Injuries in NASS-CDS

The risk and proportion of KTH injuries in real world crashes were investigated by analyzing the NASS-CDS data files for years 1993-2007 and vehicle model years (MY) 1991-2008 using a similar methodology as that presented by Kuppa et al. (2003). Frontal crashes were defined as those with impact direction between 10-2 o'clock with general area of damage in front and forward of the A-pillar. Frontal crashes were further classified into three categories representing a full frontal rigid barrier crash test (FFB), a left offset and a right offset deformable barrier crash test (LOV and ROV) as defined by Stucki et al. (1998) using impact direction, type of object contacted (fixed or vehicle), general area of damage, and the location of maximum crush. Only vehicles not involved in a rollover, and driver and front passenger occupants with an air bag available at their seating position were included. Only outboard front seat occupants (driver and right front passenger) who were at least 15 years of age and were not ejected were included in the analysis. Cases were aggregated by frontal crash mode, vehicle

model year, occupant stature, seating position (i.e., driver or passenger), restraint status, and crash DeltaV. Injury risks were calculated for multiple body regions with the lower extremities divided into the KTH complex and below knee. Additionally, KTH injuries were examined in further detail to determine the proportion of KTH injuries to the knee, thigh, and hip for various crash, occupant, or restraint types and crash DeltaVs using the knee, thigh, and hip injury categories defined by Kuppa et al. (2003).

Application of the KTH Injury Criteria to Determine KTH Injury Risk in Frontal Crash Environments

50th Percentile Male Data: Femur force-time data were extracted from frontal NCAP, FMVSS No. 208, IIHS frontal offset, and vehicle-to-vehicle frontal and offset tests for the HIII-50M. NCAP femur data were taken from tests conducted on belted HIII-50M driver-side dummies in MY 1995-2008 vehicles in 56 km/h (35 mph) frontal crash tests. The FMVSS No. 208 tests were full frontal barrier tests conducted on MY 2002-2007 vehicles at 40 and 48 km/h (25 and 30 mph), with unbelted HIII-50M dummies. Frontal offset tests from IIHS include MY 1995-2003 vehicles tested with 64.4 km/h (40 mph) closing speed. The HIII-50M driver was belted in these tests. Finally, a series of 50% left offset and collinear vehicle-to-vehicle tests conducted as part of NHTSA's compatibility research was included (Summers and Prasad, 2005). In this series, bullet vehicles impacted the stationary struck vehicle (a 2004 Honda Accord) such that the DeltaV of the struck vehicle was 56 km/h. Femur data from this test series were taken from the belted HIII-50M dummy driver with Thor-Lx/HIIIr in the struck vehicle. For the NCAP, FMVSS No. 208, NHTSA offset, and vehicle-to-vehicle crash tests, the dummies were positioned according to dummy placement specified in FMVSS No. 208. For the IIHS offset tests, the dummies were positioned according to IIHS offset barrier crash test protocol Version IX with the driver seat in the midtrack full-down position. All data are available on the NHTSA vehicle database at http://www-nrd.nhtsa.dot.gov/database/nrd-11/veh_db.html.

5th Percentile Female Data: Femur force-time data for the HIII-5F were taken from unbelted FMVSS No. 208 tests of MY 2003-2008 vehicles in full frontal barrier crash tests at 40 km/h (with the exception of one test at 32 km/h (20 mph)). Femur data were also collected from NHTSA research tests using the HIII-5F in full frontal, belted environments at 40, 48, and 56 km/h. Finally, femur data were collected from HIII-5F drivers in three 40% left offset frontal tests of MY 2002 and 2004 vehicles at 40 km/h. All tests were conducted with the HIII-5F positioned as specified for the HIII-5F in FMVSS No. 208. All data are available on the NHTSA vehicle database at http://www-nrd.nhtsa.dot.gov/database/nrd-11/veh_db.html.

Femur Force, Impulse, and Risk Calculation: Peak left and right compressive femur forces for each test were obtained after processing the femur force time histories with SAE CFC 600. The impulse of each force was then calculated by integrating the filtered femur force time history from Tzero, the time that force last equals zero prior to the peak compressive force, to the time after the peak force when the compressive force first equals 4050 N for the HIII-50M or 2750 N for the HIII-5F (Figure 5). These are the compressive forces in the Hybrid III dummies that correspond to the minimum force required for KTH injury in cadavers. If the peak compressive femur force is less than 4050 N (or 2750 N for the HIII-5F), the integral is taken from Tzero to the time of the peak force (Fmax).

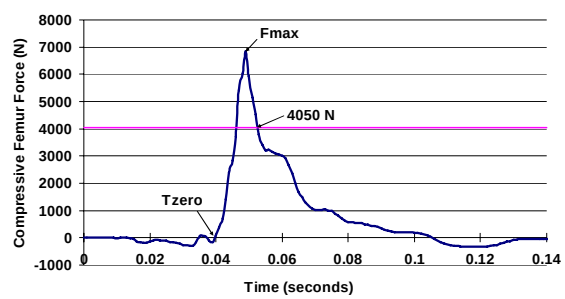

Figure 5. Impulse integration limits for the HIII-50M.

The peak compressive force and impulse values were then used in Equations 1, 3, and 4 to calculate the risks of injury to the femur and hip. A femur force time history with peak force levels lower than Fmin of Figure 1 has a hip injury risk less than X% regardless of the level of impulse. On the other hand, a short duration femur force time history with peak femur force greater than Fmin in Figure 1 has a hip injury risk less than X% only if the impulse is less than the impulse limit associated with X% injury risk. Therefore, the overall risk of hip injury (P_{hip}) is determined by the lower of the risks due to force and impulse, calculated using Equations 3 and 4. As a result, short duration femur force spikes (high peak compressive femur force with low impulse) and low force level-long duration time histories will have relatively low risk of hip injury. The overall risk of KTH (P_{KTH}) injury due to axial, compressive loading of the femur was determined as the greater of the risk to the hip (P_{hip}) and to the distal femur/knee (P_{knee})

from Equation 1. In other words,

P_{KTH}=Maximum(Minimum($P_{hip\text{-}Eqn.\ 3}$, $P_{hip\text{-}Eqn.\ 4}$), $P_{knee\text{-}Eqn\ 1}$)

This process of determining overall risk is illustrated using Figure 6 and Table 3. The 25 and 35 percent risk of KTH injury lines along with points A, B, C, and D representing four peak compressive femur force and impulse combinations for the HIII-50M dummy are shown in Figure 6. Table 3 presents the hip, femur/knee, and the overall KTH injury risk for each of the 4 combinations of force and impulse. Point A (high force and low impulse) lies on the 35 percent risk boundary associated with femur/knee injury risk. Though the peak femur force is high for Point A, the risk of hip injury is low because of the low impulse level. Point B represents a relatively high force-short duration force time history. Though the peak femur force of Point B is associated with a 62 percent hip injury risk, the impulse of Point B is only associated with a 25 percent injury risk. Point C represents a relatively low force-long duration time history. Though the hip injury risk from impulse is 74 percent, the femur force level of Point C is only associated with a 35 percent risk of injury. Point D provides another example of a low force, long duration time history. Although the hip risk due to impulse is fairly high (54%), the overall risk is determined by the risk of hip injury due to femur force, which is 30%.

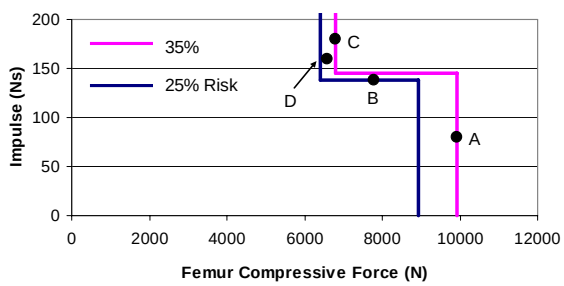

Figure 6. Peak compressive femur force versus impulse plot for the HIII-50M dummy to illustrate the process of determining KTH injury risk. Points A, B, C, and D represent four compressive femur force and impulse combinations of the HIII-50M dummy.

Table 3.
Risk of Injury to the KTH Complex using Equations 1, 3, and 4.

	A	B	C	D
Compress. Femur Fz (N)	9920	7800	6800	6585
Impulse (Ns)	80	138	180	160
Hip Injury Risk Eqn. 3	0.94	0.62	0.35	0.30
Hip Injury risk Eqn. 4	0.00	0.25	0.74	0.54
Hip Injury Risk (Min. risk of rows 4 and 5)	0.00	0.25	0.35	0.30
Femur/knee Injury Risk	0.35	0.16	0.10	0.09
Overall KTH risk (Max of rows 6 and 7)	0.35	0.25	0.35	0.30
What is injured?	femur/knee	hip	hip	hip

RESULTS

NASS Analysis of KTH Injuries

Compared to other injuries, lower extremities (KTH + below knee combined) continue to have the highest risk of all body regions of AIS 2+ injuries to front seat occupants in frontal crashes of air bag equipped vehicles (Figure 7).

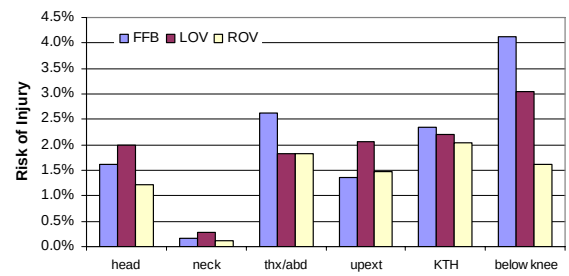

Figure 7. Risk of AIS 2+ injury by body region, for driver and front seat passenger in air bag equipped vehicles in different frontal crash modes (FFB= crashes representative of full frontal rigid barrier crashes; LOV, ROV= crashes representative of left and right offset deformable barrier crashes) (NASS-CDS 1993-2007).

Risk of KTH injury for belted occupants is 1.5-2%, while for unbelted occupants this risk is 4-7.6%. The risk for unbelted occupants was higher than that for belted occupants in each crash mode. The risk of KTH injury is higher in full frontal rigid barrier type crashes than in the left and right offset crash modes for unbelted occupants while there is not much difference in KTH injury risk in the three crash modes for belted front seat occupants (Figure 8).

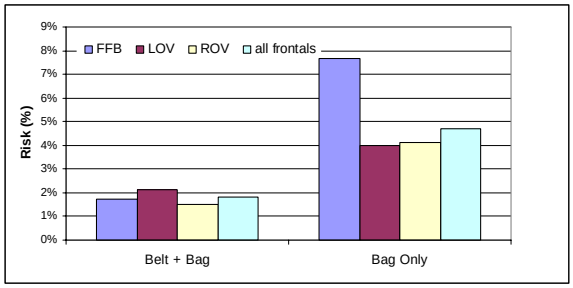

Figure 8. Risk of AIS 2+ KTH injury in belted and unbelted drivers and passengers in frontal crashes (NASS-CDS 1993-2007).

The proportion of knee, thigh, and hip injuries to drivers and passengers in all frontal crashes are similar for belted as for unbelted occupants. Additionally, knee injuries occur with somewhat greater frequency than hip injuries (Figure 9).

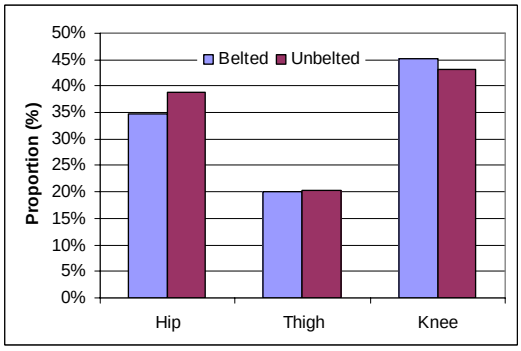

Figure 9. Proportion of knee, thigh, hip injuries among front seat occupants by restraint status (NASS-CDS 1993-2007).

Agency crash tests are conducted with both 50th percentile male and 5th percentile female-sized dummies. Because of this, NASS-CDS data files were examined using occupant stature categories according to Samaha et al. (2001) that correspond to the occupant heights representative of the HIII-5F dummy (143-162 cm) and HIII-50M dummy (163-182 cm). Since many occupant heights are listed as "unknown" in NASS-CDS, the number of observations for this category (i.e., occupant height) is much smaller than that for other categories.

The belted and unbelted front seat occupants, represented by the HIII-5F dummy size (5F) had somewhat greater risk of AIS 2+ KTH injury than those represented by the HIII-50M dummy (50M) as shown in Figure 10. The proportion of knee, thigh, and hip injuries were essentially equal in the belted 5F group while the proportion of thigh injuries were lower than hip and knee injuries in the belted 50M group. The greatest proportion of KTH injuries in the unbelted 5F and 50M groups was to the hip, although the 5F group had a nearly equivalent proportion of thigh injuries (Figure 11).

Figure 10. Risk of AIS 2+ KTH injury for belted front seat occupants in frontal crashes for small female and average male height occupants (NASS-CDS 1993-2007).

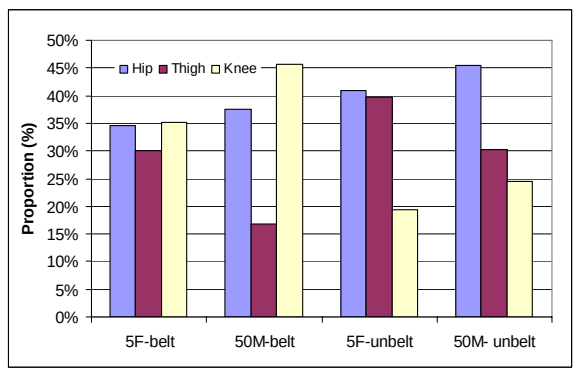

Figure 11. Proportion of KTH injuries in belted and unbelted occupants by occupant stature (NASS-CDS 1993-2007).

In addition to crash mode, restraint, and occupant size, risk of injury by vehicle model year was also examined. For belted occupants, risk of AIS 2+ KTH injury remained relatively constant between MY 1991-2000, then decreased slightly in MY 2001-2008 vehicles (Figure 12). The proportion of thigh injuries relative to all KTH injuries remained at approximately 20% for all model years, while the proportion of hip injuries decreased from 40% to 20% and the proportion of knee injuries increased from 40% to 60% from 1991-1995 MY vehicles to 2001-2008 MY vehicles (Figure 13).

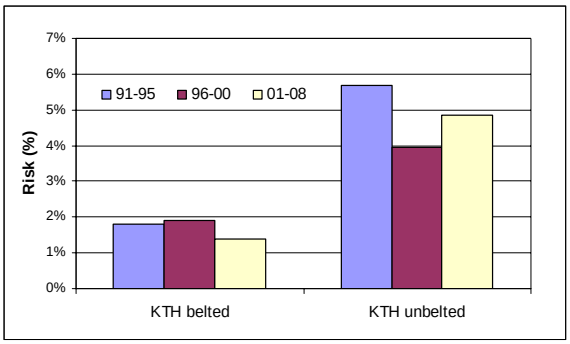

Figure 12. Risk of KTH injury by model year for belted and unbelted front seat occupants (NASS-CDS 1993-2007).

The risk of AIS 2+ KTH injury is higher among unbelted occupants than belted occupants for all three categories of vehicle model years. Additionally, hip injuries are dominant for unbelted occupants, while knee injuries are dominant for belted occupants (Figure 13). In unbelted occupants, the proportion of hip injuries increased from earlier to more recent vehicle model years, while in belted occupants it decreased in more recent model years. Knee injuries in unbelted occupants remained relatively constant from 91-95 to current model year vehicles.

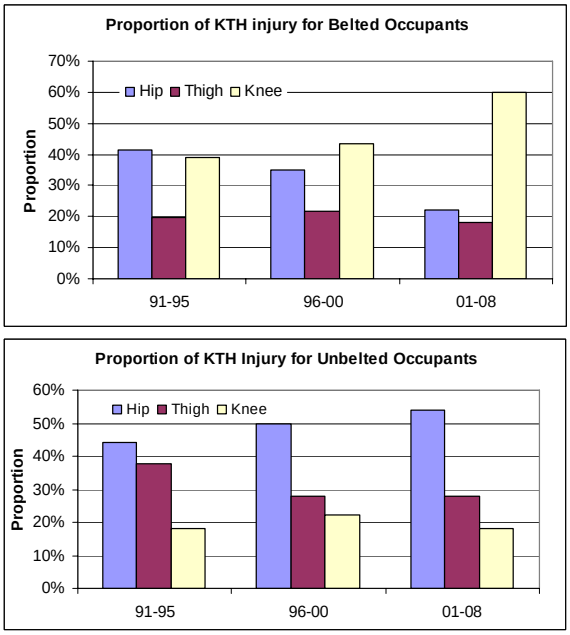

Figure 13. Proportion of AIS 2+ KTH injury by model year for belted and unbelted front seat occupants in air bag equipped vehicles (NASS-CDS 1993-2007).

To obtain real world injury risk at crash severities similar to that of the various crash tests, the NASS-CDS data files were further parsed by the crash DeltaV. For belted occupants, frontal crashes of DeltaV ranging 48-70 km/h were considered, and for unbelted occupants, frontal crashes of DeltaV ranging 35-60 km/h were considered. For simplicity, these results will be referred to as "high severity" belted and unbelted frontal crash results, to distinguish them from the results derived from crashes of all DeltaVs.

Risk of KTH injury for belted drivers in high severity frontal crashes ranged from 10% for right offset crashes to 27% for left offset crashes, and had a 20% risk for full frontal crashes. The risk of KTH injury for unbelted drivers in high severity crashes ranged from 18 to 20 percent. With the exception of unbelted passengers, the risk of KTH injury is higher for the driver in left offset crashes than in right offset crashes, and higher for the passenger in right offset crashes than left offset crashes (Figure 14). This finding is consistent with the expectation that occupants closer to the impact site are at a higher risk of injury than occupants farther away from the impact site.

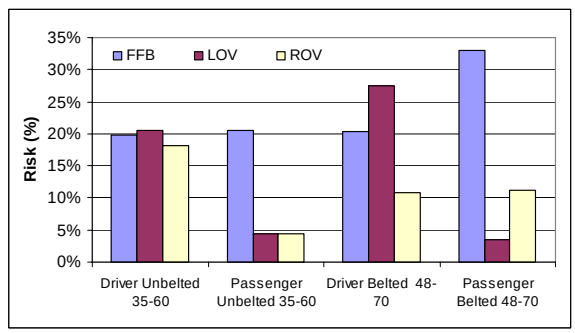

Figure 14. Risk of AIS 2+ KTH injury in high severity unbelted and belted frontal crashes (NASS-CDS 1993-2007).

Hip injuries account for a large proportion of KTH injuries in high severity unbelted and belted frontal crashes. Hip injuries account for 32 to 41% of AIS 2+ KTH injuries in these high severity belted frontal crashes and 45 to 51% of KTH injuries in unbelted frontal crashes. In both belted and unbelted occupants in high severity crashes, when looking at all frontal crash modes combined, hip injuries were most common, followed by thigh, then knee injuries. This trend was also seen in full frontal unbelted crashes. Full frontal belted crashes had nearly equal hip and thigh injuries, and somewhat fewer knee injuries (Figure 15).

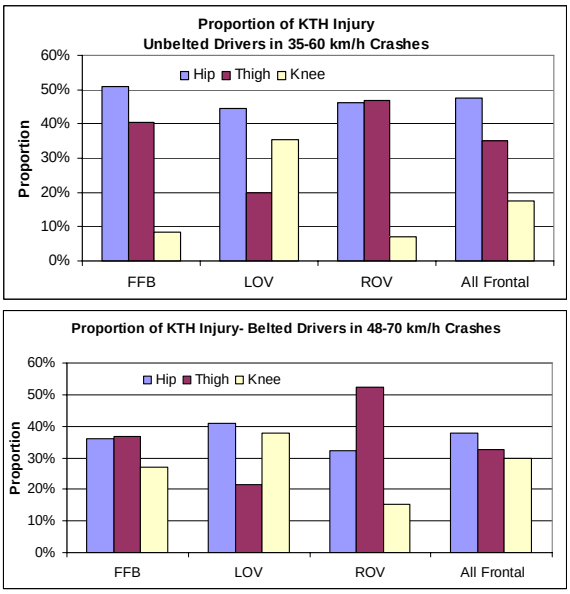

Figure 15. Proportion of KTH injuries for unbelted and belted drivers in high severity crashes (NASS-CDS 1993-2007).

Application of KTH Criterion to the 50th Percentile Male Dummy

As described previously, risk of KTH injury is defined by the maximum risk to the femur/knee or the hip. The risk of hip injury is determined by the minimum risk computed from Equations 3 and 4. For purposes of this discussion, when the hip injury risk is determined by Equation 3, it will be stated that the hip(force) has the greatest injury risk. For cases where the hip injury risk is determined by Equation 4, it will be stated that the hip(impulse) has the greatest injury risk. Equation 1 is used to determine the risk of distal femur and knee injuries and is noted as femur/knee.

NCAP Tests: The compressive femur forces and impulses for belted 50th percentile male dummies in 566 56 km/h NCAP tests of MY 1995-2008 vehicles are graphically presented in Figure 16. For reference, lines of 25% and 35% risk of KTH injury are also shown. These levels of injury risk were selected because these risk levels have been used in previous studies as injury threshold levels for lower extremity injuries (Kuppa et al., 2001). The force and impulse values from NCAP tests were input into Equations 1, 3, and 4 to calculate overall risk for the driver in each test; the risks are presented in Figure 17. The average calculated risk of KTH injury in 50th percentile male drivers in NCAP tests is 5.2%. By model year group, the average risk of MY 1995 vehicles is 7.49%; of MY 1996-2000 vehicles is 7.61%; and of MY 2001-2008 vehicles is 3.70%. This risk is quite low compared to the NASS risk for belted drivers in 48-70 km/h delta V frontal crashes of MY 1991-2008 vehicles, which was 20% as shown in Figure 14. However, the lower risk for more recent model year vehicles than previous model year vehicles is consistent with NASS results for all crash severities shown in Figure 12.

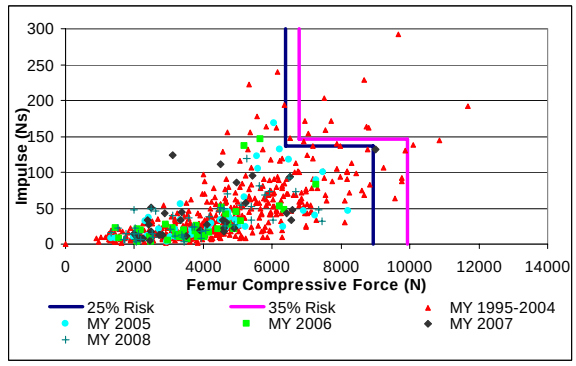

Figure 16. Peak compressive femur force and impulse in NCAP tests.

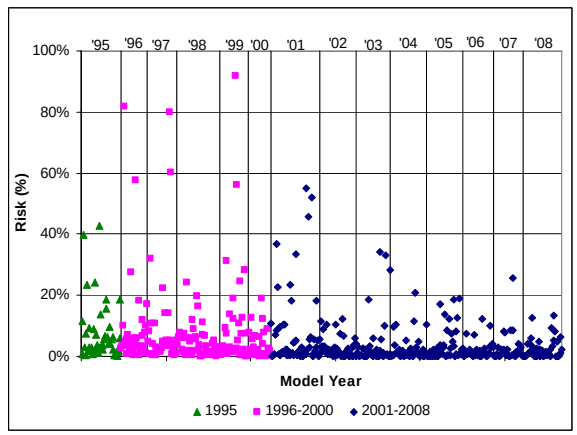

Figure 17. Calculated risk of KTH injury in the 50th percentile male in NCAP tests.

When the KTH criterion is applied to the HIII-50M in NCAP tests, risk of femur/knee injury dominates the risk of hip injury for nearly all tests. However, in most tests the risk is low. Only 21 out of 566 tests (3.71%) have an overall injury risk greater than 25%. Of these higher risk tests, risk of hip injury was greatest in MY 1995-1997 and 1999, while in 2001 and 2003, femur/knee injury risk was greatest. After 2003, only one test (in 2007, femur/knee dominant risk) failed the 25% injury risk criterion, with a risk of 25.8%. The dominant risks are presented by number of vehicles in Figure 18.

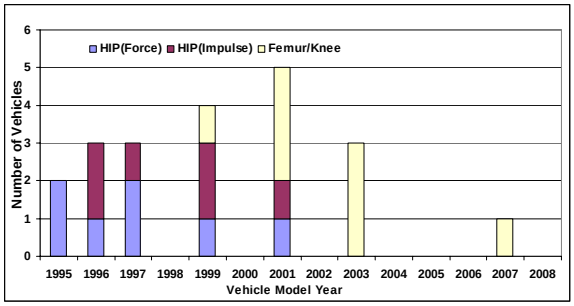

Figure 18. Dominant risk of injury for 50th percentile male driver when risk of KTH injury is at least 25%.

Although overall risk is underpredicted, the trend of increasing femur/knee injuries and decreasing hip injuries with model year is consistent with results from NASS-CDS shown in Figure 13. However, real world, high severity belted crashes show nearly equal proportions of hip and thigh+knee injuries (Figure 15), while NCAP test data indicates that among those with KTH risk greater than 25 percent, hip injury was predominant.

FMVSS No. 208 Unbelted Tests: The compressive femur force and impulse from 26 unbelted HIII-50M drivers and 26 passengers in 40-48 km/h full frontal FMVSS No. 208 tests are graphically presented in Figure 19. The average calculated risk of KTH injury in drivers and passengers of these MY 2002-2008 vehicles was 13.8%, where drivers had a risk of 11.3% and passengers had a risk of 16.3%. These risks are comparable to the real world risks of KTH injury in high severity unbelted crashes for drivers and passengers in MY 1991-2008 vehicles (about 20%), shown in Figure 14, particularly for passengers.

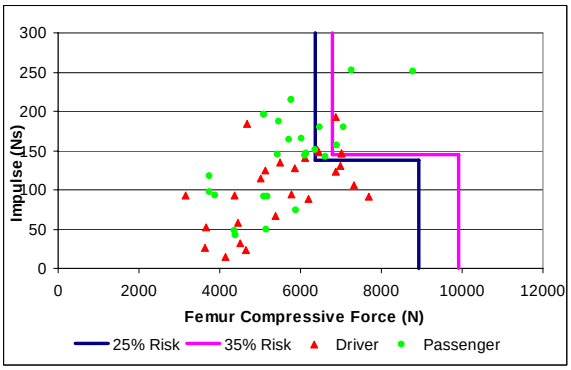

Figure 19. Peak compressive femur force and impulse in FMVSS No. 208 tests with the HIII-50M dummy.

In comparison to the NCAP tests for the same model years (Figure 18), there was a greater proportion of tests where hip injury risk was higher than femur/knee injury risk in the unbelted FMVSS No. 208 tests (Figure 20). This difference in proportion of hip injuries is consistent with the difference in proportions in the real world for unbelted high severity crashes compared to belted high severity crashes (Fig. 15), which show greater proportions of hip injuries in unbelted tests.

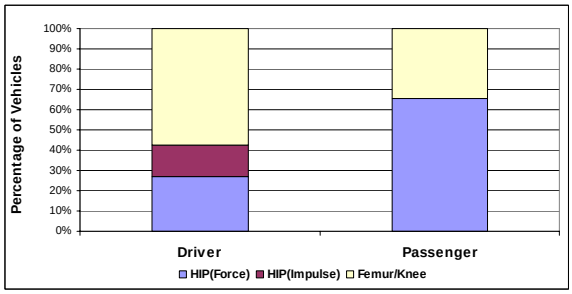

Figure 20. Dominant risk of injury, by percentage of vehicles, in unbelted 50th percentile male driver and passenger dummies in FMVSS No. 208 tests.

Of the 26 unbelted FMVSS No. 208 tests conducted with HIII-50M dummies, 5/26 drivers (19.2%) and 6/26 passengers (23.1%) had KTH injury risks above 25%. This percentage of occupants exceeding 25 percent injury risk is consistent with the real world risk of KTH injury to unbelted occupants (Figure 14). In these tests, hip(force) had the greatest risk of injury in most tests (see Figure 21). The greatest risk of injury being to the hip is in agreement with NASS data for unbelted drivers in high severity crashes, presented in Figure 15. However, the proportion of thigh+knee injury in the real world is underpredicted in these unbelted tests.

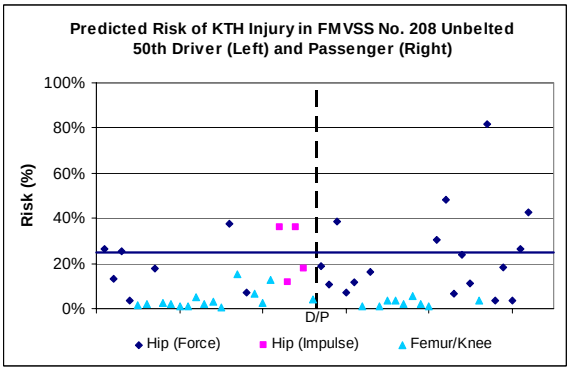

Figure 21. Dominant risk of injury in 50th percentile dummy driver (left) and passenger (right) in unbelted FMVSS No. 208 tests.

IIHS Frontal Offset Tests: Compressive femur force and impulse in 179 IIHS 40% left offset frontal crash tests are presented graphically in Figure 22. In these belted tests of HIII-50M drivers, risk of

injury to the femur/knee was found to be dominant. Like in the NCAP tests, the risk of injury was generally low (Figure 23), with an average risk of 6.93%. Note however, that the average risk in frontal offset tests is slightly higher than that in NCAP tests, just as belted left offset tests have slightly higher risk (27%) than belted frontal tests (20%) in NASS high speed belted crashes (Figure 14). In IIHS frontal offset tests, injury risk was lower in recent model years; the average injury risk for MY 2001-2003 was 3.93% compared to a risk of 14.7% for MY 1995 and 7.8% for MY 1996-2000. This decrease in risk with model year was also observed in belted NCAP tests. Among 179 frontal offset tests, only 15 (8.4%) had an overall injury risk greater than 25%. For these tests, hip(force) was the dominant injury risk, as seen in Figure 24. Hip injuries were also most prevalent in the real world crashes of this type and severity. However, the criterion does not predict the femur/knee injuries that also occur with significant proportions in the real world (Figure 15).

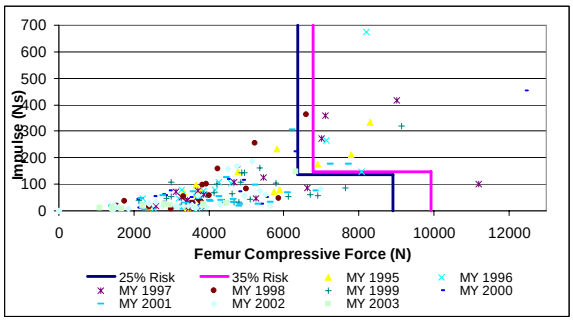

Figure 22. Peak compressive femur force and impulse in IIHS frontal offset tests with the HIII-50M dummy.

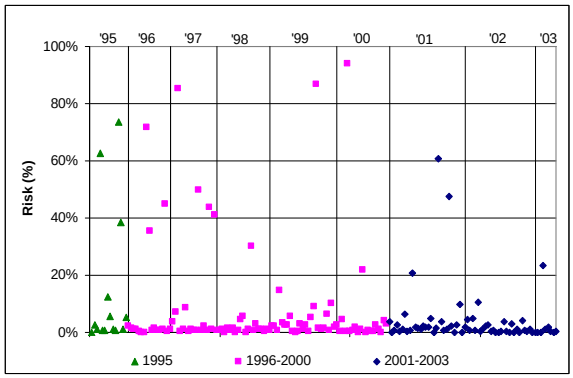

Figure 23. Predicted risk of KTH injury in IIHS frontal offset tests, by model year.

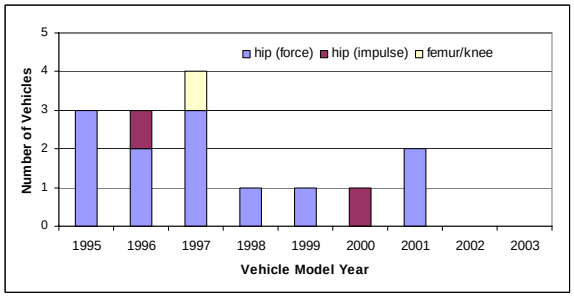

Figure 24. Dominant risk of KTH injury in IIHS frontal offset tests where risk is at least 25%.

<u>Vehicle-to-Vehicle Offset and Collinear Tests:</u> Compressive femur forces and impulses were generally low in the HIII-50M driver of a 2004 Honda Accord struck by various LTVs, as seen in Figure 25. The maximum overall risk was less than 3.6% for all nine tests, with the highest risk to the femur/knee. The extremely low risk of injury in vehicle-to-vehicle crash conditions is inconsistent with the risk of injury in high speed, belted frontal crashes in the real world, which is 20-27% as shown in Figure 14.

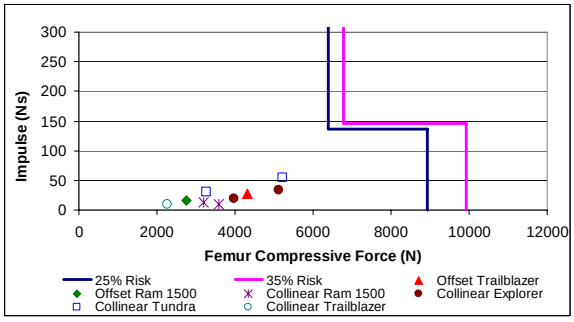

Figure 25. Peak compressive femur forces and impulses in HIII-50M driver of a 2004 Honda Accord struck by LTVs.

Application of the KTH Criterion to the 5th Percentile Female Dummy

<u>FMVSS No. 208 Unbelted Tests:</u> Compressive femur forces and impulses for 67 unbelted 5th percentile female driver and 66 passenger dummies in FMVSS No. 208 tests are presented graphically in Figure 26. There are a greater number of tests exceeding 25 or 35 percent risk of KTH injury in the passenger than the driver. The average risk of injury for the driver is 10.9% while the average risk for the passenger is 20.5%. The average risk overall is 15.7%. This is somewhat higher than the average risk for the HIII-50M in FMVSS No. 208 unbelted tests (13.8%). The HIII-5F having somewhat higher risk than the HIII-50M is consistent with the real

world data shown in Figure 10. Additionally, the passenger risk of 20.5% is in agreement with the real world injury risk for unbelted passenger occupants in high severity full frontal crashes (about 20%, as shown in Figure 14). However, the average risk for drivers is somewhat lower than the corresponding real world injury risk shown in Figure 14.

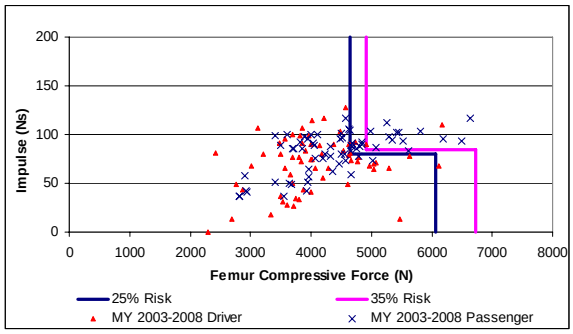

Figure 26. Peak compressive femur force and impulse in FMVSS No. 208 unbelted 5th percentile female frontal crash tests.

In this unbelted environment, the dominant risk of KTH injury was the femur/knee for the driver and the hip(force) for the passenger. For occupants with a calculated KTH injury risk of at least 25%, the dominant risk in five out of six tests for the driver was to the hip(force) (Figure 27). These six tests represent 9.1% of the number of tests conducted. In the passenger, 22 tests exceeded 25% risk of injury (33.3% of tests conducted), with the hip having the highest risk of injury for all tests. Hip(force) had the highest risk for 16 passenger tests, and hip(impulse) for six tests. The high risks of hip injury are in reasonable agreement with real world data, which shows high proportions of hip injuries (Figure 15). However, NASS data shows an almost equal proportion of thigh+knee injuries, which are not represented in the crash test data.

Compared to proportions of risks in the HIII-50M unbelted tests, the HIII-50M risks greater than 25% were all to the hip, while the HIII-5F had one risk greater than 25% to the femur/knee. Figure 11 shows that in the real world, unbelted occupants with height represented by the HIII-50M have a higher proportion of hip than thigh or knee injuries, compared to the 5F unbelted occupants with nearly equal proportions of hip and thigh injuries. Although NASS and the crash test data are in some agreement in this comparison, since the HIII-50M had no femur/knee risks greater than 25% and the HIII-5F had one, in general femur/knee injuries are underpredicted for both dummy sizes.

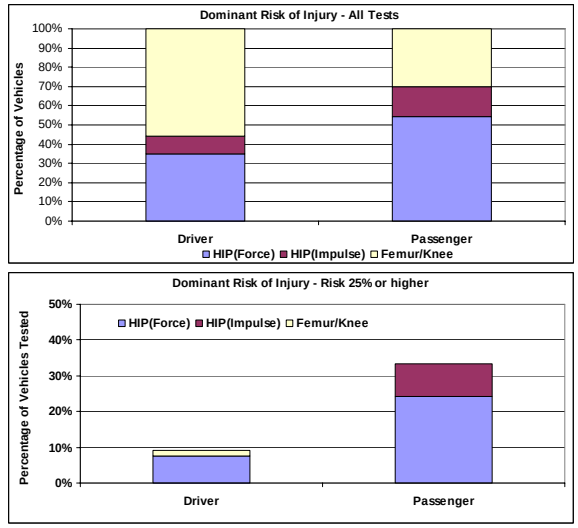

Figure 27. Dominant risk of injury in unbelted 5th percentile female frontal crash tests for all tests and for tests where risk is at least 25%.

Belted Frontal Research Tests: Only one out of 71 tests of the HIII-5F driver in a belted full frontal crash test environment had a calculated risk of KTH injury greater than 25%, as seen in Figure 28. Two other tests had risks close to 25%, but the majority of calculated risks were well below this level, with an average risk of 3.14%. Compared to real world risk for belted drivers in high severity full frontal crashes (20%), this risk is very low.

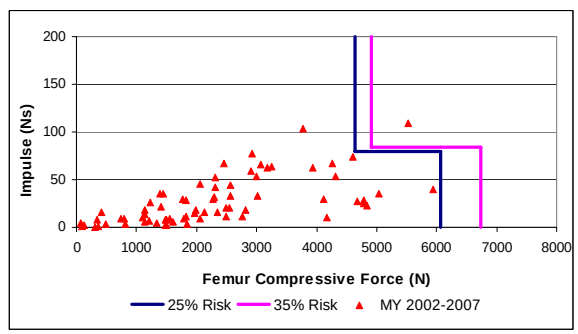

Figure 28. Peak compressive femur forces and impulses in belted frontal crash tests with 5th percentile female drivers.

97% of the drivers in this belted test have their greatest risk of injury to the femur/knee. However, in the one test with risk greater than 25%, the dominant risk was to the hip(force). Real world injuries occur in equal proportion to hip and thigh, with only somewhat smaller proportion to the knee (Figure 15). The predicted risks do not reflect the real world injuries for this crash condition.

Frontal Offset Tests: Three frontal offset tests at 40 km/h were conducted with belted 5th percentile

female dummies in the driver position. In all three tests, there was essentially zero risk of KTH injury (average calculated risk = 0.024%). This is a very small sample of crash tests, but the real world risk for high severity left frontal offset crashes is much higher at 27% (Figure 14). However, this real world risk may be elevated somewhat because it was determined from higher deltaV crashes (48-70 km/h) than were simulated in these crash tests.

DISCUSSION

The compressive femur forces and impulses in FMVSS No. 208 unbelted tests are noticeably greater than those in the belted NCAP tests (or belted research tests, for the 5th percentile female) even though the NCAP tests and many of the belted research tests were conducted at higher speeds than the FMVSS No. 208 tests. This is because the unbelted dummy in the FMVSS No. 208 test strokes the knee bolster to a greater extent than the belted dummy. Higher forces and impulses lead to higher average calculated risks in the unbelted tests than the belted tests. This observation is consistent with real world crash data, which shows higher risk for unbelted occupants than belted occupants.

The risk of KTH injury obtained from 48-64 km/h frontal crash tests with belted dummies underestimated the observed risk in corresponding real world crashes with belted occupants. This observation is similar to that reported by Saunders et al. (2004) where KTH injury risk obtained in frontal offset deformable barrier crash tests with belted dummies using the current FMVSS No. 208 femur injury criterion, was found to under-represent the corresponding real world injury risk. This underestimation of real world KTH injury risk using belted dummies may be related to the low levels of dummy knee-to-knee bolster interaction, as evidenced by the low femur force and impulse values in belted dummies compared to unbelted dummies in frontal crash tests.

Although KTH injury risk was underestimated in belted crash tests, in both NCAP and IIHS, the calculated risk was lower in recent model year vehicles than in older model year vehicles. This trend is consistent with NASS data, which showed a lower risk for belted occupants in MY 2001-2008. Decrease in risk could be attributed to improved restraints, such as pretensioners, that help to reduce the occupant's forward travel and engagement with the knee bolster or other vehicle structures. Improved restraints could have also played a part in the decrease in hip injuries with vehicle model year, a trend that was seen in both the crash test data and the real world data for belted occupants.

The frontal crash tests examined were collinear crashes where the dummy knees contacted the knee bolster with knee loading primarily along the femur longitudinal axis. However, many of the real world frontal crashes investigated were oblique impacts, which could result in varied occupant kinematics. The dummies representing two specific occupant statures were positioned in the crash tests using set procedures. However, occupant shape, size, weight, posture, and seating position relative to the passenger compartment are quite varied in the real world. As a result, the knee impacts in real world crashes may have been with surfaces other than the knee bolster and in various impact directions other than along the femur axis. Additionally, risk derived from the crash test "fleet" was not adjusted to account for the distribution of vehicle models in real world crashes. All these factors may have an affect on the comparison between the KTH injury risk estimated from the crash test data and that observed in the real world.

The Rupp KTH injury criterion applied to the Hybrid III dummy is able to discern the relative risk of hip and femur/knee injury for a given femur force time history using both the peak compressive femur force as well as the associated impulse of force. This additional information may aid in the design of knee bolsters where both peak dummy femur force and the impulse are used as optimization parameters to minimize the risk of KTH injury for belted and unbelted occupants.

In unbelted full frontal crashes, overall risk of KTH injury, as well as the occurrence of hip injuries, was reasonably well predicted by the KTH criterion. However, the thigh and knee injuries that occur in large proportions in the real world are not represented in these crash tests. This may be partly due to the fact that the femur/knee portion of the KTH injury criterion only addresses distal femur and knee injuries and does not account for injuries in the femur shaft that can occur due to bending. Therefore, KTH injuries in the real world that occur due to bending stress in the femur may not be fully accounted for with this criterion.

This KTH criterion was developed using human cadavers but could not be directly applied to the Hybrid III dummies due to differences in response between the dummies and cadaveric subjects to axial knee impacts (Rupp et al. 2003a, 2005) and because hip forces cannot be directly measured in the Hybrid III dummy. Therefore, a new KTH injury criterion formulation applicable to the Hybrid III dummies was developed by applying the cadaver KTH criterion to simulations using mathematical models of the cadavers and dummies under similar impact conditions (Rupp et al., 2009). However, this

formulation did not take into consideration differences in kinematics and interaction with the restraint environment between humans and dummies. Use of a dummy with KTH responses and knee restraint interaction similar to the human and with instrumentation to directly measure hip forces would allow direct application of the Rupp et al. (2009) KTH cadaver injury criterion to the dummy. This would eliminate any uncertainties that may arise from the additional step of developing injury risk formulations applicable to the dummy.

CONCLUSIONS

The KTH criterion developed by Rupp et al. (2009) was applied to various frontal crash tests using the HIII-50M and the HIII-5F femur data. Using this criterion, the risk of AIS 2+ KTH injury was underpredicted for belted occupants. However, injury risk predicted for unbelted occupants was reasonably close to the real world risk. Trends by model year (i.e. decreasing overall risk and risk of hip injury for belted occupants) are consistent between real world and crash test data, even though the risk level in belted crash tests is very low. For unbelted occupants, hip injuries are the dominant injury mode for both the real world and the crash tests. However, femur and knee injuries that occur in the real world are underpredicted in frontal crash tests with the HIII dummies.

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