A SIMULATION STUDY ON THE KNEE-THIGH-HIP LOADING OF THE THOR COMPARED TO HUMAN BODY MODELS

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ABSTRACT

The THOR-50M dummy is instrumented with acetabulum force sensors which is a novelty when compared to previous dummies like the Hybrid III. It has been proposed to use the acetabulum resultant force to predict hip injuries. Injury Risk Curves (IRCs) for cadavers have previously been developed, however it is not clearly established if the cadaver IRCs can directly be applied to the THOR measurements or if a transfer function is needed. As femur and acetabulum forces are located on the same load path, it is also questionable if it is necessary to use two different injury criteria to predict knee-thigh-hip injuries.

To investigate these questions, a simulation study was performed using a THOR model and two human body models (HBMs). Load cases included impactor tests derived from published cadaver testing as well as sled simulations in belted and unbelted configurations with a validated environment. The knee, femur and acetabulum forces measured in the different models were compared and the ratios between these forces were also analyzed. Additionally, based on the measurements from the THOR and HBMs simulations and published Injury Risk Curves for cadavers and the THOR, the risks of hip and knee/femur injuries were calculated for each load case.

Results show that the relationship between the forces measured in the THOR model and in the HBMs could depend on the loading conditions. The forces measured in the unbelted sled simulations are similar between the three models, however the acetabulum forces measured for the HBMs in the belted sled configuration are significantly lower than that of the THOR. For impactor configurations, the risk calculated at the hip for the THOR overestimates the likelihood of cadaveric injuries. For sled configurations, no cadaver test result was available, findings are based on simulations only and comparison with field data. For all simulations, the risk of hip injury predicted for the THOR was significantly higher than the risk predicted for both HBMs. The risk of hip injuries for the THOR was also, for all simulated load cases, higher than the risk of knee/femur injuries which is contrary to the injury frequencies observed in the field for belted occupants.

Overall, the risks calculated for the THOR from the acetabulum forces seem overestimated which is likely caused by the transfer coefficient used to calculate the THOR risks based on the human IRCs. An adjustment of the transfer coefficient is necessary and might require a different value for belted and unbelted cases.

This study has limitations. Firstly, the ability of the human body models to measure accurately the acetabulum force in sled configurations is not established due to the lack of relevant cadaver data. Secondly, parameter studies and real car simulations would be needed to generalize the results.

To conclude, it is necessary to define a transfer function for the acetabulum force to predict hip injury risks properly. This transfer function might be load case dependent.

INTRODUCTION

Several studies have emphasized that lower limb injuries are the most common AIS2+ injuries sustained in frontal crashes [1] [2]. In a more recent study, [3] observed that newer car models show a significant decrease in Knee-Thigh-Hip (KTH) injuries which could be explained by the progressive introduction of knee airbags [4]. These types of injuries could be more prevalent for small overlap and oblique frontal crashes for the driver and front passenger [5]. NHTSA reviewed NASS-CDS data from 2000 to 2015 for belted and airbag restrained drivers in frontal crashes [6]. Most of the KTH injuries were to the knee or femur, however two-third of hip/pelvis injuries occurred in the absence of knee/femur injuries. The vast majority of these injuries occur in compression.

It is known that the hip joint is the weakest part of the KTH complex, meaning that under the same force level, the hip joint would sustain injuries before the thigh and the knee [7] [8] [9]. However, during a frontal impact only a certain percentage of the force is transferred from the contact surface at the knees to the hip joint. The percentage of force transmitted is related to several factors such as mass recruitment, contact surface stiffness, adduction/abduction, and flexion angle at the hip. Generally, the more mass is recruited behind the hip and the softer the impact surface, the more the percentage of force transmitted from the knee to the hip is, leading to increased risk of hip injuries.

In FMVSS No. 208 and frontal NCAP tests, only the peak femur compressive force is used to predict the KTH injury risk. However, contrarily to the Hybrid III dummy, the THOR is instrumented with acetabulum force sensors in addition to the femur force sensors. NHTSA recommended to use the axial compressive femur force to predict knee/femur injuries and the resultant acetabulum force to predict hip/pelvis injuries. NHTSA also proposed corresponding Injury Risk Curves (IRCs) [6]. A transfer coefficient for the acetabulum was defined to account for differences in KTH force transmission between THOR and humans.

The current study investigates, with the help of dummy and human body models (HBMs) simulations, the force transmission between the knee, the thigh and the hip and evaluates the NHTSA proposed injury assessment of the THOR KTH injuries.

METHOD

All simulations were performed using LS-Dyna MPP single precision version 9.3.1 r140922. Three occupant models were used:

- The THOR-50M model from ATD-MODELS version D0.15
- The THUMS M50 version 5.03
- The GHBM M50 version 6.0

The use of the THUMS version 5 rather than the THUMS version 4 was justified because the hip modeling in version 4 is deficient, particularly the acetabulum surface seems unrealistically flat, and the cartilage is not represented leading to a lack of geometrical congruence with the head of the femur. For both HBMs, bone failure was deactivated so as not to affect the force transmission, allowing a proper comparison with the dummy. HBMs were instrumented in a similar way as the THOR, particularly, femur and acetabulum force sensors were defined in the corresponding bony structures at a similar position. For the femur force, only the axial compressive component was measured whereas for the acetabulum, the resultant force was calculated. Forces measured at the acetabulum while the femur was under tension were not considered. The knee force was defined as the resultant contact force between the impactor, or in the sled simulation the knee pad, and the knee of the occupant. Force signals were all filtered in accordance with CFC600.

Load cases

Three different load cases were selected, an impactor test with a fixed pelvis, an impactor test with a free pelvis and a sled test.

- Fixed pelvis impactor test
  [7] performed 35 PMHS impactor tests at 1.2 m/s. Pelvis, sacrum, and lower extremities were removed before testing. The iliac wing was fixed to the test apparatus after removal of the iliac wing flesh. A stiff molded interface was positioned at the knee interface before impact. A 250 kg platform was accelerated to 1.2 m/s before impacting a ram attached to the molded knee interface. Between the ram and the platform, energy absorption materials consisting of a combination of Hexcel (9.5 mm cell diameter) and 13 mm thick flotation foam were used to limit the knee loading rate under 300 N/ms. The pelvis was positioned so that the angle between the horizontal and a line from the pubic symphysis to the anterior superior iliac spine (ASIS) measured in the xz plane was 120°. This angle was varied around this reference position. The femur was for all tests aligned to the global x-axis. Hybrid III tests were performed in a similar configuration, the only difference being that the pelvis was not included, and the femur head positioned in metallic acetabular cup. A finite element model of this setup was developed and validated based on the comparison of the Hybrid III test and the corresponding simulation results (see appendix 1).

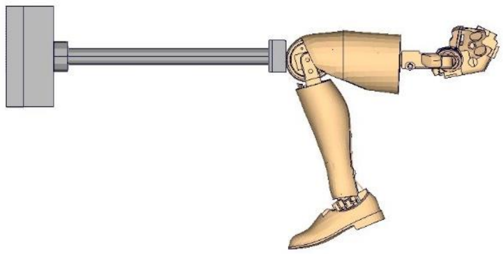

Figure 1. Fixed pelvis impactor load case.

- Free pelvis impactor test
  [10] performed a series of sub-injurious tests on 15 (3*5) PMHS at velocities of 1.2, 3.5 and 4.9 m/s. The cadavers were seated on a bench and a symmetric horizontal load was applied to both knees using a 255 kg weighted platform accelerated pneumatically. The left and right knee impact surfaces were padded. In the tests with 1.2 m/s, the padding consisted of a single 38 mm thick, 50-durometer Sorbethane (Sorbethane Inc., Kent, Ohio) block. In the 3.5 and 4.9 m/s tests, the padding consisted of a 25 mm thick, 50-durometer block placed over a 70-durometer, 25 mm thick one. The knee force was measured via a loadcell placed behind the impacting surface. The femur force was measured directly using a loadcell implanted in the bone, whereas the force at the hip was calculated from the femur force using inertial compensation. The test setup was modeled, and Hybrid III test results reported in the same paper were used for validation (see appendix 2).

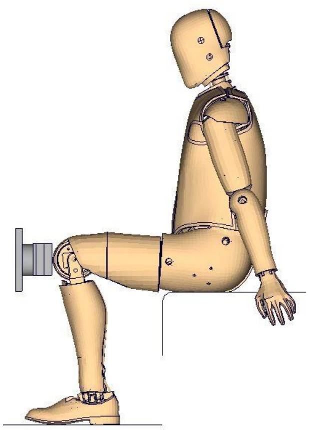

Figure 2. Free pelvis impactor load case.

- Sled load case
  PDB used a simplified vehicle-like sled environment for frontal testing. It consists of a rigid seat, a rigid dashboard, a deformable knee bolster, a 3-point belt system with pre-tensioner and a 4 kN load limiter, and a deployed and pressurized airbag. The pulse was derived from a 0° full-width rigid wall test. This environment has been used to test various dummies and a corresponding simulation model has been validated with the corresponding dummy models. Comparison of simulation and experimental tests for the THOR-50M dummy can be found in appendix 3. Sled simulations in this study were performed both belted and unbelted. All three occupant models were positioned similarly with a particular focus on the pelvis and leg position. The x-position and the angle of the pelvis, measured between the horizontal and a line connecting the pubic symphysis and the ASIS, for the HBMs were matched to those of the THOR model which was positioned according to the experimental tests. Feet positions and distance between the knees for the HBMs were also matched to the THOR simulation model.

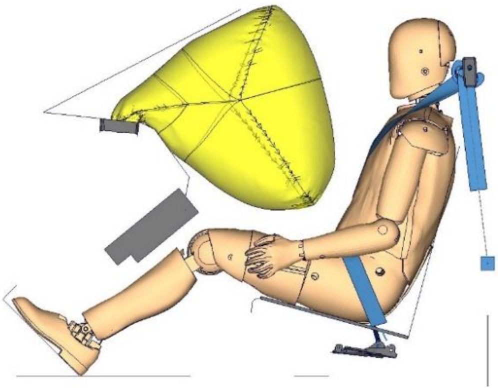

Figure 3. sled impactor load case.

Analysis

To analyze the load transmission through the KTH complex, several force ratios were calculated for each simulation:

$R_{fk} = \frac{F_f}{F_k}$,

$R_{af} = \frac{F_a}{F_f}$,

$R_{ak} = \frac{F_a}{F_k}$,

With F_k, the knee force; F_f, the femur force and F_a, the acetabulum force.

Additionally, risks of knee/femur AIS 2+ and hip AIS 3+ injuries were calculated using the IRCs proposed by Craig et al. (2020) for the THOR-50M:

Knee/Femur injury risk: $p(AIS\ 2+) = \Phi\left[\frac{ln(1.299 * F_f) - 2.62}{0.3014}\right]$ (1a)

Hip fracture injury risk: $p(AIS\ 3+) = \Phi\left[\frac{ln(T_{hip} * F_a) - 1.5751}{0.2339}\right]$ (1b)

Where:

Φ is the cumulative normal distribution function.

T_{hip}, the ratio of estimated PMHS hip force to THOR measured peak acetabulum resultant force. NHTSA proposed a value of 1.429 for T_{hip}.

F_f and F_a the previously described femur and acetabulum forces.

RESULTS

First the peak forces obtained with the three models in the free pelvis impact simulations were compared to box plots derived from corresponding PMHS results published by [10] as illustrated in Figure 4 and Figure 5. Generally, for all models, the knee forces and the acetabulum forces are within or very close to the range of the PMHS. From these results, it is considered that both HBMs are validated for KTH loading and that the THOR shows comparable biofidelity for this loading.

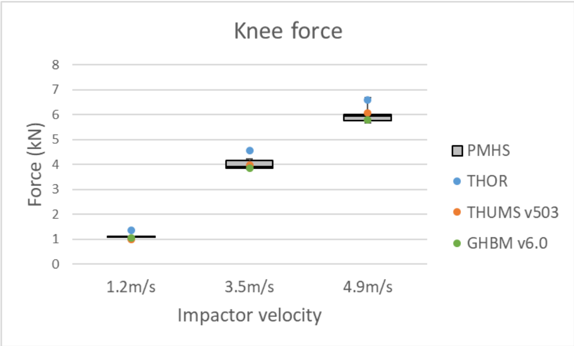

Figure 4: Knee force in Rupp et al. 2008 simulations compared to PMHS results.

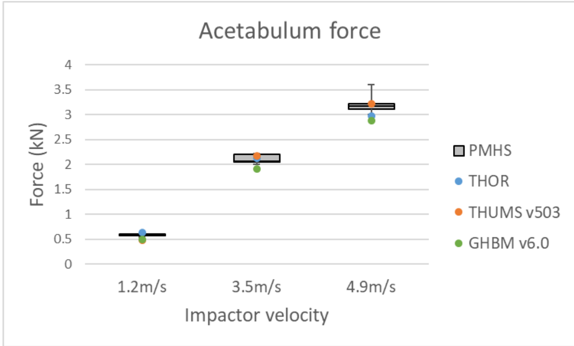

Figure 5: Acetabulum force in Rupp et al. 2008 simulations compared to PMHS results.

Free and fixed pelvis impactor tests resulted in fundamentally different behavior in terms of force transmission from the knee to the hip. When the pelvis is fixed, mass recruitment is not relevant anymore and 100% of the force is transmitted from the knee through the femur and to the acetabulum (see Figure 6). On the contrary, when the pelvis is not fixed, only a portion of the knee force is transmitted to the femur and an even lower portion to the acetabulum (see Figure 7).

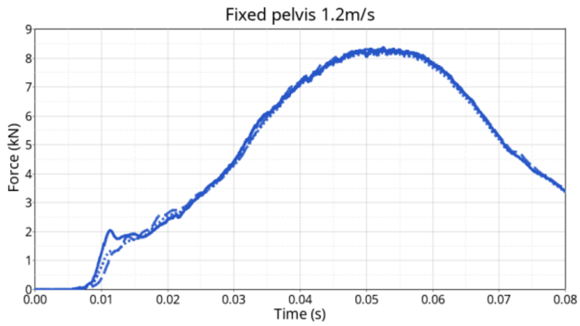

Figure 6: Knee (solid), femur (dashed) and acetabulum (dotted) forces in the 1.2 m/s fixed pelvis impactor simulation with THOR.

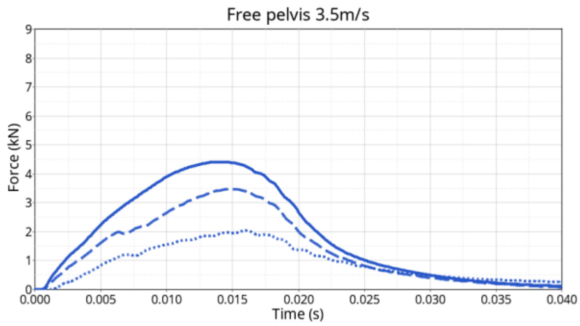

Figure 7: Knee (solid), femur (dashed) and acetabulum (dotted) forces in the 1.2 m/s free pelvis impactor simulation with THOR.

For the fixed pelvis impact tests, the forces are directly related to the overall stiffness of the KTH complex and differ between the three tested models (see Figure 8, Figure 9 and Figure 10). In the free pelvis tests, the three models show similar knee, femur, and acetabulum forces for the three impact velocities. The peak forces increase with velocity and decrease when moving from the knee to the acetabulum ($F_k < F_f < F_a$).

The same trend between knee, femur and acetabulum forces is observed for the sled simulations whether belted or unbelted. The force levels are similar for the three models in the unbelted configuration; however, the forces are significantly lower in both HBMs compared to the THOR model in the belted configuration. Note, for reason of simplification, the left and right forces have been averaged for the sled simulations.

The general kinematic is similar in the sled simulations between all three models, however, in the belted simulation, some differences are observed at the pelvis level. Indeed, the HBMs showed a backward rotation, whereas the THOR showed very little pelvis rotation. Also, the HBMs had less peak pelvis forward excursion (THUMS v503: -6.5 mm, GHBM v6.0: -10 mm). The timing of the knee impact was similar between all models at around 40 ms.

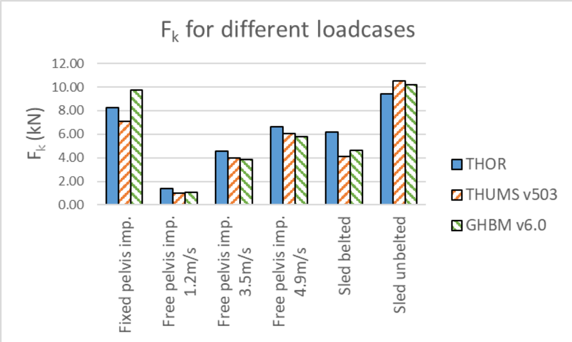

Figure 8: Knee force in simulated load cases.

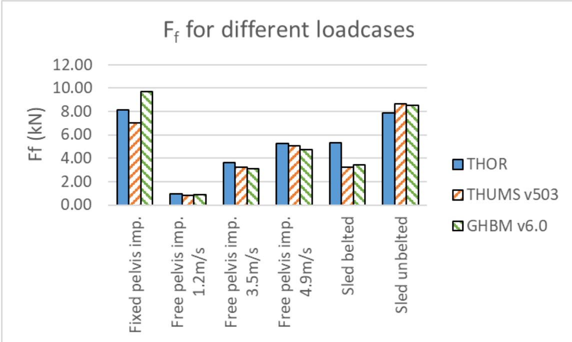

Figure 9: Femur force in simulated load cases.

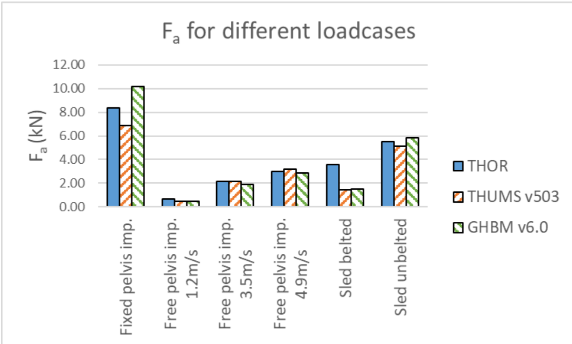

Figure 10: Acetabulum force in simulated load cases.

Table 1 shows the calculated risks based on the Injury Risk Curves from [6] for the femur and acetabulum forces. For the HBMs, the factor T_{hip} has been set to 1, meaning that the HBMs are treated as if they were PMHS. Some notable differences are observed, particularly, the risk of hip injuries is consistently higher for the THOR when compared to both HBMs. The GHBM model predicts higher risks of knee/femur injuries for the fixed pelvis than THUMS and THOR. Both HBMs predict no risks for all impactor tests with a free pelvis and the belted sled case whereas the THOR predicts significant risks of hip injury for the 4.9 m/s impactor and both sled simulations.

Table 1.
Injury risk for every simulated load case.

		THOR		**THUMS v503**		**GHBM v6.0**	
		AIS2+ Risk knee/femur	AIS3+ Risk hip	AIS2+ Risk knee/femur	AIS3+ Risk hip	AIS2+ Risk knee/femur	AIS3+ Risk hip
Fixed pelvis	1.2 m/s	0.19	1.00	0.09	0.94	0.38	1.00
Free pelvis	1.2 m/s	0.00	0.00	0.00	0.00	0.00	0.00
	3.5 m/s	0.00	0.02	0.00	0.00	0.00	0.00
	4.9 m/s	0.01	0.29	0.01	0.04	0.00	0.01
Sled belted	Left	0.01	0.34	0.00	0.00	0.00	0.00
	Right	0.02	0.78	0.00	0.00	0.00	0.00
Sled unbelted	Left	0.17	0.98	0.26	0.58	0.24	0.78
	Right	0.17	0.98	0.26	0.62	0.24	0.79

DISCUSSION

As presented in the results for the belted sled simulations, the THOR showed generally much higher forces at the knee thigh and hip compared to the HBMs. An analysis of the kinematic and the belt forces, shows that the interaction between the seatbelt and the pelvis is very different. The HBMs show an earlier engagement of the seatbelt with the iliac wings which is confirmed by a much higher lap belt force than for the THOR. The main cause for this is the geometry of the thigh and abdomen. The THUMS model has thinner thighs compared to both other models, which leads to a lower position of the lap belt compared to the pelvis, the upper edge of the lap belt being around the same height as the ASIS. The GHBM and the THOR differ in the abdomen geometry, the THOR abdomen is flat at the junction with the thigh, whereas the GHBM has an inward curvature in the same region. Due to this curvature, the belt lies closer to the iliac wing in the GHBM simulation. Thigh size and abdomen shapes can vary significantly between individuals even for a given percentile and are influenced by the posture and the types of clothes worn [11] [12], so it is not possible to make a definitive statement as to which model is more human-like.

All tested PMHS (n=26) were injured in the fixed pelvis cases and most of the injuries were to the hip or pelvis which is consistent with the injury prediction for all models in this load case. The free pelvis tests were designed to be sub-injurious and none of the PMHS were injured (n=5 per velocity). The THOR predicts very little risk for the 1.2 and 3.5 m/s velocities. However, an injury risk of 29% for the hip is calculated for the 4.9 m/s case, which seems overestimated. On the contrary, both HBMs show low injury risk for all three velocities. HBMs also predict no injury risk for the belted sled test; whereas the THOR predicts relatively high (Left: 0.34, Right: 0.78) hip injury risks but no knee/femur injury risk. Field data show on the contrary that for belted occupants the occurrence of knee/femur injuries is significantly higher than that of hip injuries [6]. This risk prediction seems particularly inconsistent with field data when considering that the hip injury risk is calculated for AIS3+ injuries while the risk of knee/femur is calculated for AIS2+.

The incidence of KTH injuries in frontal crashes for unbelted occupants is about three times higher than that for belted occupants [13] and the proportion of knee/femur and hip injuries seem to be consistent between the belted and unbelted cases. All three models predict higher risks of hip injuries than knee/femur with the THOR showing the highest hip injury risk (98%) and the lowest knee/femur risk (17%).

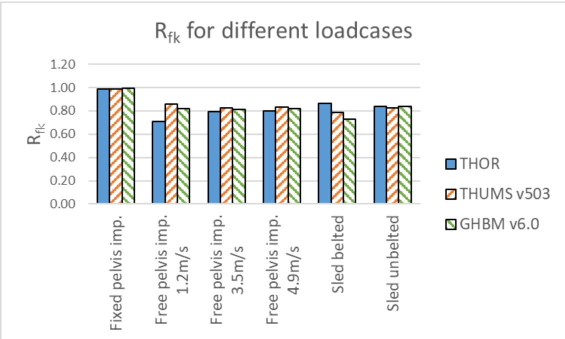

Figure 11: Ratio of femur to knee force in all simulated load cases.

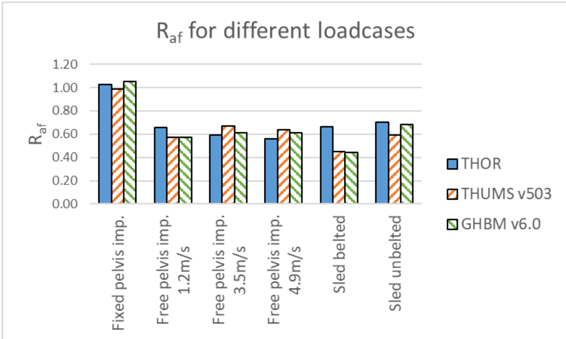

Figure 12: Ratio of acetabulum to femur force in all simulated load cases.

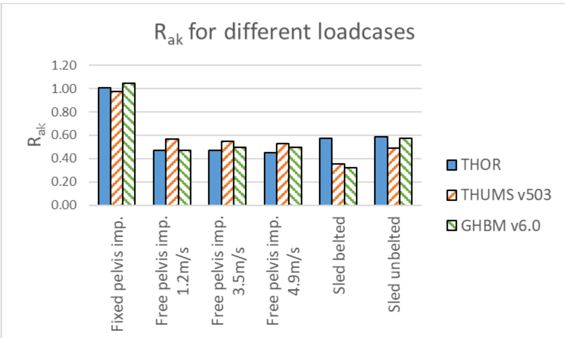

Figure 13: Ratio of acetabulum to knee force in all simulated load cases.

Given that the THOR seems to overestimate the risk of hip injuries for the free pelvis impactor tests and for the sled simulations, it is worth questioning the validity of the T_{hip} value. This value was calculated using the equation below [6]:

$$T_{hip} = \frac{r_{PMHS}}{r_{THOR}} = \frac{r_{PMHS}}{r_{fk} * r_{fa}} = \frac{0.55}{0.77 * 0.5} = 1.429 \quad (2)$$

Where:

$r_{PMHS} = r_{ak}(PMHS)$

$r_{THOR} = r_{ak}(THOR)$

The value of 0.55 for r_{PMHS} is based on the PMHS results from [10]. This value is relatively close to the values observed in the HBM simulations for the free pelvis simulations and the unbelted sled as can be seen in Figure 13. However, 0.55 is an approximate value, recalculating the mean based on the values reported in paper leads to a value of 0.54. For r_{fk} [6] assumed that the THOR behaves similarly to the Hybrid III and therefore defined the same value for both dummies. Generally, the values found in this study are slightly higher for this ratio except for the free pelvis at 1.2 m/s which might be due to the low impact velocity in this case. Excluding this load case and the fixed pelvis one, which is not representative of a frontal crash loading, the mean r_{fk} value in this study is 0.83. The 0.5 value for r_{fa} is based on an analysis by [14] of THOR-NT test results. A review of internal dummy experimental tests in the same belted sled condition described in this paper lead to a value of 0.61±0.05 over 29 tests involving 7 THOR dummies. This value seems consistent with the results from the simulation study. Recalculating T_{hip} with $r_{PMHS} = 0.54$, $r_{fk} = 0.83$, and $r_{fa} = 0.61$, leads to a value of 1.07. Figure 14 shows the ratio of the acetabulum force for the HBMs to the THOR for the simulated cases. The ratio is close to 1 for the 3.5, 4.9 m/s and unbelted sled tests. The ratio is much lower, around 0.4 for the belted case, meaning that in this case, the HBMs predict only 40% of the acetabulum force predicted by the THOR.

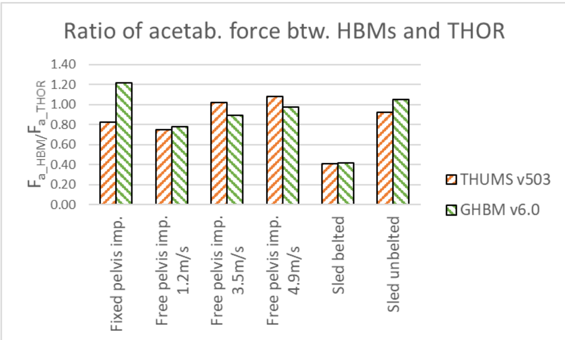

Figure 14: Ratio of acetabulum force between HBMs and THOR.

Based on the observations described above, a value of T_{hip} of 1 was considered and all risks for the THOR model were recalculated (Table 2). The risks for the impactor tests are consistent with the PMHS injuries, particularly the hip injury risk for the free pelvis case at 4.9 m/s is reduced from 29% to 2%. Hip injury risks calculated for the belted sled tests are reduced from 34% and 78% to 3% and 23% for the left and right side respectively. For the unbelted case, the risks are reduced from 98% on both sides to 73% on the left and 72% on the right side. However, in both sled simulations, the hip injury risks are still higher than the knee/femur injury risk which is not consistent with expectations based on field data. It could be that T_{hip} is lower than 1.0 in the belted configuration as is suggested by the difference between THOR and the HBMs in this study, but this needs to be confirmed by experimental results.

Table 2.
Injury risk for every simulated load case with T_{hip}=1.429 and T_{hip}=1.0.

		THOR		
		AIS2+ Risk knee/femur	AIS3+ Risk hip for $T_{hip} = 1.429$	AIS3+ Risk hip for $T_{hip} = 1.0$
Fixed pelvis	1.2 m/s	0.19	1.00	0.99
Free pelvis	1.2 m/s	0.00	0.00	0.00
	3.5 m/s	0.00	0.02	0.00
	4.9 m/s	0.01	0.29	0.02
Sled belted	Left	0.01	0.34	0.03
	Right	0.02	0.78	0.23
Sled unbelted	Left	0.17	0.98	0.73
	Right	0.17	0.98	0.72

In the experimental sled tests mentioned above, the R-square value between the femur and acetabulum force data from the experiments is 0.89 which suggests a good correlation between these two values. This could be due to the high repeatability and reproducibility of the sled tests when compared to real situations including various car models and/or various loading conditions (e.g., direction, speed). However, in the simulations, R_{af} for the THOR remains also relatively close to 0.6, except the fixed pelvis test, despite the different nature of the impactor tests compared to the sled tests. More data are necessary to conclude on the variability of the R_{af} ratio, however, based on currently available data, there is no indication that it is varying significantly. If this is confirmed, it is likely that independently of the IRCs, one sensor will consistently predict higher risks than the other. Therefore, the use of both the knee/femur and the hip injury risks for the THOR would be redundant and unnecessary and it would seem more suitable to use only one of the two sensors. More research is needed to determine which of these two sensors should be used and if only one is used how the corresponding IRC would be defined, particularly if both types of injuries (knee/femur and hip) should be considered.

This study has limitations. Firstly, the ability of the human body models to measure accurately the acetabulum force in sled configurations is not established due to the lack of relevant cadaver data. Another point is that the results in the belted sled configuration seem to be very sensitive to the belt position which mostly depends on the thigh and hip geometry. It could be that the difference observed between the HBMs, and the THOR are very specific to the particular parameters of this load case such as belt system or knee pad stiffness. To generalize the results, it would be necessary to run parameter studies as well as to verify the findings in real car environments.

CONCLUSION

A simulation study was performed using a THOR-50M model and two HBMs to investigate Knee-Thigh-Hip injuries. It has been previously proposed to use the THOR acetabulum force sensor to predict hip/pelvis injuries and the femur force sensor to predict knee/femur injuries. The current studies show that over different loading conditions, the femur and acetabulum force measurements have a very good correlation, and it might therefore not be necessary to use both measurements. The Injury Risk Curve for hip/pelvis proposed by NHTSA overpredicts the injury likelihood. Based on the results of this study, the overprediction is most likely due to the transfer coefficient defined between the THOR and humans. The proposed value of 1.429 for this coefficient is generally too high and could be load case dependent. Based on the presented results, a transfer coefficient of 1 seems reasonable for the unbelted cases; and for belted cases, a coefficient of less than 1 is necessary. Further investigation is needed possibly using parameter studies and real car interior models.

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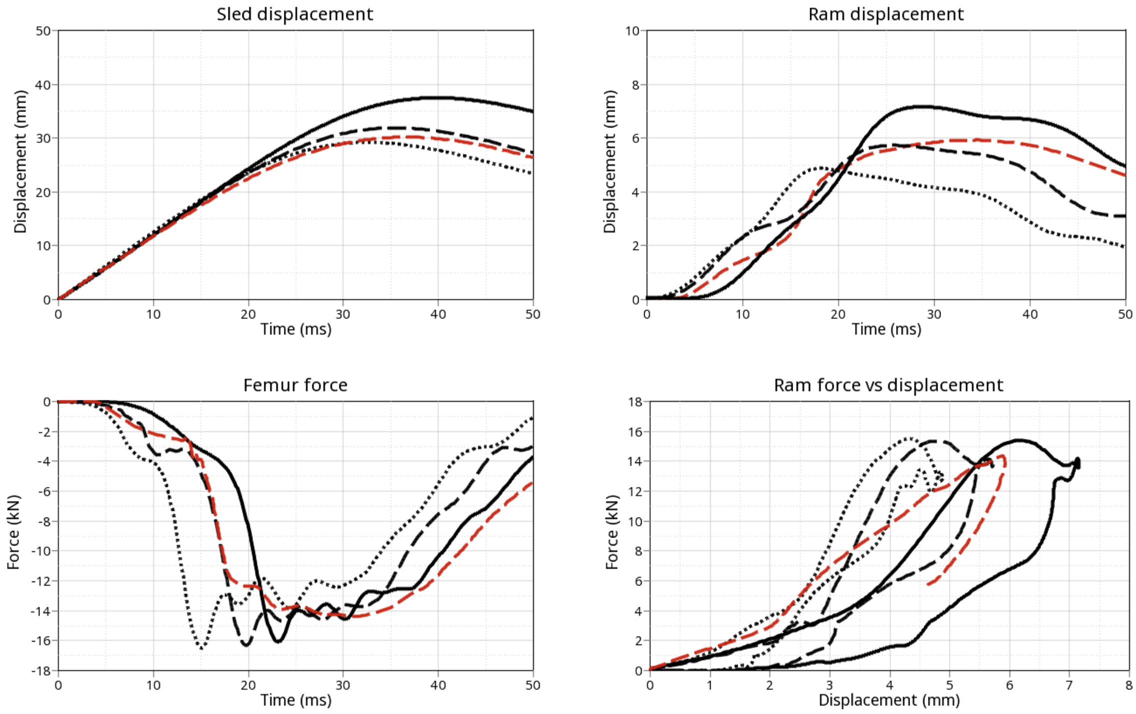
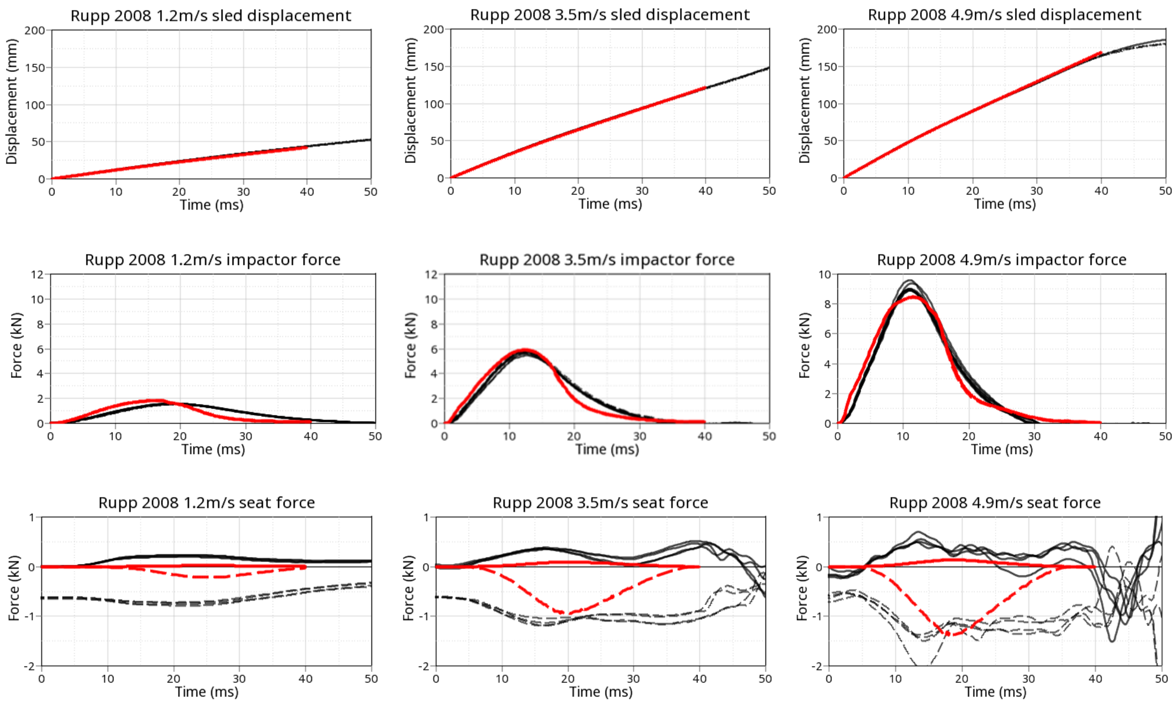
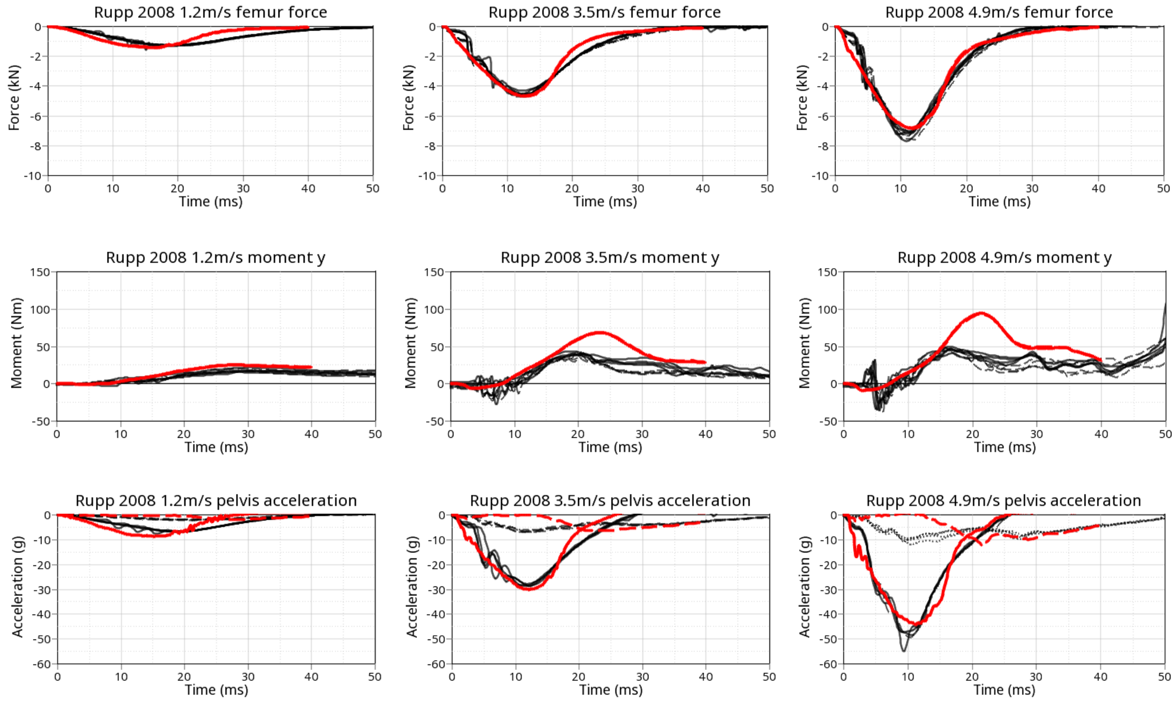
Appendix 1: Validation of fixed pelvis simulation environment based on Hybrid III-50 simulations

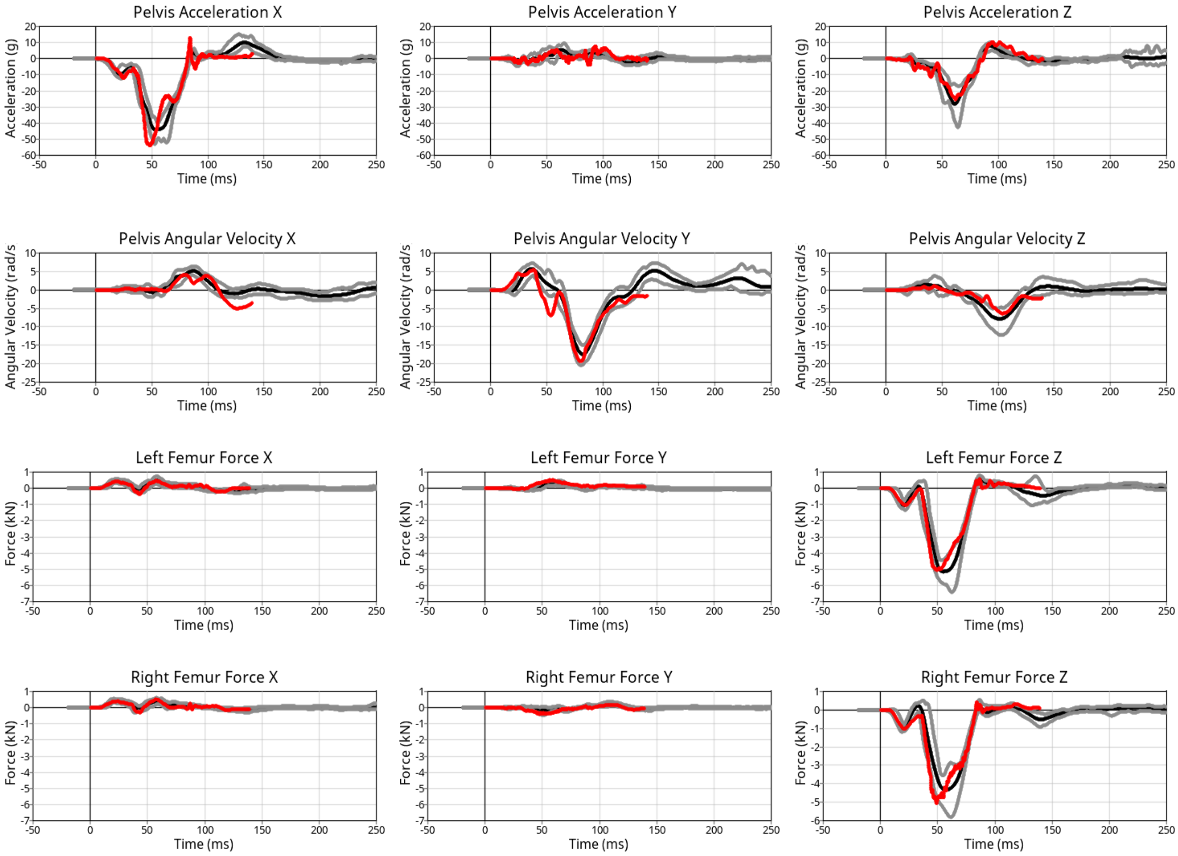


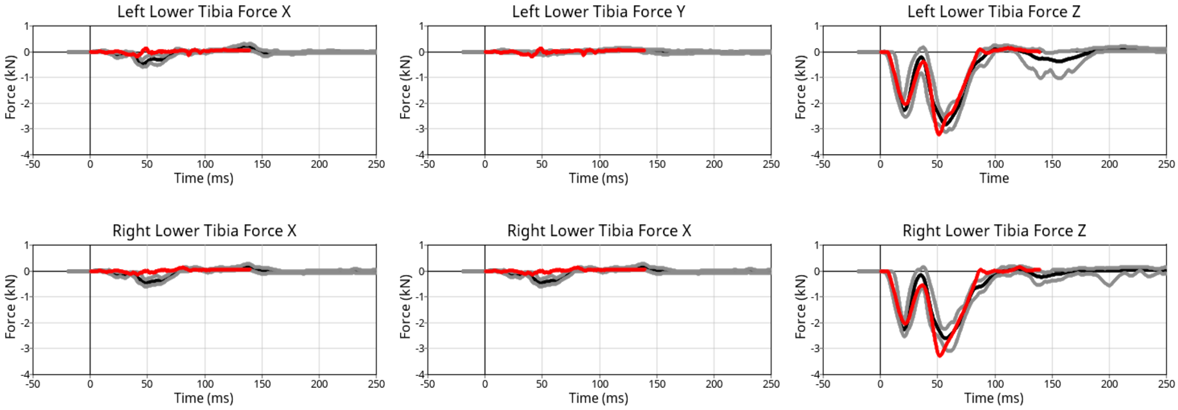
Appendix 2: Validation of free pelvis simulation environment based on Hybrid III-50 simulations





Appendix 3: Validation of belted sled simulation environment based on THOR-50M simulations




Left Lower Tibia Force X
Left Lower Tibia Force Y
Left Lower Tibia Force Z
Right Lower Tibia Force X
Right Lower Tibia Force X
Right Lower Tibia Force Z
Force (kN)
Time (ms)
Time
1
0
-1
-2
-3
-4
-50
0
50
100
150
200
250