HUMAN FE MODEL TO ESTIMATE HEAD CONTACT TIME FOR PEDESTRIAN PROTECTION

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ABSTRACT

PCA based statistical analysis of NASS-PCDS (National Automotive Sampling System – Pedestrian Crash Data Study) database clearly shows that post-impact pedestrian kinematics is complex and depends on various factors, such as impact speed, height of the pedestrian, front-end profile of the striking vehicle and pedestrian posture, etc. The findings from the NASS-PCDS study were also confirmed and verified with the help of numerical simulations that were performed using two modified JAMA human FE models. An adult model (male, 175cm and 72kg) and a properly scaled child model (6 years old, 120cm and 24.5kg) were effectively utilized to investigate the post-crash kinematics in different conditions. The focus of this study is to investigate those factors that determine the post-crash pedestrian kinematics of children and small adults related to the head impact time (HIT) as specified in Euro-NCAP pedestrian protocol.

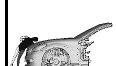
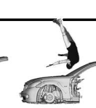
INTRODUCTION

Even though the motor vehicle occupant fatalities are decreasing in many countries, the overall percentage of pedestrian casualties is increasing compared to that of vehicle occupants. Annual fatalities, for every 1,000,000 people, are 12.3 in Australia, 15.7 in the EC, 16.4 in the US and 21.8 in Japan. The numbers in developing countries are even higher. Mizuno et al. reported their detailed investigations of pedestrian accident databases from countries including Australia, Germany, Japan and the US (1605 cases, 9463 injuries, include 3305 AIS2+) [1]. According to their reports, in one third of those cases, pedestrians were reported to have suffered injuries to their heads and/or lower extremities. Previous studies on pedestrian crash cases pointed out that the vehicle front geometry, the height and the posture of the pedestrian affect the injury mechanism [2]. Further studies [3, 4] targeting child pedestrians' injury distribution pointed out that anthropometry influences impact kinematics. This study focuses on the leading factors affecting the post-crash pedestrian head trajectory and head impact time with the help of a 6-year old (6YO) human FE model. It is modeled accurately based on anthropometric data and other biomechanical responses such as compression, bending, torsion, and shear characteristics of the spinal joints.

ACCIDENT ANALYSIS

In NASS-PCDS 'Vehicle pedestrian interaction (variable 524)', indicates the post-crash pedestrian kinematics. There are 17 codes to describe the types of interaction [4].

Table 1 PCDS data categorized in 4-types A,B,C,D.

NASS-PCDS (variable 524)	*Type A 35 cases*	*Type B 82 cases*	*Type C 138 cases*	*Type D 20 cases*
Ped. height	158cm	163cm	168cm	172cm
Impact speed (standard dev.)	20 km/h (12.2)	22 km/h (11.2)	41 km/h (19.6)	67 km/h (10.5)
FE analysis (adult& 6YO)				

Four of those codes are picked out in accordance with frequencies of occurrences. They are categorized as four main types A-D (Table1). Based on this basic statistical information, human FE model simulations were carried out to verify the kinematics for corresponding types of impact. The range of average impact speed in these four categories matches with the initial input velocities of FE simulations. From the simulation results, corresponding to four different (Type A-D) kinematical modes, it is observed that:

Type A differs from the other three types in the relative velocity after impact.

The Type A pedestrian is accelerated in the same direction in which the vehicle is traveling. The pedestrian's body is thrown forward in front of the vehicle.

In the other three types, Types B, C and D, the pedestrians are accelerated by the impact, up to a speed not more than the speed of the vehicle. The torso of the pedestrian travels relatively backward with respect to the front end of the vehicle.

Types A and B include children and small adults.

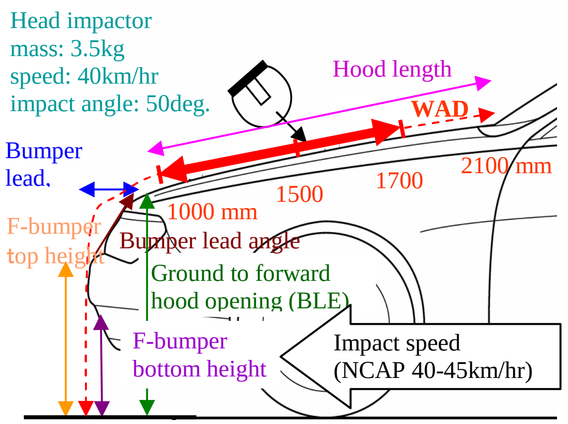


Figure2a. NASS-PCDS database vehicle profile parameters superimposed with Euro-NCAP regulation head impact testing region related to children and small adults.

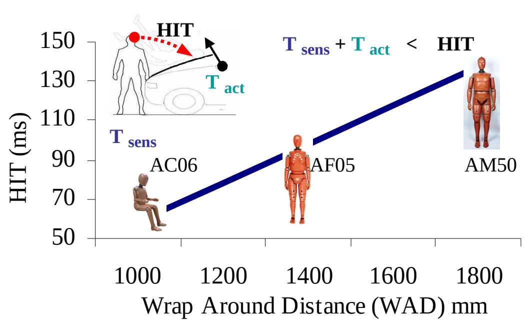


Figure2b. Approximate relationship of Wrap around Distance (WAD) and Head Impact Time (HIT) as defined in EuroNCAP protocol.

The Euro-NCAP pedestrian test protocol procedures specifically indicate the head impact evaluation region for children and small adults as shown in Figure2 for a range of WAD from 1000 to 1700mm. Data related to this region is selected from PCDS and analyzed to find out those factors of the vehicle front-end-profile and pedestrian that have maximum influence on the post-crash kinematics as defined in Euro-NCAP protocol. HIT being directly proportional to WAD, one can assume that a principal component analysis (PCA), using the real world accident data of this region, will be a useful tool in identifying the most influential factors related to HIT. The results of the PCA study are shown in Table2 that clearly reveals the following facts:

Table 2 Results of PCA (refer Figure.3)

Variables of NASS-PCDS *Accidental Year 1994-1998* *552 pedestrian crashes* *42 cases in WAD 1000-1700* *(1,2,3 indicate Component No.)*	Results of first three principal components	
	Child	Child & Small Adult
Ground to forward hood opening (same as Bonnet Leading Edge, BLE)	1	1
F-bumper top height F-bumper bottom height	1 1	1 1
Bumper lead	3	2
Impact speed		1,2,3
Bumper lead angle	1	1
Pedestrian height & weight	1,2	1,2
Pedestrian leg orientation	2	2
Hood length Results based on first 3 principal components	2	2

Figures in gray color indicate less contribution

(i) The BLE height from ground is the most influential factor together with forward bumper top and bottom heights and also the bumper lead angle as they appeared in the 1st principal component (Figure3).

(ii) Pedestrian's height and weight are also important as they contribute maximum in the 2nd principal component. Again, as they appear in the 1st principal component also with lower order of contribution, it may indicate that the inertia (mass x length^2) of the upper part of the pedestrian above BLE may be a key factor.

(iii) The influence of speed of impact is moderate for the pedestrian whose average height is above 155cm (close AF05 size) and very low if the average height is less than 145cm (grown-up child).

(iv) Looking at the detail individual amounts of contribution in PCA results, a part of which is shown in Figure3, one can guess that the relative height of the pedestrian or in other words, the position of its center of gravity (COG) with respect to the BLE of the striking vehicle and to some extent the bumper lead might be the crucial design parameters of the front end profile of a vehicle to control the value of HIT. The result of sensitivity analysis using 6YO-child FE model is described in detail in the following sections (refer Table3) to confirm the above statement. The sum of sensing-time T_{sens} and actuation-time T_{act} for those vehicles fitted with activated pop-up hood has to meet the present Euro-NCAP requirements ($T_{sens} + T_{act} < HIT$) based on shortest HIT condition. The HIT is usually lowest for 6YO-child whose weight lies in the range of 19-32kg with an average weight of 24.5kg (refer Figure 8a).

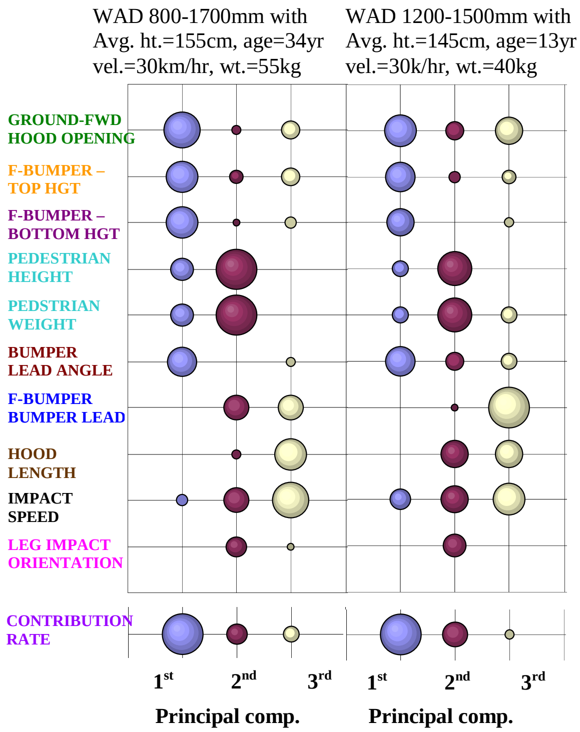


Figure3. Distribution of first three principal components of PCA results for two different WAD regions with approximately 65% (1st: 34%, 2nd: 17%, 3rd:14%) cumulative contribution.

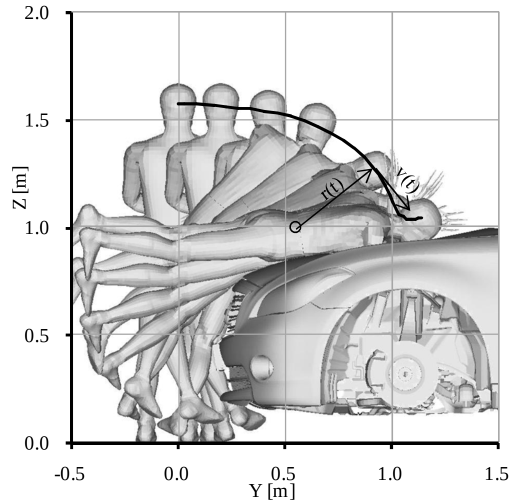
FE ANALYSIS OF HUMAN MODEL

An adult male pedestrian model was developed by JARI (Japan Automobile Research Inst.) under the supervision of JAMA (Japan Automobile Manufacturers Association) in 2010 [7, 8, 10]. The post-crash pedestrian kinematics, including head trajectory, are already validated with PMHS experiments [7,15]. In this paper, the head center of gravity (COG) trajectory of the pedestrian and the head impact time (HIT) with the hood are discussed.

The adult model was modified in-house to create a 50th%ile 6YO-child FE model. The adult 50th%ile adult male model is developed in the JAMA human model consortium. All parts of the 6YO-child FE model are scaled according to the European-children anthropometry data [3, 9].

The two superimposed FE simulation results of overall kinematics of an adult and a child, as shown in Figure 4(a, b), clearly show the influence of the ratio of hood height with respect to pedestrian height "hp" and the vertical position of center of gravity with respect to bonnet leading edge [4].

(a) adult



(b) 6YO-child

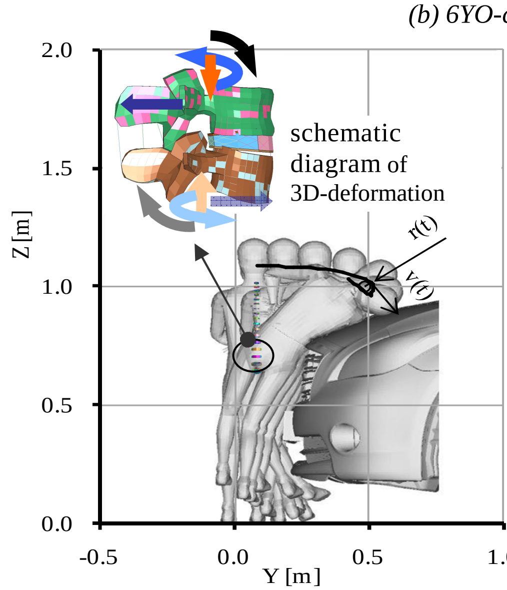


Figure4. Superimposed animations of (a) 50%ile AM50 adult and (b) 6YO-child with a magnified schematic diagram of the 3D-deformation of a typical spine joint.

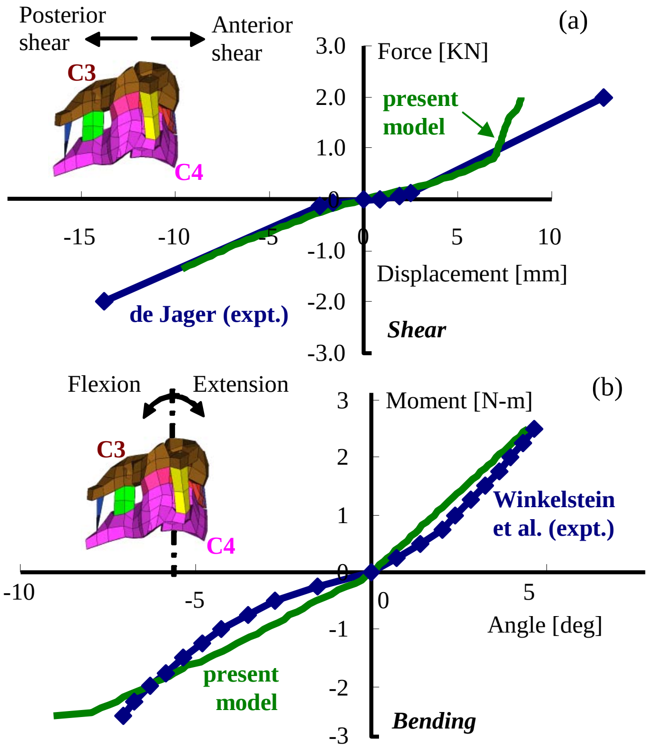
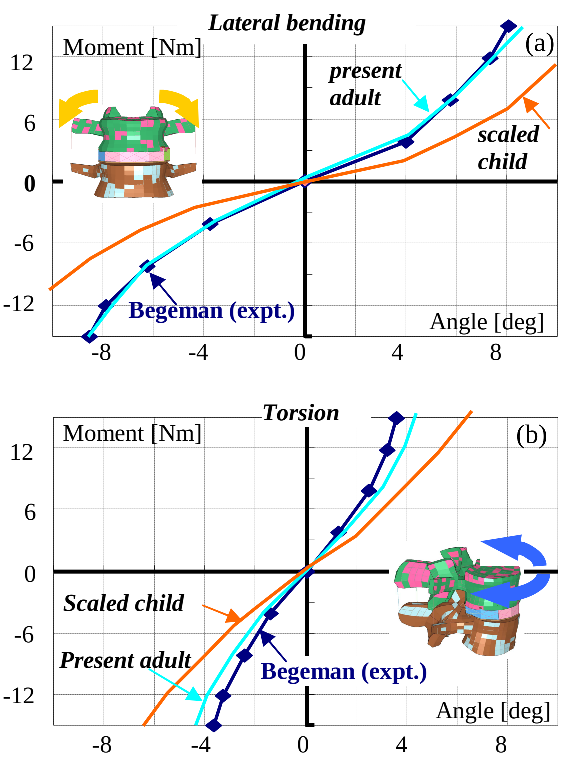


Figure5. Component level responses of upper spine (C3-C4) joint for an adult in shear and bending mode.



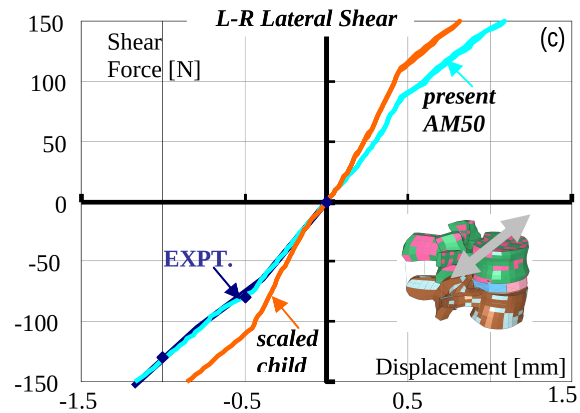


Figure6. Component level responses of lower spine (L3-L4) for adult and geometrical scaled 6YO-child. from AM50 adult, (a) lateral bending, (b) torsion, and (c) lateral shear.

Identification of the overall spine deformation kinematics (especially in lateral bending, torsion and lateral shear mode) of the upper body is important. Deformation pattern of two adjacent vertebrae connected by soft tissues influences the kinematics of the head. Hence, proper identification of load-deformation characteristics at different portions of the entire spine is important. Figure5 shows the quasi-static response identification results of the upper cervical spine (C3-C4) joint for adult in shear and bending. Figure6 shows the quasi-static response identification results of the lower lumbar spine (L3-L4) joint of the present AM50 adult and 6YO-child scaled model [10, 13, 14]. The results of response identification for different modes of deformation of the present simulation model match well with those of biomechanical experiments. Due to geometrical scaling effect, the response of the equivalent 6YO-child, scaled from AM50 adult, will be reduced due to smaller cross-sectional area. However, the response characteristic will be still stiffer in response compared to children as mentioned in a recently published paper [18]. Proper adjustments of material properties, such as, Young’s modulus, are necessary to match dynamic response of a child.

HEAD IMPACT TIME

HIT is dependent on various parameters. The task of determining and identifying the factors related to HIT, is an important activity to select the optimum design parameters of the front-end module of the vehicle at the early stage of design. In addition, one has to estimate the shortest possible HIT value with different pedestrian size, varying from adult to children and the location of impact, as mentioned in Euro-NCAP protocol.

In general, say for typical sedan-type vehicle profiles, the shorter is the height of the pedestrian, the faster is the time of head contact with the hood as mentioned in Figure2b. Different phases of 6YO-child pedestrian kinematics are plotted in Figure 7 to visualize the influences of different factors for a typical sedan.

Phase 0: At the start of impact, the low (center of gravity) of the 6YO-child pedestrian is completely under the bonnet leading edge of the vehicle.

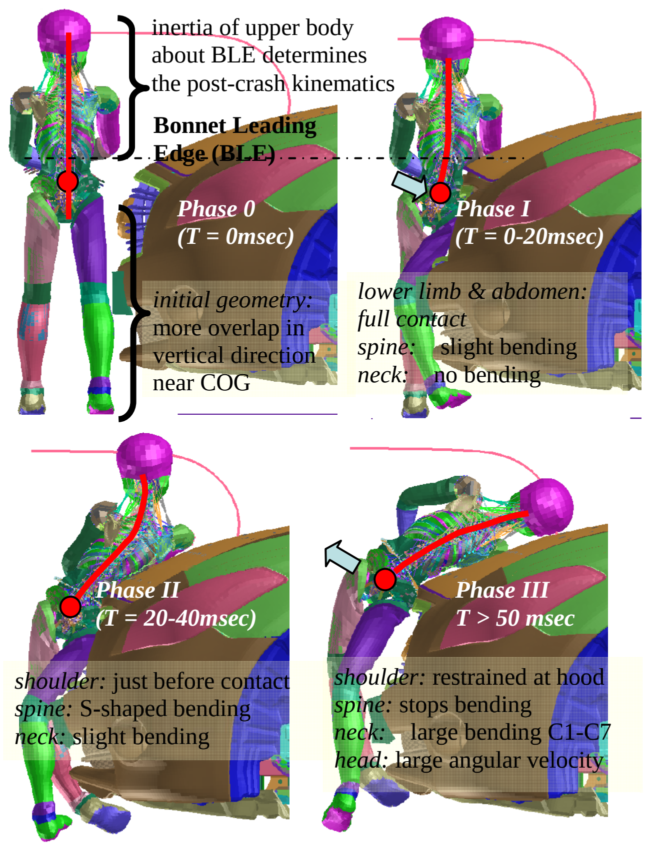


Figure7. Different phases of spinal deformation of a 6YO-child from the start of impact until the head come in contact with the hood.

Phase I: The lower limb and the abdomen are in full contact with the front end of the vehicle. The lower part of the lumbar spine is slightly pushed forward. The portion of spine above the abdomen is almost vertical with head remained straight without any rotational movement.

Phase II: The spine undergoes S-shaped bending. The hip is fully restrained by the hood. With abdomen and chest fully compressed by the bonnet leading edge, the shoulder is about to touch the front end of the vehicle. At this instant of time, the head starts rotating much faster.

Phase III: The head rotates very fast with high angular velocity with shoulder remains fully restrained just before hitting the hood.

Performing a number of simulations with various initial postures, angles and locations of impact of the pedestrian with respect to the vehicle, it is clearly observed that the shoulder and hand interaction, in between the space of the head and the hood of the vehicle, will affect the value of HIT just before the head comes in contact with the hood. Similar result is observed in the PCA study also, as mentioned in Table2 and Figure3, which show some small amount of contribution coming from leg impact orientation.

HIT value is influenced by the impact speed as shown in Figure8.The sensitivity at lower impact speed (V<25km/h) is more than that at higher speed (V>30km/h). It is non-linear and there exits an inflation-point or a change in gradient at this region (25-30km/h). However, it will depend on the type of vehicle and the shape of the front-end profile. Similar result is observed in the PCA study also as mentioned earlier in Figure3, which shows some amount of contributions in 2nd and 3rd principal components. It is to be noted that the effect of impact speed is relatively less estimated in PCA compared to that of the FE analysis. This may be due to the limitation of the PCA based multivariate statistical method, which is effective, efficient and accurate for linearly distributed Gaussian multivariable dataset. In order to verify that one has to reinvestigate in more detail with advanced statistical tools such as non-linear PCA, usually known as Kernel-PCA, before making any general conclusion on the degree of the contribution of speed of impact on WAD or HIT based on real world accident data. However, it is beyond the scope of this present study. The influence of braking and steering on WAD is discussed in detail in earlier publications where it is clearly stated that one has to be careful in selecting the relevant data from real world accident database [4].

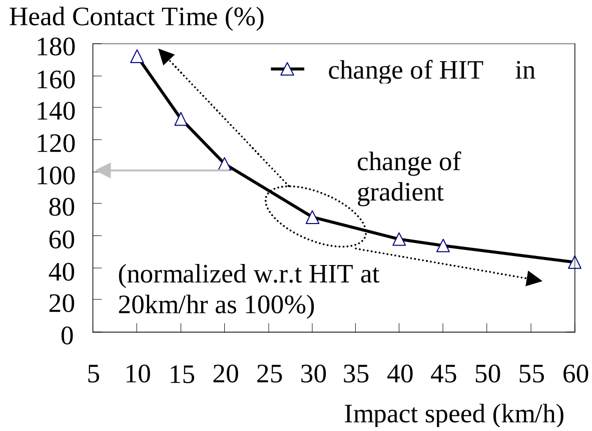


Figure8. Sensitivity of head impact time with respect to speed of impact.

Table3. Sensitivity analysis of different parameters affecting HIT estimation.

Parameter		Degree of influence on HIT at speed 40-45 km/hr
Pedestrian / BLE height: h_p (position COG wart to BLE)		High
Bumper lead and angle		Medium
Location of impact w.r.t. center		High (Min. at CL)
Spine	later bending	medium
	shear	medium
	torsion	low
Ligaments (not spinal)	neck peripheral	low
	thorax-shoulder	low
Upper extremity	interaction of hood-shoulder	medium at center very low at corner
Pedestrian mass (with same COG)	Refer Figure 8	low
Bone fracture	lower-limbs	very low
	upper-limbs	very low
Thorax (chest, abdomen)	compression	Low
Lower extremity	posture	Low

high:> 6%, medium:3-6%, low:2-3%, very low:0-2%

Apart from the impact speed of the vehicle, Table3 shows the "degree of influence" of the other parameters related to 6YO-child FE model, influencing the head contact time as estimated from human FE simulation results. With recent advancement of CAE based FE crash analysis, one can easily capture more accurately the basic trend and the mechanism of complicated post-crash pedestrian kinematics to supplement accident database if sufficient number of simulations are performed by matching the boundary conditions in real world accidents.

Parametric study with FE simulation

The parametric study, as shown in Table3, is carried out to find the effect of geometric scaling of a 6YO-child model, which is accurately scaled from AM50 model.

Effect of mass: 6YO-child 50%ile model compatible to EuroNCAP protocol with stipulated heel-to-heel gap and the ground to pelvis height in standing position. The mass of the present 6YO-child FE model is 24.5kg. The corresponding statistical range of the weight of European 6YO-children is 19-32kg[3]. The influence of the mass of the 6YO-child FE model is simulated by changing the mass without altering the position of the COG of 6YO-child FE model. A 30% increase in weight from the mean value (50%ile 24.5kg → 95%ile 32kg, Figure8b) will lead to an increase in HIT value by a few percent.

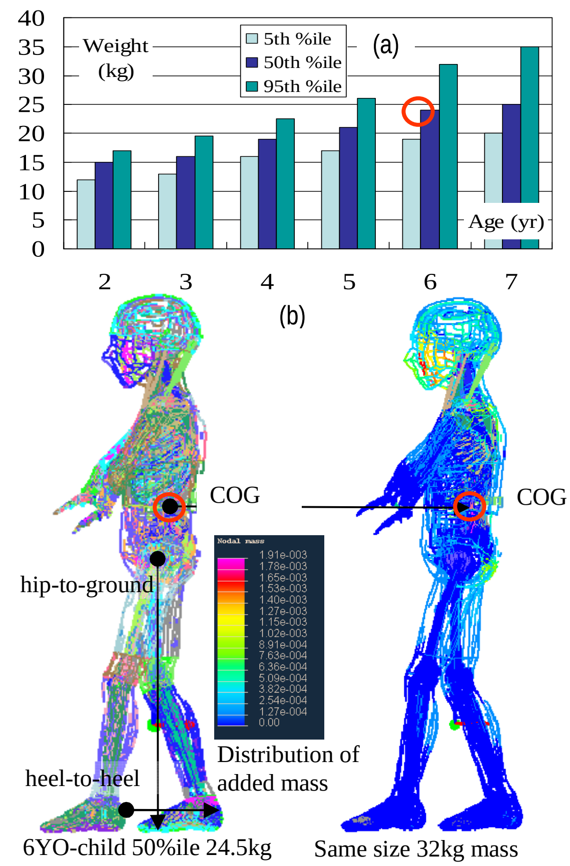


Figure8. (a) Change in weight of child with age (b) Distribution of added mass to convert 6YO-child 50%ile 24.5kg to 32kg mass 6YO-child with same COG.

Effect of COG w.r.t BLE: The change in value of "h_p", i.e., the ratio of pedestrian height with respect to the height of the bonnet leading edge, has maximum influence. The higher is the value of "h_p" ratio, the longer is the value of HIT. This is due to the increase in inertia with longer lever-arm and larger mass of the free region of the upper body above the BLE of the vehicle.

Effect of spine stiffness: Lateral bending and lateral shear and torsional deformation of the spine also influences the value of HIT to some extent, approximately 2-4%.

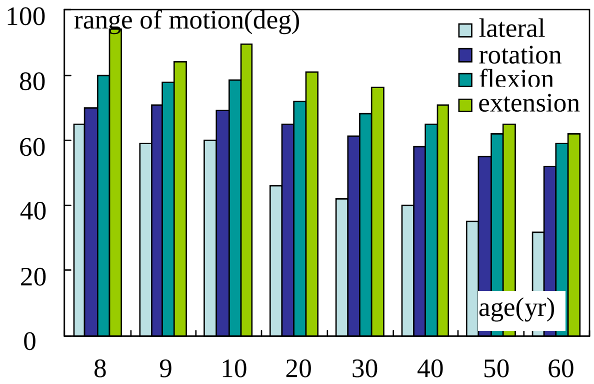


Figure9 Cervical range of motion with age [12].

Effect of upper extremity: Simulation results indicate that the shoulder-hood interaction, the degree of constraint and the timing of the shoulder restraint on the hood, will affect the rotational movement of the head especially at the center of vehicle. However, the degree of shoulder interaction is very low in case of bumper corner impact. This interaction is dependent on the initial posture and the initial angle of impact of the pedestrian that will decide what will be the degree of interaction among the shoulder, arm and head in the final phase of the impact.[4, 17].

Effect of location (centerline vs. corner): From FE simulation, it is observed that, the lateral position or location of impact of the pedestrian at the corner of the vehicle has very large influence on the value of HIT. At the initial phase, the pedestrian hits the bumper causing some initial bumper deformation along with an initial increase in the longitudinal contact force FY acting on the lower part of the pedestrian to make him/her lean laterally towards the hood. In case of corner impact, after sometime (t=15msec), the pedestrian slides along the curvature of the bumper and consequently the longitudinal contact force FY acting on the lower part of the pedestrian becomes constant as shown in Figure 11. Unlike the case of corner impact, for the case of impact at the center-line of the vehicle, the reaction force exerted by the deformed front-end profile of the bumper goes on increasing with lateral contact force FX remains almost zero, causing the upper half of the pedestrian above the BLE, to lean more and faster towards the hood. In all the cases of simulations at different angles of impact (-20deg., -10deg., ref:0deg., +10deg., +20deg.) with respect to the longitudinal direction of the vehicle at different speeds of impact (V=30,35,40,45 km/hr), the estimated HIT values at the center line of the vehicle is always less than those corresponding to the impact cases at the left and right corners of the vehicle. The amount of offset distance of the pedestrian with respect to the center line of the vehicle for corner impact cases, is selected in such a way that the head just touches the corner of the hood as shown in Figure11.

It is also observed that the variation of angle of impact hardly has any influence on the shoulder-hood interaction in case of corner impact. In contrast to that, in case of vehicle center-line impact, the variation of initial angle or the initial orientation of the pedestrian about the vertical axis does show some influence on HIT values.

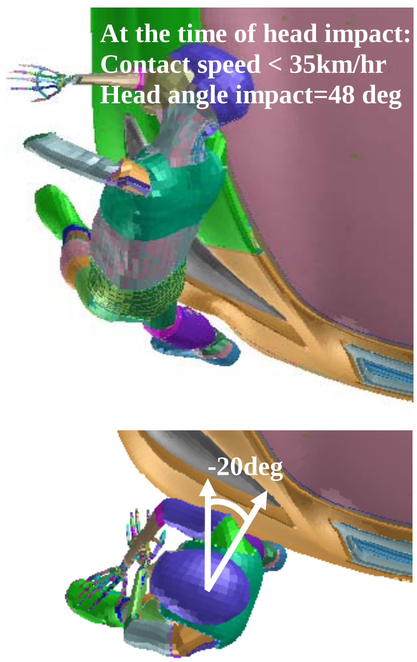


Figure10. Modes of impact at the corner of the vehicle with head contacting just inside the edge of the hood with direction of impact -20deg.

It is also to be noted that at the time when head impacts with hood, for both the locations of impact (at bumper center and corners) the head impact angle of 6YO-child is very close to 50deg. as defined in EuroNCAP test. However, the speed of head contact with the hood is 20-25% less than the initial speed of the striking vehicle. So, one might think of reconsideration of the headform testing speed in accordance with different WAD regions on the hood, based on the results of future research studies for different types of vehicle.

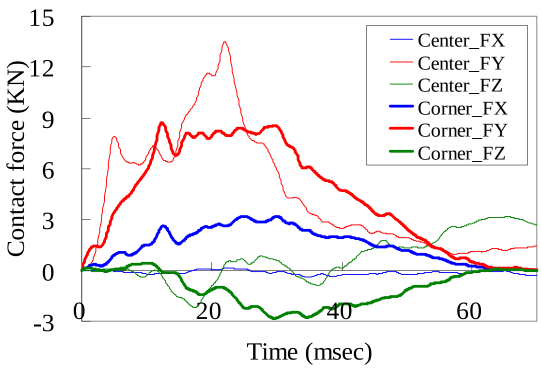


Figure11. Comparison of external contact force in X(lateral), Y(longitudinal), Z(vertical) directions on 6YO-child hit at the center line and at the corner of vehicle at 0-degree angle of impact.

So, reconsideration of testing with the same impactor speed of 40km/hr for different WAD regions may be necessary in future based on the results of more research and studies on different types of vehicle.

CONCLUSIONS

This paper briefly discussed the main factors determining the post-crash pedestrian kinematics based on a detailed study on NASS-PCDS. Those cases are categorized into four types (Type A-D) of post-crash pedestrian kinematics.

The 6YO-child model, developed by accurate scaling of different parts from existing JAMA human adult model is effectively used to identify the main parameters related to head impact time.

Both FE simulation and the PCA of NASS-PCDS data, reveal that the relative position of the bonnet leading edge with respect to the center of gravity of the pedestrian (COG: approx. 55% of the pedestrian height), bumper profile and the speed of impact are the main influential factors in determining the time of contact of head with the hood.

The lateral bending and shear responses of the 6YO-child affects HIT also..

In general, for standard sedan types of vehicle the HIT value for 6YO-child is shortest for the location at the centerline of the vehicle.

It is to be noted that, the range or degree of influence will vary from vehicle to vehicle. However, with respect to an equivalent actual 6YO-child which is more softer and flexible than the present scaled model, the estimated value of HIT calculated by a 6YO-child FE model scaled geometrically from a validated AM50-adult FE human model, will most probably give a conservative or lower-bound estimate of true HIT value.

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