THOR-NT: HIP INJURY POTENTIAL IN NARROW OFFSET AND OBLIQUE FRONTAL CRASHES

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ABSTRACT

Previous studies have shown that hip injuries are prevalent in frontal crashes, particularly those with an oblique, narrow overlap. This paper investigates whether the risk of sustaining such injuries can be evaluated in full-scale vehicle crash tests using the THOR-NT, a dummy that is uniquely equipped for such an evaluation. The THOR-NT is shown to measure acetabular loads that are consistent with pelvic injuries observed in real-world crash victims. Test results reveal that high acetabular loads occur in narrow offset and oblique crashes. Further analysis shows that acetabular loads are dependent upon the position of the thigh, the trajectory of the torso, and intrusion of the instrument panel. Results also show that right-to-left hip loads vary significantly. Abduction of the thigh is also correlated with hip loads. The study provides new insights into how injurious loads are transferred to the pelvis through the thigh via knee bolster contact in frontal offset conditions where oblique loading takes place.

INTRODUCTION

Although seat belt use rates have increased over recent years and vehicle crashworthiness has improved, occupants continue to sustain fatal injuries in frontal crashes. NHTSA sought to understand the crash circumstances leading to fatal injuries to belted occupants in contemporary passenger vehicles. In a detailed review of 122 real-world fatal crashes reported by Rudd et al. (2009), few if any of the 122 fatal crashes were full-frontal or offset-frontal impacts with good structural engagement, unless the crashes were of extreme severity or the occupants exceptionally vulnerable. The other major factors most prevalent in the fatal crashes were:

- Limited vertical structural engagement
- Elevated occupant age
- Semi-trailer underride

NHTSA concluded that corner impacts and oblique frontal crashes should be a priority area for future vehicle crashworthiness research.

Hip Injuries in the Narrow Offset Dataset. Prompted by the study of 122 fatalities, NHTSA began a new analysis of narrow offset and oblique collisions. To study the epidemiology of the problem, a dataset of more than 250 real-world crashes has been extracted from the National Automotive Sampling System-Crashworthiness Data System (NASS-CDS) and the Crash Injury Research and Engineering Network (CIREN). This dataset is referred to herein as the "Narrow Offset Dataset." The inclusion criteria are described in Pintar et al. (2010) and Rudd et al. (2011) provides a full analysis of the dataset.

The dataset reveals that in narrow offset crashes, air bag coverage is not always sufficient to prevent occupant-to-vehicle contacts. In addition, narrow offset crashes are susceptible to intrusion of interior components contributing to lower extremity injuries and pelvic fractures. For reference, the various bone structures of the pelvis are shown in Figure 1. As compared to frontal crashes in general, pelvis injuries have been shown by Pintar et al. (2010) to be more prevalent in narrow offset crashes. Moreover, injuries to the outboard leg are much more frequent. When pelvic injuries in the narrow offset database are broken down further, acetabular injuries predominate as shown in Figure 2.

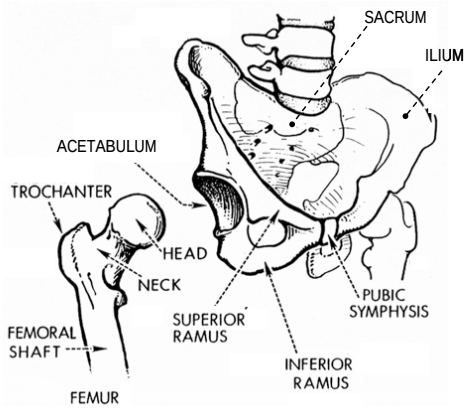


Figure 1. Structure of the Pelvis Bone

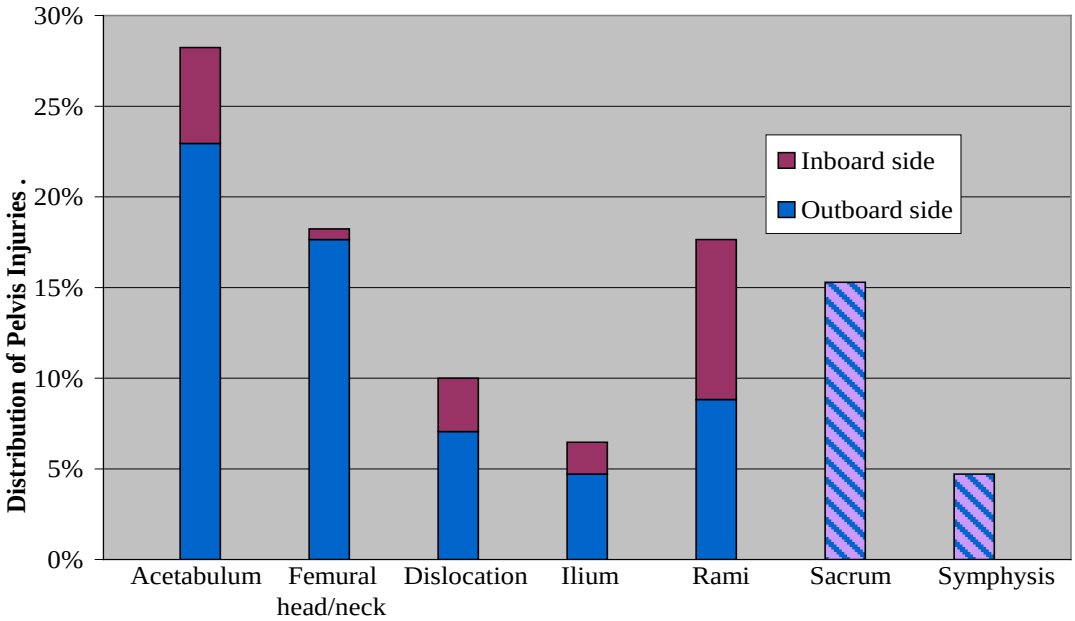


Figure 2. Incidence of AIS 2+ hip and pelvis fractures in the Narrow Offset Dataset. (One injury per pelvic bony structure per occupant. Each occupant sustained at least one AIS3+ pelvic injury).

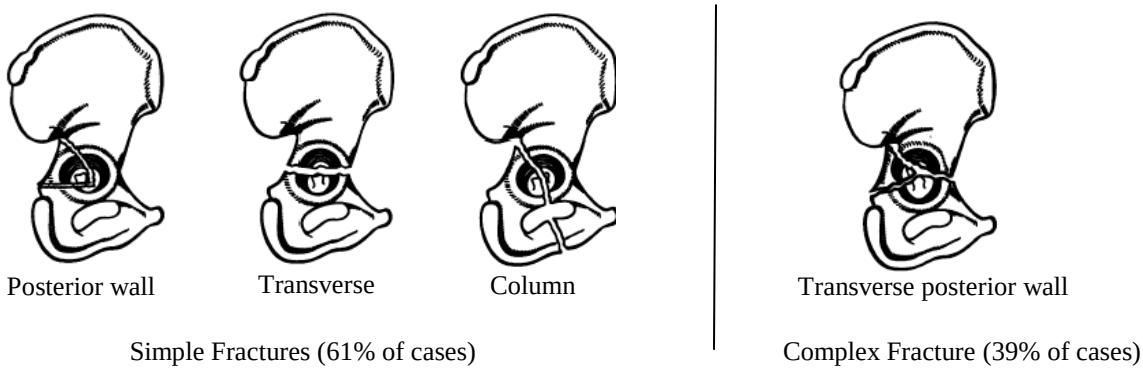


Figure 3. Examples of acetabular fracture patterns in the Narrow Offset Dataset.

The outboard aspect (left hip for drivers) is particularly susceptible to injury, as seen in Figure 2. When the cases within the dataset are examined for specifics on acetabular injuries, they can be grouped into three primary fracture patterns by wall, transverse, and column (Figure 3). These fracture patterns are described more fully by Saterbak et al. (1996). They are primarily used by clinicians to characterize fixation and therapeutic possibilities, and to assess outcome potential. A wall, column, or transverse fracture occurring in isolation is considered to be "simple" acetabular fracture. When simple fractures occur in combination, the resulting fracture pattern is considered to be a "complex" acetabular fracture.

The different fracture patterns highlight another area of concern. Although all acetabular fractures are rated alike on the Abbreviated Injury Scale (i.e., AIS 3 for open fractures and AIS 2 for all others in the 2005 version of AIS[1]), they are very different in terms of post-operative complications.

In a meta-analysis of clinical data, Giannoudis et al. (2005) assessed acetabular fracture patterns using a functionality score (known as the Merle d'Aubigne score) based on mobility, pain, and walking ability. These included acetabular fractures from all sources, not just automotive trauma, and some fracture patterns – such as anterior wall fractures – were not observed in the Narrow Offset Dataset. But for the types of acetabular fractures that *were* observed, complex acetabular fractures were found to have a significantly higher percentage of fair/poor outcome

[1] In the Update 98 version of AIS 1990, comminuted and displaced acetabular fractures are also classified as AIS 3.

scores than simple fractures (about 30% vs. about 17%).

NHTSA's narrow offset/oblique crash test program. In conjunction with the findings of the real-world crash analyses, NHTSA has initiated a narrow offset/oblique crash test program to study the problems more fully. Two basic crash configurations are being evaluated: a small overlap configuration and an oblique impact configuration. These tests include vehicle-to-vehicle crashes, crashes involving a moving deformable barrier, and crashes into a pole with the intent to replicate vehicle crash characteristics, occupant kinematics and injury patterns seen in the real-world. Details of the crash tests are reported by Saunders et al. (2011).

In all, nineteen crash tests have been scheduled, including some with vehicles that are believed to have countermeasures that may be effective in narrow offset and oblique crashes. If tests results show potential for reducing the injury risk, NHTSA will perform a larger fleet study. This fleet study is likely to include vehicle-to-vehicle crashes of two vehicles with different size classifications and with different built-in structural countermeasure designs.

INJURY SOURCES AND THE THOR-NT

The THOR-NT 50th percentile male dummy is being used in NHTSA's oblique and narrow offset crash test program. The program is still underway (Saunders et al., 2011) and much of the data is yet to be reduced and analyzed. This paper focuses on just one of the many objectives of the test program: to provide insights into hip injuries that are prevalent in these types of crashes. The decision to use the THOR-NT was partly based on current knowledge of how hip injuries occur. It was felt that the dummy's enhanced biofidelity and instrumentation package made it the best choice to assess hip injuries. This is discussed in more detail later in this paper.

How hip injuries occur. In the years prior to the study of 122 crashes, NHTSA sought to understand why hip injuries had become more prevalent in all frontal crashes (not limited to oblique or narrow offset crashes). Beginning in 2000, this was the focus of NHTSA-sponsored research at the University of Michigan Transportation Research Center (UMTRI). Several studies focused on the knee-thigh-hip complex (referred to as "KTH") have been produced since then.

The UMTRI body of work on KTH produced an understanding that in a frontal crash, nearly all hip injuries arise from loads transferred axially through the femur to the hip. It was observed that newer cars have softer knee bolsters to reduce axial load thru the femur. The softer knee bolsters protect the knee and distal femur by lessening the contact force, but they increase the loading duration so that a higher percentage of the load is transmitted through the femur to the hip. And since the hip has a lower injury tolerance than the distal femur, pelvis fractures have become more commonplace.

In one of the more notable KTH studies, Rupp et al. (2008) explained how bolster contact produces force at the knee that is transferred all the way back to the hip. The percentage that is transferred depends upon:

• Mass recruitment (timing/impulse) – Hip loads increase with added "reaction mass" behind the hip. The recruitment of the reaction mass is impulse-dependent. Knee impacts having long impulses are needed to recruit a high reaction mass behind the hip.

• Bolster stiffness – This affects mass recruitment depending on ramping and rate.

• Symmetric loading of hip – Asymmetric loading can create a greater reaction mass behind one of the hips.

• Ab/adduction and flexion – If the femur attitude changes, the effective reaction mass behind the hip will change, too. For example, a greater reaction mass is associated with abduction because the femur is driven into the (massive) pelvis.

These findings are supported by cases within the Narrow Offset Dataset where pelvis fractures are present. In many such cases, abduction of the outboard leg of the driver of the vehicle was apparent. These cases are typified by an investigation highlighted in Dakin et al., (1999) where the driver sustained a transverse posterior wall fracture (complex fracture pattern) of the left acetabulum.

As a follow-on to this understanding of KTH injuries, NHTSA developed a hip injury criterion in full-frontal crash tests (Rupp et al., 2009) based on the axial load measured within the femur load cell of a crash test dummy. The criterion and its applicability to the THOR-NT are discussed later in this paper.

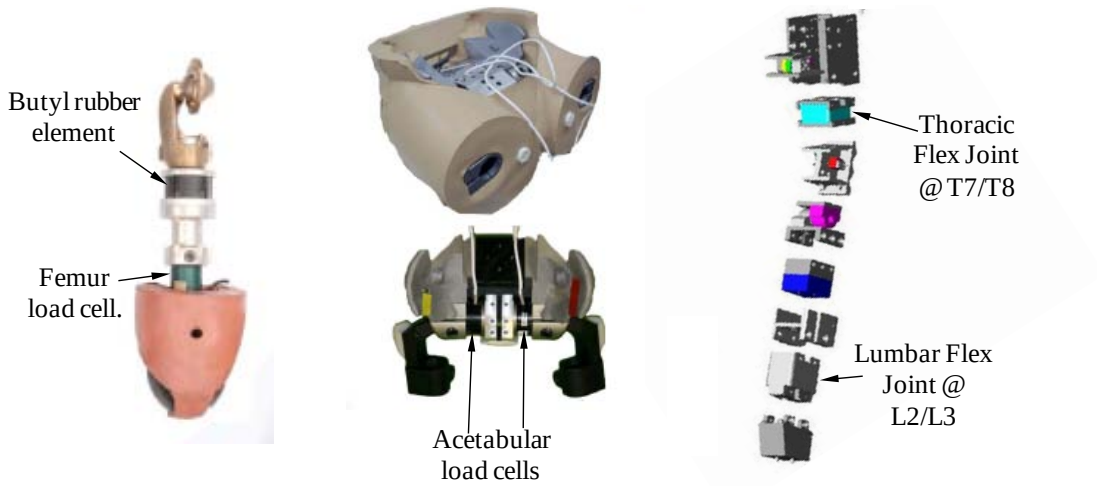


Figure 4. Unique features of the THOR-NT. Left: femur assembly; Center: pelvis within flesh (top) and removed (bottom) showing hip instrumentation; Right: exploded view of spine showing two butyl rubber flex joints in spine.

Use of THOR-NT in Narrow Offset Test Program A unique feature of the THOR-NT is that hip loads are measured directly at the acetabulum, which is where the majority of hip injuries occur in real-world frontal crashes. The THOR-NT pelvis itself provides a range of motion for the femur that is about the same as humans: 45 degrees in abduction, 30 degrees in flexion. Range of motion, as discussed later in this paper, is an important factor in assessing hip injuries under oblique loading.

These unique features are depicted in Figure 4, along with several others. As shown, the THOR-NT spine has two butyl joints for added spine flexibility over other ATDs and thus produces more realistic whole-body movement during a crash. The added flexibility in the torso results in greater right-to-left mass shift in an oblique crash, an important consideration when assessing injury potential in the acetabular region.

Figure 5. Range of motion of the THOR-NT. Maximum abduction is 45° from neutral position.

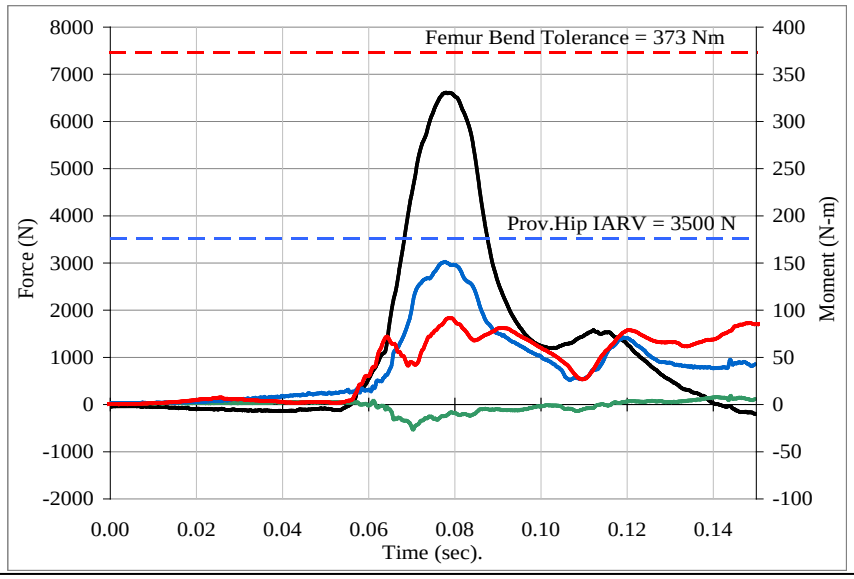
The buttocks of the THOR-NT promotes more human-like interaction with the vehicle seat. While other dummies have a pre-compressed buttocks flesh, the buttocks of the seated THOR-NT compresses under its weight and interacts with the cushion in a more realistic manner.

HIP INJURY REFERENCE VALUE FOR THOR-NT

NHTSA's work sponsored at UMTRI may be used to establish a provisional hip injury reference value applicable to the THOR-NT. The THOR-NT has a rubber element built into the femur as shown in Figure 4. Among other crash test dummies used in NHTSA's regulatory activities, this design feature is unique to the THOR-NT. It is meant to provide a more biofidelic response under knee loading. The femur assemblies of most other dummies do not have a rubber element and have been shown to be very stiff (Rupp et al.. 2003).

Idealized sled tests. A series of THOR-NT tests were carried out to establish the rate of load transfer from the femur to the hip. The effects of pre-test posture on the rate of load transfer were observed by altering the amount of knee flexion and femur abduction. These 46 km/hr tests were conducted using an idealized knee bolster constructed from energy absorbing foam material with constant-stiffness properties.

The dummy was unbelted (a "catch" belt system was configured to catch the dummy late in the event to prevent total ejection) and was seated in a production seat. However, there was no instrument panel, air bag, steering wheel, or windscreen present. In other words, the only interaction between the dummy and the sled was through the knee bolster and the pelvis sliding along the seat. The full test matrix is given in the appendix.



Key:

Femur axial load, N. Fz load as measured by a load cell in the distal portion of the femur (Fx and Fy loads were low in most tests). +Fz indicates femur compression (signal was inverted for display purposes.) A reference value of 10,000 N, represents a 25% probability of a femur fracture (Eppinger et al., 1999).

Acetabulum resultant force, N. Resultant force measured by the load cell in the pelvis. The provisional injury reference value of 3500 N is indicated by a blue dashed line.

Femur bending moment, Nm (use right axis). Resultant of the Mx and My components of moment as measured by the femur load cell. A femur bending tolerance of 373 Nm (reported in Martsen et al.) indicated by a red dashed line.

Acetabulum Fy-force, N. The Fy component of the acetabulum force indicating a medial-lateral force at the acetabular cup (-Fy for right; +Fy for left).

Figure 6. THOR-NT left hip response in an idealized 46 km/hr frontal sled test. Maximum femur compression: 6605 N; maximum acetabular load: 2999N.

A typical result is shown in Figure 6 for the cases where the femur was placed in neutral positions of flexion (30°) and abduction (15°). In this test (test no. b9937) as in the others in the series, the resultant load in the acetabulum rises and falls with the femur axial load. A nominal transfer of force of 50% from the femur to the acetabulum is observed at the point of maximum femur compression. And since the femur remains unabducted throughout the event, it follows that loading of the acetabulum is mainly in the anterior-posterior direction so that lateral forces through the hip are very low and femur bending is modest. (This is seen in Figure 6 where acetabular Fy loads and resultant of the femur Mx and My moments are relatively low).

The result shown in Figure 6 is consistent among all other frontal tests in the test series. During pre-test positioning of the dummy, a modest increase in knee flexion (about 6 degrees) and abduction (apart by about 15 degrees) or adduction (together by about 5 degrees) did not effect the transfer rate appreciably. The effects of the pre-test positioning affected the resultant acetabular loads predictably: more abduction gave greater lateral Fy contribution; more knee flexion resulted in greater Fz.

Oblique Tests. As an aside, two tests in this series were carried out in an asymmetric oblique mode in which the buck was angled 15º. For these tests, the transfer rate through the leading femur (right femur in this case) was elevated by about 3% and that through the left leg diminished by about 1%. This result mimics those observed previously in the human cadaver KTH complex as reported by Rupp et al. (2002): the oblique loading mode creates unequal reaction masses behind the right and left femurs. Since more mass is recruited by the forward-most side of the body, the reaction – or the percent of force transfer from femur to hip – is elevated. Higher moments and higher y-force contributions were also observed in the oblique mode. These observations are very relevant to the narrow offset/oblique test program and are discussed later.

Test reference information for all tests in this test series are provided in the appendix. The test data itself is available through NHTSA's on-line Biomechanics Database.

THOR-NT Hip Fracture Injury Reference Value. As reported in the UMTRI study by Rupp et al. (2009), the transfer of force from the knee to the hip in a human cadaver is about 55% for knee interactions with modern knee bolsters such as those represented by the idealized foam material described above. It was also shown that the force transferred from the knee to the femur load cell in the Hybrid III dummy is about 80% in such interactions. For the THOR-NT, the knee assembly is the same assembly as that of the Hybrid III. Since the femur load cell in both dummies is located just proximal to the knee assembly, we have assumed the knee-to-load cell transfer rate to be the same in the THOR-NT.

For the THOR-NT, the force transfer from the femur load cell to the hip is about 50% as shown in Figure 6. Thus, a scaling ratio of (55%) / (80% * 50%) ≈ 1.3 may be used to relate the human hip injury tolerance to THOR-NT load cell measurements. The 1.3 ratio is primarily an inertial compensation that accounts for the fact that the acetabular load cell is not located at the hip joint center. The 1.3 scaling ratio is used under the assumption that the THOR-NT produces the same force at the knee as a human. The validity of this assumption is discussed later in this paper.

Table 1 summarizes the THOR-NT provisional criteria for hip injuries. The value of 3500 N for hip injuries was derived from previous UMTRI studies and the 1.3 ratio described above. As reported in Rupp et al. (2010), a force at the acetabulum of 4560 N is shown to represent a 25% risk of a hip fracture for a 50th male human in a neutral posture. Using the 1.3 scaling rate, a provisional injury reference value of 3500 N represents the same 25% risk of a hip fracture as measured by the THOR-NT. This value is applied herein to assess injuries in the narrow offset and oblique crash test program.

Table 1. Provisional Hip and Femur Injury Reference Values for THOR-NT

Value	Risk factor	Measurement	CFC	Reference
3500 N	25% risk of hip fracture	Resultant acetabular load, Fx, Fy, Fz	600	Rupp et al (2009) and herein
10,000 N	35% risk of femur fracture	Axial femur load, Fz	600	Eppinger et al. (1999)
373 Nm	Femur bending tolerance	Resultant femur moment, Mx and My	600	Martsen et al. (1986)

The femur bending tolerance was established by Martsen et al. (1986) for proximal femur shaft fractures. The 10 kN limit on axial femur compression is the reference value used in FMVSS No. 208 representing a 35% risk of a distal femur fracture (Eppinger et al., 1999).

CRASH TEST DATA: ACETABULAR LOADS

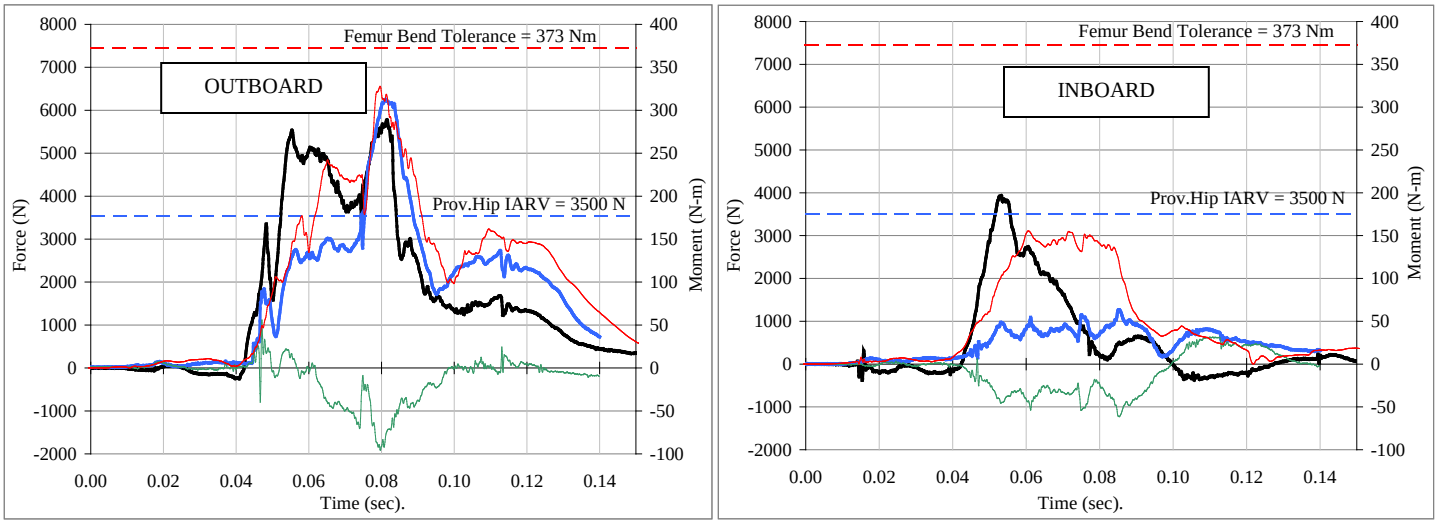
The advantages of using the THOR-NT in the narrow offset and oblique test program may be demonstrated by comparing femur and acetabular signals from three select tests as shown in Table 2. All three tests made use of the THOR-NT placed in the driver's position with the seat in the mid-track setting. Three-point seat belts were used in all three tests.

The oblique Taurus test was selected because it is representative of the oblique crash configuration in which high THOR-NT hip loads were experienced. The Yaris tests are included for comparative purposes. One test was run under the narrow offset crash configuration, and it also had high hip loads. The other was run using the crash configuration used by the Insurance Institute for Highway Safety (IIHS) to rate frontal crashworthiness. It had low hip loads as reported by Yaguchi et al. (2009). Both were run using similar versions of the Toyota Yaris – a 4-door sedan in the narrow offset test, a 5-door hatchback in the IIHS test. The two versions are considered sister vehicles in NHTSA's Five-Star Safety Rating program and received four stars for driver safety in a frontal impact under the pre-2011 rating criteria.

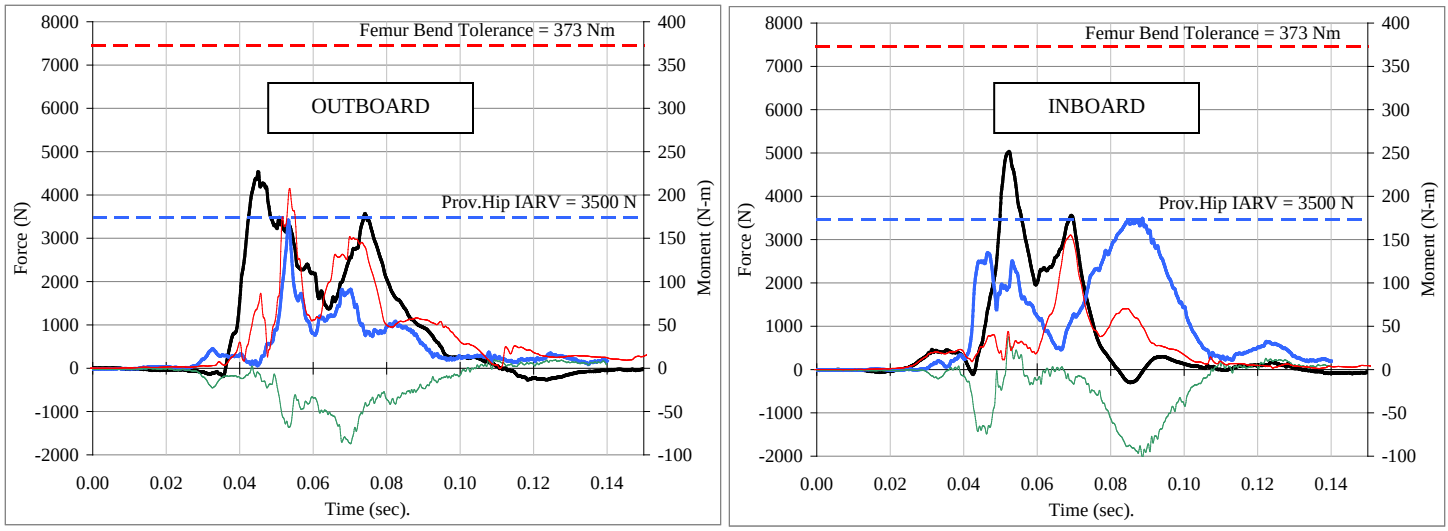
Sensor data related to femur and hip loads are given in Figure 7 and summarized in Table 3 to demonstrate how loading patterns in the hip vary depending upon the test configuration. Reference information for these tests is provided in the appendix. The test data itself is available through NHTSA's on-line Vehicle Crash Test Database.

Table 2. Select crash tests for study of THOR-NT hip response.

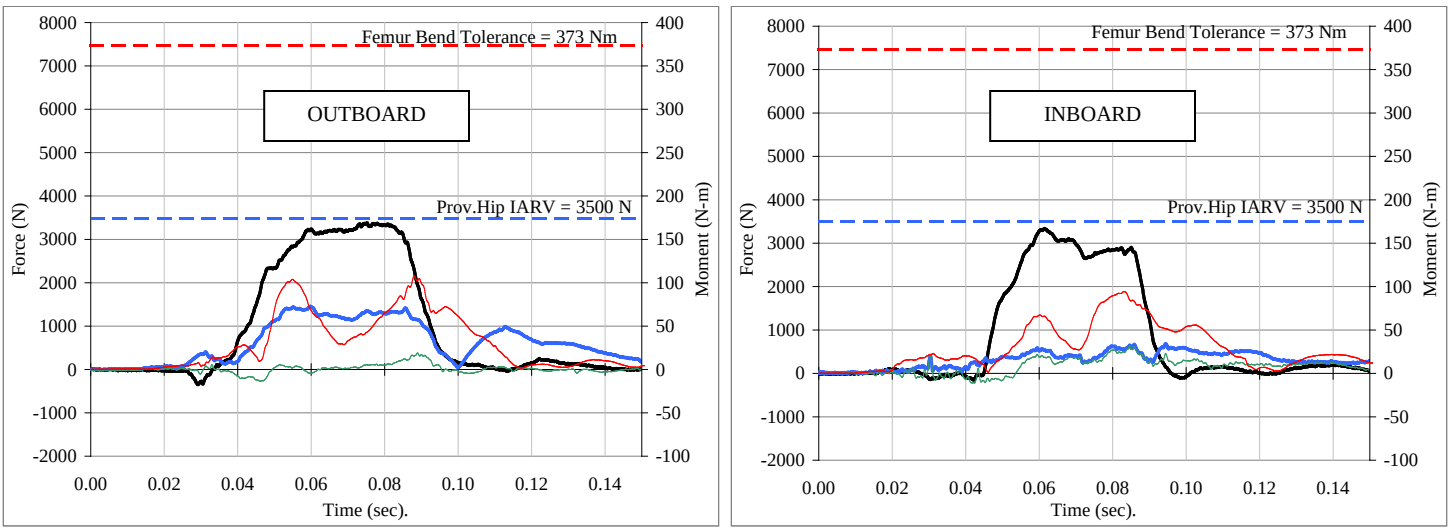
Vehicle	Crash configuration	Delta-V (km/hr)	Angle	Overlap
'07 Ford Taurus	Oblique Vehicle to vehicle	56	15º	50%
'10 Toyota Yaris	Narrow offset Vehicle to vehicle	56	7º	Align frame rails
'08 Toyota Yaris	IIHS Deformable barrier	64	0º	40%



7a. Oblique Taurus test, v6830



7b. Narrow offset Yaris test, v7293



7c. IIHS Yaris test, b9894

Key (same definitions as previous key):

- Femur axial load, N.
- Acetabulum resultant force, N.
- Femur bending moment, Nm (RH axis).
- Acetabulum Fy-force, N.

Figure 7. THOR-NT femur and hip response in three crash tests.

Table 3. Peak measurements in test data. For medial-lateral loads, "out" equates to femur head pulled out of socket.

Test	Aspect	Femur Compression Fz (N)	Femur Bending R(Mx,My) (Nm)	Acetabular Resultant R(Fx,Fy,Fz) (N)	Acetabular medial-lateral Fy (N)	Knee Bolster Intrusion (mm)	Lap Belt Load (N)
Idealized sled b9937	Left	6605	217	2999	543 (in)	---	---
	Right	6236	149	3523	324 (in)	---	
Oblique Taurus v6830	Outboard (L)	5773	327	6235	1939 (out)	238	1651
	Inboard (R)	3993	155	1267	1226 (in)	172	
Narrow offset Yaris v7293	Outboard (L)	4537	207	3436	1719 (out)	77	2044
	Inboard (R)	5031	155	3503	2015 (in)	1	
IIHS Yaris b9894	Outboard (R)	3378	108	1458	390 (out)	24*	3137
	Inboard (L)	3331	94	677	627 (in)	16*	
Injury Ref. Values		***10,000***	***373***	***3500***	---	---	---

* Instrument panel intrusion. Knee bolster intrusion unavailable.

THOR-NT INSIGHTS ON HIP INJURIES

Loading Impulse. One of the more noteworthy trends seen in the data signals of Figure 7 is the differences in the load impulses to the outboard (left) leg in the oblique and narrow offset tests vs. the IIHS test.

In the IIHS Yaris test, femur and hip loading appear very controlled, indicative of an optimized, well-performing system. Right vs. left femur loads are about the same, and both reach a plateau that is safely below the injury reference value of 10kN. Femur bending and acetabular Fy-loads are also low, indicating minimal knee ab/adduction. As a result, outboard hip loads are also fairly low with a loading pattern very similar to that seen in the idealized sled test: the outboard hip load is essentially the same as the femur load scaled by 40%.

The hip loading patterns in the IIHS test are consistent with simple acetabular fractures seen in real-world crashes. Lacking the abduction, the femur head typically loads the isolated posterior wall of the acetabulum resulting in a simple fracture or dislocation. In other words, if a human (instead of the THOR-NT) was used in this test and suffered a hip injury, it most likely would have been a simple acetabular fracture rather than a complex fracture.

In contrast to the IIHS-Yaris test, the narrow offset/oblique impulses exhibit much more unevenness. A double peak appears in the outboard acetabular loads. This loading pattern is repeated in several other tests in the series. Moreover, femur and acetatular loads are much higher in the narrow offset/oblique tests despite a lower crash Delta-V (56 km/hr vs. 64 km/hr in the IIHS test). The rate of the initial femur loading is also much higher in the narrow offset/oblique tests.

In all three tests, the risk of hip injury is directly related to the force impulses through the femur. Table 4 shows five critical factors which influence hip injuries that may be observed in the three crashes. These factors highlight the differences between narrow offset and oblique crashes versus collinear, 0º frontal crashes such as those represented by the IIHS barrier test and the idealized sled tests described earlier. The factors are discussed below in context with the biofidelity of THOR-NT and its ability to assess hip injuries.

Table 4. Factors influencing hip injuries in frontal crashes.

FACTOR	HUMAN INJURIES	THOR-NT OBSERVATIONS			
	Indicative human injuries in Narrow Offset Dataset	***Idealized sled tests***	***IIHS-type test***	***Narrow offset and oblique tests***	***Indicative THOR-NT dummy measurement***
Asymmetric hip loads	High incidence of outboard leg injuries vs. inboard leg.	Fully symmetric	Symmetry in distal femur load only.	Pronounced asymmetry.	High loads in outboard femur and hip; significant left-ward body trajectory seen in videos.
Femur ab/adduction	Abduction → complex hip fx. Adduction → simple hip fx. (Wide area of knee bolster contact seen in vehicle inspection report.)	None	None	Both ab- and adduction in many cases.	Significant acetabular Fy-loads; knee bolster paint transfer shows knee movement.
Femur bending loads	Femur shaft fracture.	Very low	Low	High in some cases.	High femur Mx and My loads usually accompanied by high lateral loads in acetabulum.
Medial-lateral hip loads	Medial: Complex acetabular fracture; Lateral: Hip dislocation.	Very low	Low	High in some cases.	High acetabular lateral (Fy) loads.
Belt-to-trochanter loads	Hip injury in absence of knee injury.	None (no belt)	Low	High in some cases.	High lap belt loads; high lateral acetabular loads in the absence of significant femur loads.

Asymmetric loading. Force transferred to the hip from the knee is highly dependent upon the loading symmetry. In full-frontal crashes such as those represented by the idealized sled tests, knee loading is symmetric and both right and left hips experience about the same loads. Under such a condition, one may assume that the percentage of force applied to the knee that is transmitted to the hip is fixed. However, the farther a knee-loading condition deviates from applying similar forces to both knees, the less applicable the fixed assumption becomes. When knee loading is asymmetric, the amount of mass behind one of the hips is greater (usually the hip on the side in where knee force is higher). This will increase the percentage of force that is transmitted to the hip from the knee, which thereby increases the risk of hip injury.

As seen in the IIHS Yaris test, right and left femur loads are fairly alike, but the symmetry dissipates as loads are transferred to the hips. In the narrow offset/oblique tests neither the hip loads nor the femur loads show much symmetry. In particular, for the oblique Taurus test the outboard hip experiences a load that exceeds that of the femur. It also exceeds the provisional hip injury criteria of 3500 N. Asymmetric loading is also evident in the narrow offset Yaris test.

In narrow offset/oblique crashes, significant outward body trajectory contributes to asymmetric loading. Even in the IIHS tests, a small left-to-right asymmetry appears to have affected mass coupling on different sides of the dummy. Shifting of mass also arises from the rotation of the pelvis induced by the crash configuration. The rotational inertia of the pelvis contributes to the mass imbalance, which increases the percentage of force applied to the knee that is transferred to the hip.

Femur abduction and adduction. Abduction is seen in many of the real-world cases of the Narrow Offset Dataset in which pelvis injuries occur. It is inferred by evidence of contact to the left portion of the driver's side lower instrument panel and knee bolster. Abduction is as evidenced by knee bolster damage seen in post test inspections. Fracture patterns of the hip are dependent on ab/adduction. Though the

dependence is not absolute, fractures generally occur as follows:

Abduction (knees apart) → complex hip fracture
(e.g., transverse-posterior wall fx)

Adduction (knees together) → simple hip fracture
(e.g., posterior wall fx)

Abduction raises the threshold for an acetabular injury because it forces the femur head into the socket, whereas adduction forces it out. In other words, wall fractures and dislocations have relatively low thresholds for injury because there is physically less bone to oppose the forces that cause them. Since abduction redirects these forces into the pelvis, overall hip injury risk is reduced. On the other hand, abduction increases the likelihood of a transverse-posterior wall (complex) hip fracture. And although a transverse-posterior wall fracture may have a higher force tolerance, the outcome for victims who sustain such an injury is much worse.

Real world data reveals that both types of fractures are occurring in narrow offset and oblique crashes. Thus, it is important that the knees of the dummy interact with the knee bolster in a human-like manner and it appears that the THOR-NT does so. In several of the narrow offset/oblique crash tests, the THOR-NT femurs were observed to undergo adduction (left leg) and abduction (right leg) as the pelvis moved leftward and the knees wedged against the bolster. Evidence of knee movement appears in test signals shown in Figure 7, where load signals are seen to rise initially, diminish, and then rise again. Evidence of abduction is also seen in post-test inspection of the knee bolster in the form of paint transfer.

The oblique Taurus and narrow offset Yaris data show hip loads that are consistent with both simple and complex fracture patterns. For the case of simple fractures, correspondingly high Fy acetabular loads appear in the inboard (adducted) hips. For the case of complex fractures, high Fy loads appear in the inboard (abducted) hip. All this is consistent with the injuries observed in the Narrow Offset Dataset.

Moreover, ab/adduction is usually associated with asymmetric loading. And if the adducted knee bears most of the load, then a higher knee-to-hip transfer of force will usually be experienced because a greater reaction mass opposing the axial femur load sits behind the hip. This will work to lower injury tolerance and further increase the probability of sustaining a hip injury in this loading condition.

Femur bending. Elevated acetabular forces are partly due to the fairly long impulse running axially thru the femur and partly due to a shift in mass to the left side of the body during the crash event. Moreover, femur bending is also elevated in the oblique Taurus and narrow offset Yaris tests. There appear to be multiple bending sources, not all of which stem from axial compression. Pocketing or entrapment of the knee in the presence of bolster intrusion and lateral pelvis excursion may contribute to pure bending of the femur in narrow offset and oblique crash modes.

In any event, the reaction to the bending moment at the hip probably contributes to the high acetabular load. This reaction gives rise to a significant acetabular Fy component acting to either pull the femur head out of the socket (dislocation: simple fracture) rather or drive it through the pelvis (complex fracture).

This observation is consistent with many injuries seen in the Narrow Offset Database. A high incidence of femur shaft fractures indicates significant femur bending. Moreover, the reaction at the hip associated with femur bending may have contributed to a high incidence of acetabular injuries.

Loading of trochanter by lap belt. In a typical 0° collinear crash test such as the IIHS test, lap belt loading is fairly low and the trochanter is essentially under no load. But in the narrow offset Yaris test and in other tests in the series, THOR-NT lateral hip loads are observed to be high even though femur loads are low both axially and in bending. This may be the result of other loading sources, such as lap belt loading of the trochanter. Crash test videos revealed a large inboard-to-outboard pelvis excursion which may have contributed to loading of the trochanter through the lap belt. On the other hand, hip loading via door intrusion does not appear to be a loading source in either the crash tests or real-world cases since the door panel buckles outward. These observations may help explain how some occupants in the Narrow Offset Dataset sustained a hip injury.

Hip flexion. Hip flexion occurs two ways: when the torso rotates forward and when the knee itself moves upward. Both of these instances are observed in videos of narrow offset and oblique tests. In other narrow offset crash tests, videos show that the left femur goes into flexion, sliding up so that the Fx and Fz loads in the acetabulum are diminished. Also, the Fx and Fz components of acetabular force are observed to swap as the femur goes into flexion. Flexion becomes most pronounced as the occupant space becomes compromised by intrusion. It occurs

during pelvis rotation as the torso of the dummy lurches to the outboard side of the air bag.

Hip flexion lowers the force threshold for an acetabular wall fracture or dislocation, and thus increases the risk of such an injury. Flexion acts to drive the femur in a direction inferior to the pelvis (+z direction) where there is physically less bone to oppose the forces. This is also consistent with the high incidence of hip dislocations seen in the Narrow Offset Dataset.

Utility of the THOR-NT. In the real-world Narrow Offset Dataset, left hip injuries outnumber right hip injuries by a margin of five to one. Thus, in order to accurately assess hip injury potential in narrow offset and oblique crash tests, it is important to use a dummy that is sensitive to asymmetric loading. The THOR-NT is well suited for this task. With its flexible spine, compliant femur, and soft buttocks flesh, it is able to move within the occupant compartment and interact with the seat and knee bolster in a life-like manner.

Furthermore, the THOR-NT's increased range of motion lessens the likelihood of binding of the hip joint which would result in unrealistic body kinematics and hip loading. (In comparison, the Hybrid III femur range of motion in abduction is only about +20°/-10° from the neutral position.)

INJURY ASSESSMENT: Narrow Offset/ Oblique vs. Frontal, 0º Colinear

KTH criteria background. In past work at UMTRI, the focus was placed on femur and hip loading in colinear (0º) frontal crashes. The KTH criterion developed by Rupp et al. (2009) is based on cadaver tests with femur loads that were primarily axial (Fz) with very little bending. Thus, it is only valid for loads borne by the hip axially thru the femur and is most suitable for use in 0º frontal crashes.

The KTH criterion was developed for use with the Hybrid III 50th male and 5th female dummies as demonstrated by Kirk and Kuppa (2009). As such, it predicts hip injuries without actually measuring force at the hip. Instead, the criterion is based on the axial force through the femur load cell in which the force impulse is used to indicate whether or not a sufficient amount of femur force is transferred to the hip. The criterion was developed for an ideal case of a force-limited knee bolster and symmetric knee loading with the femurs positioned in a neutral position (30° flexion, 15° abduction) similar to the position specified in a typical standardized frontal test.

The KTH injury criterion assumes that the percentage of force applied to the knee that is transmitted to the hip is fixed. But if the surface impacting the knee is rigid and loading durations are short, then the percentage of force transmitted from the knee to the hip is much smaller. Because the duration is short, there isn't enough relative motion of the femur to recruit the amount of mass behind the hip that is necessary to generate the reaction force at the hip. Thus, the actual force transfer is lower than the assumed (fixed percentage) force transfer. The KTH criterion tries to account for hard vs. soft knee impacts by adjusting the hip injury reference value downward as the length of the impulse at the femur load cell increases.

THOR-NT acetabular force criteria. Narrow offset and oblique crashes violate many of the assumptions under which Rupp et al.'s femur-based KTH criteria is applied. Femur loads alone do not account for important variables that influence hip injury potential, such as mass transfer, flexion, abduction, or other load sources (such as lap belts and door interaction). Furthermore, other established femur reference values (373 Nm for femur shaft fracture, and 10,000 N distal femur fracture) are not particularly useful in assessing hip injury potential.

In collinear, 0º frontal crashes like the IIHS Yaris test, femur moments have not generally been considered to be primary measurements for injury assessment because femur bending is caused by axial compression. Thus, femur fracture from bending is thought to be limited by injury criteria based on peak femur loads. This is not always observed to be the case in narrow offset tests, such as the narrow offset Yaris test (left leg). For this case, femur bending correlates to the acetabular load much more closely than to axial femur compression. Thus, an acetabular load-based criterion offers a measure of safeguarding against femur shaft fractures, which are also shown to be more abundant in real-world narrow offset and oblique impacts (Rudd et al, 2011).

Furthermore, lateral hip loads such as those associated with the reaction forces at the hip due to femur bending were not addressed in previous work at UMTRI. These loads were negligible in the UMTRI testing and modeling and they are shown to be negligible in the IIHS Yaris test. For the narrow offset and oblique tests, however, they are shown to be quite significant.

Thus, a provisional hip injury criterion for THOR-NT is necessary to assess hip injury potential in narrow

offset/oblique tests. Its basis is measurements from the three-axis load cell at the acetabulum which provides a direct measurement of the force at the hip. The acetabular load cells measure directly any non-symmetric loading, which has been observed to result in more force being transferred to the hip in oblique tests.

Applicability of criteria. We note that the criterion developed by Rupp et al. (2009) is very suitable to the hip loading seen in the idealized sled tests and the IIHS Yaris test. In these tests, the overall response of the knee, femur, and acetabular loading was very much like the loading patterns studied in the UMTRI cadaver tests from which the criterion itself is based. These tests indicate general adherence to the KTH criteria assumptions:

- Symmetry – equal femur loading right vs. left.
- Controlled knee bolster interaction.
- Acetabular force - 50% of axial femur load (outboard side).
- Very low lateral (Fy) force component into the acetabulum.
- No observable abduction or adduction.

As noted earlier, the Yaris performed well in the IIHS test under any injury measure, including the femur-based KTH impulse criterion. It is likely that the bolster design of the Yaris was optimized for the IIHS test using a Hybrid III dummy. The good performance using the THOR-NT provides added support that it would carry over to humans. Furthermore, a matching IIHS Yaris test run with a Hybrid III 50th male (reported by Yaguchi et al., 2007) reveals the THOR-NT and the Hybrid III to be essentially equivalent based on FMVSS No. 208 metrics (Femur Fz) and the Rupp et al. femur-based KTH criterion.

Thus, the well-performing Yaris knee bolster is reflected by low injury metrics as measured by either the THOR-NT or Hybrid III in an IIHS test. This applies to all relevant criteria, including Rupp et al.'s femur-based KTH impulse criterion and THOR-NT acetabular loads. We also observe that many of the unique features of the THOR-NT are not exercised to their full extent in the IIHS test configuration:

- Flex spine – not needed because all body movement is in the anterior-posterior direction.
- Femur range of motion – no abduction is observed, and little knee flexion.
- Compressive femur element – not as critical if injury criterion is based on femur load cell, which is located at proximal end of femur.
- General knee biofidelity – controlled interaction with knee bolster.

Most of the assumptions under which the Rupp et al. femur-based KTH impulse criterion applies held true in the IIHS Yaris test. However, nonconformities to the assumptions did exist to a limited extent. For example, acetabular loads were unequal despite near identical axial femur loads. And even in full frontal crashes with the THOR-NT, perfectly symmetric loading of the knees is rarely observed. Thus, when the THOR-NT is used in any frontal test, the use of an acetabular load criterion to assess hip injuries is advised.

CAVEATS

There are two caveats with applying the provisional hip criteria developed for the THOR-NT. We note that these caveats also apply to the femur-based KTH criterion developed by Rupp et al.:

Caveat 1, THOR-NT-to-human scaling ratio. As mentioned earlier, the 1.3 ratio compensates for the acetabular load cell not being located at the hip joint center. Moreover, the ratio is based on sled tests with symmetric loading and a neutral posture. We have assumed that it also applies to situations where there is hip flexion and femur ab/adduction. This assumption is buttressed by observations from the idealized sled tests where abduction and flexion do not influence the transfer rate appreciably. We have also assumed that the ratio applies to all forces, including lateral loads induced primarily by femur bending and trochanter loading.

For asymmetric loading, the ratio of knee-to-hip forces in the THOR-NT will vary due to mass effects. A reasonable assumption is that the ratio of forces in a human would vary similarly. Under this assumption, the scaling ratio of 1.3 applied herein would still be valid under asymmetric loading.

Caveat 2, knee-to-hip singular relationship. As discussed earlier, the knee-to-hip ratio of force is:

THOR-NT = (0.80 * 0.50) = 40%
Human (cadaver) = 55%

As shown in Figure 8, the injury tolerance scale of 55/40 $\approx$ 1.3 applied herein is based on knee interaction with a force-limiting knee bolster.

For knee bolsters constructed with non-force limiting padding (or loading less than the limit), the peak force applied to the THOR-NT knee – and hence, the

force measured by the femur load cell – will always be greater than the peak force applied to the human knee. This is because the THOR-NT KTH complex has greater effective mass and stiffness than that of a human, and will therefore penetrate further into the knee bolster. In other words, there is no singular relationship between peak force at the THOR-NT femur load cell and peak human hip force that is valid over the full range of knee bolster force vs. deflection characteristics. So for many bolster loading cases, the criteria will over-predict injury.

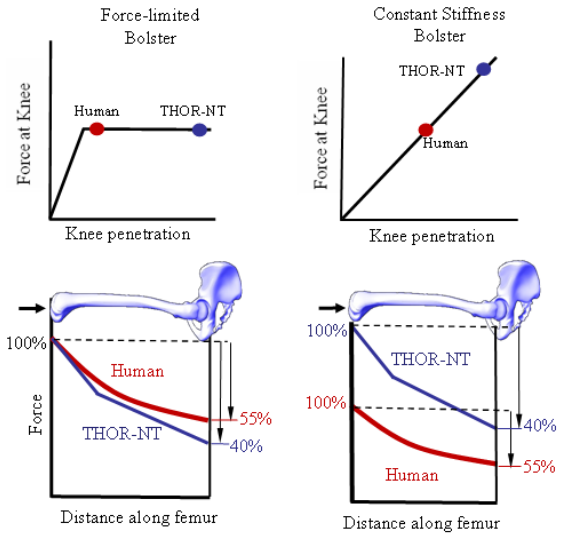


Figure 8. Effects of knee bolster characteristics on human vs. THOR-NT knee forces. Left: Force-limiting bolster: equivalent knee loads; Right: constant-stiffness bolster: higher knee loads in THOR-NT.

THOR-NT MOD KIT

The knee bolster limitation described in Caveat 2 has been relieved greatly by recent updates to the THOR-NT. Parent at al (2011) describes the latest hardware and instrumentation package to be installed in the dummy. These modification kits provide improved biofidelity in the knee-thigh-hip complex as well as other body regions. The modification kit provides additional femur compressive properties that results in knee loading equal to that of the cadaver for all types of bolsters, not just an ideal force-limiting bolster. Therefore, this modification overcomes the problem discussed earlier in Caveat 2. In other words, there <u>does</u> exist a singular relationship between the peak forces at the modified THOR-NT and cadaver hips that is valid over a wider range of knee bolster force vs. deflection characteristics.

In another feature of the modification kit, the pelvis flesh has been made so that it is less tightly coupled to the femur bone. This makes it more like humans. It is important because the tight grip of the flesh to the femur in the current THOR-NT can influence the effective reaction mass behind the hip, and hence, the load to the hip – particularly when the dummy has rotational inertia as seen in the narrow offset and oblique tests.

OPPORTUNITIES FOR FINE TUNING INJURY CRITERION

The THOR-NT offers additional opportunities for an enhanced hip injury criterion. In a human, the area of the acetabular surface able to resist force applied through the femur and the volume of bone behind depends on hip posture. The observations from the Narrow Offset Dataset and from experimentation at UMTRI show that hip injury tolerance is dependent upon abduction. Hip injury tolerance is completely due to the manner in which posture changes how load is borne by the pelvic bone: knees together – hip more easily dislocated by an axial femur load (low tolerance); knees apart – femur vector is aimed more towards center of pelvis (higher tolerance).

A provisional THOR-NT hip injury criteria has been applied herein based on the resultant acetabular load (Fx, Fy, Fz). If there were a way to measure hip flexion/extension or ab/adduction in the THOR-NT it may be possible to come up with a hip injury criterion that was posture dependent rather than one that just uses a typical hip posture. One possibility would be to parse out the contributions of Fx, Fy, and Fz loads in the acetabular load cell. But using the relative Fx, Fy, Fz contributions of acetabular force to determine hip posture could be highly problematic given the likelihood of trochanter loading (either from the seatpan, the lap belt, or the door) and femur bending reactions which could induce considerable error into the calculated posture. Other instrumentation may be required.

Furthermore, our understanding of hip injury tolerances is based mostly on laboratory tests at UMTRI with very little lateral Fy loading into the acetabulum. We did not consider hip reaction to femur bending moments or trochanter belt loading as primary sources of hip loading. But high levels of lateral loads into the acetabulum were observed in the narrow offset/oblique tests. This is consistent with complex acetabular fractures observed in the Narrow Offset Dataset. Thus, further analysis of injury tolerances associated with complex acetabular fractures are needed in order to develop a criterion in which lateral loading is treated separately.

As for the THOR-NT dummy itself, there is currently no specification for the range of motion or joint torque requirements in ab/adduction, and it is unknown whether THOR-NT dummies are consistent from one to another in this regard. Given the importance of ab/adduction in determining hip injury potential, it may be important to specify joint torque requirements.

Also, there are no biofidelity specifications for the flesh that covers the trochanter. If belt loading is found to be a significant contributor to hip injuries, human flesh specifications would be needed so that the THOR-NT flesh properties could be adjusted as needed.

LIMITATIONS

• The study is limited to a sample of crash tests, each with unique features. There were no repeat tests. In addition, only the driver seating position was evaluated.

• We were not able to clearly observe or readily measure the amount of hip flexion and ab/adduction experienced by the THOR-NT during the crash events. Flexion and ab/adduction could only be approximated by observing video and post-test knee-to-bolster paint transfer.

• No attempt was made to determine the left to right variations in the reaction mass behind the hip with any precision. General inferences on mass recruitment were made based on the transfer of force from the femur to the hip and from dummy kinematics observed in crash videos.

• The THOR-NT modification kit has not been evaluated for its knee-to-hip transfer of force. In all likelihood, the kit will change the ratio of force transfer between the knee and the hip. Also, it has not been verified whether the THOR-NT modification kit produces the same knee force as humans for all bolster designs.

• The difference in knee-to-hip transfer rates between the THOR-NT and humans is partly due to the location of the acetabular load cell, which is not located precisely at the acetabulum. As shown in Figure 4, an aluminum socket adapter (0.3 kg) sits between the load cell and the femur head. As the pelvis (total mass: 11.7 kg) opposes femur loads during a dynamic event, the inertia of the socket opposes the inertia of the pelvis rather than adding to it. So, the force at the load cell will always be diminished by the mass of the socket. The pelvis modification kit does not change this configuration. Thus, even after the modification kit is in place, the force recorded by the acetabular load cell will probably still need to be scaled up.

• In the IIHS Yaris test, the left acetabular Fx and Fz forces (those forces resisting the rearward, longitudinal movement of the femur) apprear to be unreasonably low and may be the result of an error in the sensitivity factor or an instrumentation malfunction. The low forces are not consistent with other THOR-NT tests.

• In the idealized sled tests, the test conditions and dummy kinematics were highly symmetric, yet the left femur loads were about 5% greater than the right, and the right acetabular loads where about 15% greater than the left. This trend was consistent for all tests in the series. This result may indicate errors in the application of load cell sensitivity factors. Hence, the nominal force transfer factor of 50% used to establish the provisional injury criterion was based on an average of the left and right hip forces.

AVAILABILITY OF DATA

All reports and data, including time-history traces, videos, and still photos from the tests described herein may be downloaded by accessing NHTSA's online Biomechanics and Vehicle Crash Test Biomechanics Database at: http://www.nhtsa.gov/ Research/Databases+and+Software. Reports include descriptions of the test set-ups and instrumentation. Data channels collected, but not reported herein, include over 100 signals per test.

SUMMARY

Full-scale vehicle tests were performed with the THOR-NT crash test dummy to gain insight into the root causes of injuries sustained by occupants involved in narrow offset and oblique crashes. The dummy was shown to measure hip loads that are consistent with pelvic injuries observed in real-world crash victims. Hip loads exceeded the expected injury threshold (3500 N) for an acetabular fracture. Moreover, hip loading patterns were shown to be very different in narrow offset and oblique crashes from those seen in co-linear 0º crashes such as an IIHS 40% offset crash test. Some of the key observations are listed below.

1. Hip loads are dependent upon the position of the thigh, the trajectory of the torso, and intrusion of the knee bolster.

2. As opposed to co-linear 0º tests, right-to-left femur and hip loads vary significantly in narrow offset and oblique tests.

3. In co-linear 0º crashes, hip loading extends from axial femur compression, whereas hip loading in narrow offset and oblique tests may emanate from other sources such as femur bending and trochanter loading.

4. Lateral hip loading – which is not seen in co-linear 0º tests – is manifested by the asymmetry and ab/adduction occurring in narrow offset and oblique tests. These loads are consistent with acetabular fractures observed in the real world.

5. Knee bolster interaction is much less controlled in narrow offset and oblique tests, and vehicle intrusion contributes to knee movement and high hip loads.

6. The THOR-NT – with its unique biofidelic features and instrumentation package – provides significant insight into hip injury causation. Such insights cannot be discerned from the signals of the femur load cell alone. An injury criterion based on THOR-NT's acetabular load cell measurements shows promise for assessing hip injuries in narrow offset and oblique crashes.

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APPENDIX

Idealized sled tests

Test No.	Knee position (ab/adduction)	Knee position (hip flexion)	Nominal Delta-V (km/hr)	Angle
b9937	Neutral	Neutral	46	0º
b9938	Neutral	Knees raised	46	0º
b9939	Wide Apart	Neutral	46	0º
b9940	Together	Knees raised	46	0º
b9941	Neutral	Neutral	46	0º
b9942	Wide Apart	Knees raised	46	0º
b9943	Neutral	Knees raised	46	0º
b9944	Wide Apart	Neutral	46	0º
b9945	Together	Knees raised	46	0º
b9946	Wide Apart	Knees raised	46	0º
b9947	Neutral	Neutral	46	0º
b9948	Neutral	Neutral	46	15º
b9949	Neutral	Neutral	46	15º

Full-scale vehicle crash tests

Test No.	Vehicle	Test Type	Crash Configuration	Nominal Delta-V	Angle	Overlap
b9894	2008 Toyota Yaris	IIHS - THOR-NT	DB	64 km/hr	0º	40%
b9893	2008 Toyota Yaris	IIHS - Hybrid III	DB	64 km/hr	0º	40%
v7293	2010 Toyota Yaris	Narrow offset	VTV	56 km/hr	7º	Coincident frame rails
v7292	2007 Ford Taurus	Narrow offset	VTV	56 km/hr	7º	Coincident frame rails
v7145	2010 Toyota Yaris	Narrow offset	Pole	56 km/hr	7º	---
v7144	2007 Ford Taurus	Narrow offset	Pole	56 km/hr	<7º	---
v6873	2009 Honda Civic	Narrow offset	Pole	56 km/hr	7º	---
v6872	2005 Honda Civic	Narrow offset	Pole	56 km/hr	<7º	---
v6855	2007 Ford Taurus	Narrow offset	MDB	48 km/hr	15º	18%
tbd	2007 Ford Taurus	Narrow offset	MDB	56 km/hr	7º	Align outer edge of frame rail
tbd	2010 Toyota Yaris	Narrow offset	MDB	56 km/hr	7º	Align outer edge of frame rail
v6865	2007 Ford 500	Oblique (HIII)	VTV	56 km/hr	15º	50%
v6831	2007 Ford 500	Oblique	VTV	56 km/hr	15º	50%
v6830	2007 Ford Taurus	Oblique	VTV	56 km/hr	15º	50%
tbd	2010 Toyota Yaris	Oblique	VTV	56 km/hr	15º	50%
v6937	2007 Ford 500	Oblique	MDB	56 km/hr	15º	50%
v6852	2007 Ford Taurus	Oblique	MDB	56 km/hr	15º	50%
tbd	2007 Ford Taurus	Oblique	MDB	56 km/hr	15º	35%
tbd	2007 Ford 500	Oblique	MDB	56 km/hr	15º	35%
tbd	2010 Toyota Yaris	Oblique	MDB	56 km/hr	15º	35%
tbd	2010 Ford Fusion	Oblique	MDB	56 km/hr	15º	35%