Validation of a Finite Element Human Model Throw Distance in Pedestrian Accident Scenarios

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ABSTRACT

Increasing number of hit and run pedestrian accidents highlights the importance of accident reconstruction tools used in forensic investigations. The tools used nowadays are based on simplified assumption of particle to particle interactions (Searle's model), or real life accidents (Happer's model) which enable for prediction of collision velocity based on pedestrian throw distance evidence obtained at the scene of the accident. Unfortunately, vehicle impact speeds can only be estimated as a range of velocities, as the Searle's model forms a velocity corridor which widens with the increase of measured throw distance giving a large number of predictions.

Development of computing architecture together with the advancement in computer human modelling opens the opportunity for bringing accident reconstruction studies to the next level and reducing the predicted velocities range. Nevertheless, to achieve this, the computer human models need to be reliable and robust. In this study, the Total Human Model for Safety (THUMS) was validated against analytical pedestrian throw distance models.

The validation studies were performed with THUMS 4.01 using 5 different stances, namely: two standing, two walking and one running pedestrian as well as 3 different vehicle impact velocities (20, 30 and 40). Analyses results were validated against Searle's and Happer's throw distance models.

THUMS kinematics agreed well with the current accident reconstruction tools in terms of model behaviour and predicted throw distance. The behaviour of the THUMS model is different for low and high velocity impacts showing good agreement to the field data in terms of body kinematics. In particular, low impact velocities cause wrap projection of the human body, while high impact velocities are characterised by the somersault and fender vaults trajectories of the THUMS model.

1 INTRODUCTION

Pedestrian accidents could be described as a crash event with many different parameters which affect the pedestrian trajectory and throw after collision. Current forensic investigation tools [1] [2] [3] are based on the simplified approach, which predicts car impact velocities from particle to particle interactions and simple impact dynamics, or as a regression model from the statistical data. These models do not consider differences related to car geometries, pedestrian stance, motion and other parameters. Therefore, they do not fully reflect the reality in the best possible way. Development of FEA and increasing power of high performance computers enable for assessment of the pedestrian impact collisions in much more details which should allow for better prediction of the car impact velocities.

In this work, the throw distance of THUMS model is assessed and compared to 2 existing accident reconstruction techniques, namely Happer [1] and Searle [2], in order to investigate whether the throw distance/car velocity FEA predictions are comparable. This would enable for further, more extensive studies which would establish the usefulness of FE techniques in forensic investigations to reduce the velocity scatter provided by analytical models.

1.1 PEDESTRIAN KINEMATICS

Behaviour of the pedestrian after impact will vary depending on the car front end geometry, impact speed and location of the pedestrian centre of gravity (CG). Ravani [4] classifies post impact kinematics of pedestrian into five categories: wrap projection, forward projection, fender vault, roof vault, and somersault.

- Wrap projection occurs when the impacting vehicle is decelerating at the moment of collision. A pedestrian after the collision wraps around the front end of the vehicle. In this type of impact, the pedestrian CG is above the leading edge of the vehicle, as depicted in Figure 1.

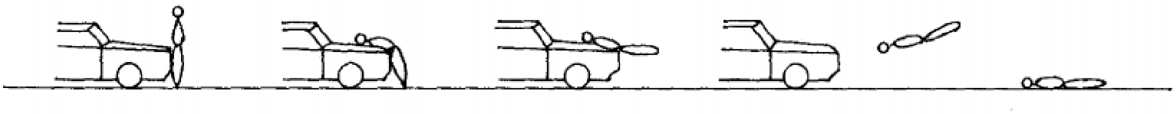


Figure 1 Wrap Trajectory [4]

- Forward trajectory, unlike wrap trajectory, happens when the pedestrian CG is lower than the leading edge of the vehicle. Consequently, the pedestrian is accelerated in the direction of vehicle's motion and projected forward rather than upward. This type of collision becomes more common recently due to increasing popularity of SUV vehicles.

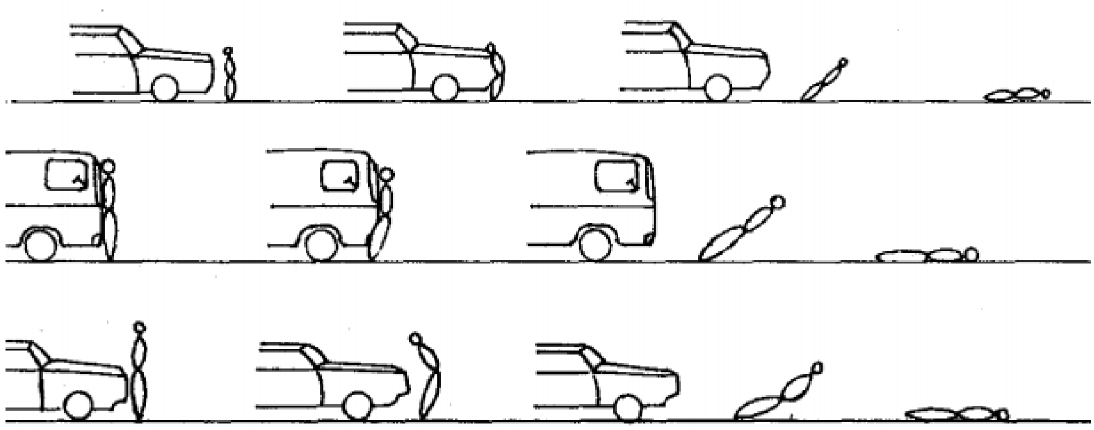


Figure 2 Forward trajectory [4]

- Fender vault collisions occur for braking and non-braking vehicles when the pedestrian collides with the vehicle near the front corner of the car. The position and inclination of impact results in pedestrian going over one of the vaults of the vehicle, as illustrated in Figure *3*.

Figure 3 Fender Vault [4]

- Somersault, shown in Figure 4, is a variation of the wrap trajectory and occurs at higher impact velocities (above 35 mph [5]) when the car is breaking, however the velocity of the car at the collision is still high. Due to the increased impact velocity, the pedestrian is projected into the air and rotates after impact. These types of pedestrian kinematic can result in the secondary contact with the vehicle [5].

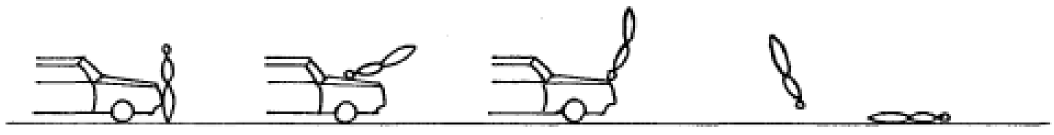


Figure 4 Somersault *[4]*

- Roof vault impact trajectories, illustrated in Figure 5, are another type of wrap trajectories which occur when the pedestrian CG is higher than the leading edge of the vehicle. After the collision pedestrian slides from the hood to the windshield and further to the roof of the vehicle. Depending on the vehicle behaviour (breaking or not breaking) the pedestrian can have multiple contacts with the vehicle before hitting the road. This types of impact usually happens at high impact velocities or in cases of not breaking vehicle [5].

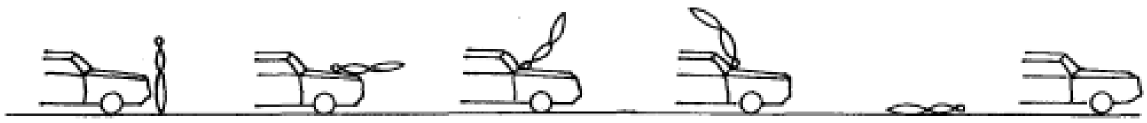


Figure 5 Roof Vault [4]

The injuries sustained by the pedestrian during the collision event are a combination of impacts with the vehicle and the ground. The first impact can be characterised by the contact of the pedestrian with the vehicle. This could be followed by the multiple contacts with the different vehicle parts. For this study, all the contacts between the pedestrian and vehicle are categorised as primary impact.

After primary impact, the pedestrian is thrown into the air due to the transfer of the momentum from the vehicle and falls on to the ground, leading to the secondary impact and further interaction with the ground until pedestrian is brought to rest.

1.2 CURRENTLY USED ACCIDENT RECONSTRUCTION TOOLS

The throw distance measured after the vehicle-pedestrian collision is the distance between the initial impact location, determined by skid marks and debris on the road, and the final position of pedestrian centre of gravity. Based on this distance and the trajectory assumption the vehicle velocity is calculated using different analytical models.

Happer et al. [1] presented the analytical method for impact velocity prediction based on regression analysis of vehicle/pedestrian collisions. The model was developed through investigation of 106 real world collisions, taking into consideration adults and children pedestrians. Regression model proposed by Happer et al. for wrap trajectories is given with equation (1), representing pedestrian impact throw distance excluding SUV collisions.

$$V_v = 12.7(d_t)^{1/2} - 2.6 \quad [\pm 9.0\ km/h] \tag{1}$$

Where, V_v is vehicle impact speed and d_t the throw distance. Happer's model does not take into account road friction coefficient. Note that Happer's corridors for SUVs vary according to equation (2), which is not addressed in this paper.

$$V_v = 11.4(d_t)^{1/2} - 0.4 \quad [\pm 10.5\ km/h] \tag{2}$$

The most commonly used and providing the smallest scatter between the minimum and maximum velocities is a Searle's [6] [2] velocity prediction model (given with equations (3) and (4)). Searle's analytical model is derived from equation of motion of a spherical particle travelling over a surface with ever changing upward reaction force. The equation includes airborne distance, sliding distance as well as bouncing distance travelled by pedestrian in pedestrian vehicle impact. Searle's model accommodates differences in road coefficient of friction.

$$V_{min} = \sqrt{\frac{2\mu g s}{1+\mu^2}} \tag{3}$$

$$V_{max} = \sqrt{2\mu g s} \tag{4}$$

Where, V_{min}, V_{max} are minimum and maximum impact corridor velocities respectively, μ the coefficient of friction, g the gravity constant and s the pedestrian throw distance.

The above models fall under many assumptions and not all car-pedestrian collisions are suitable for prediction of the impact velocity based on throw distance. Figure 6 shows the idealised scenario illustrating which displacement is taken into calculations of impact velocity. Throw distance is the distance between the body centre of gravity and the collision spot, measured along the direction of body throw. Therefore, the correct throw distance for the scenario shown below is 14.5 m.

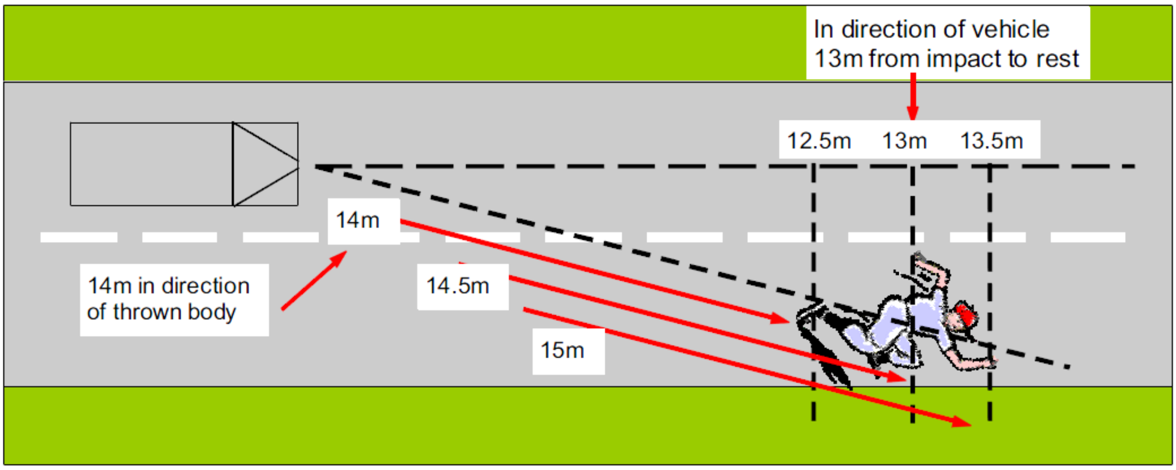
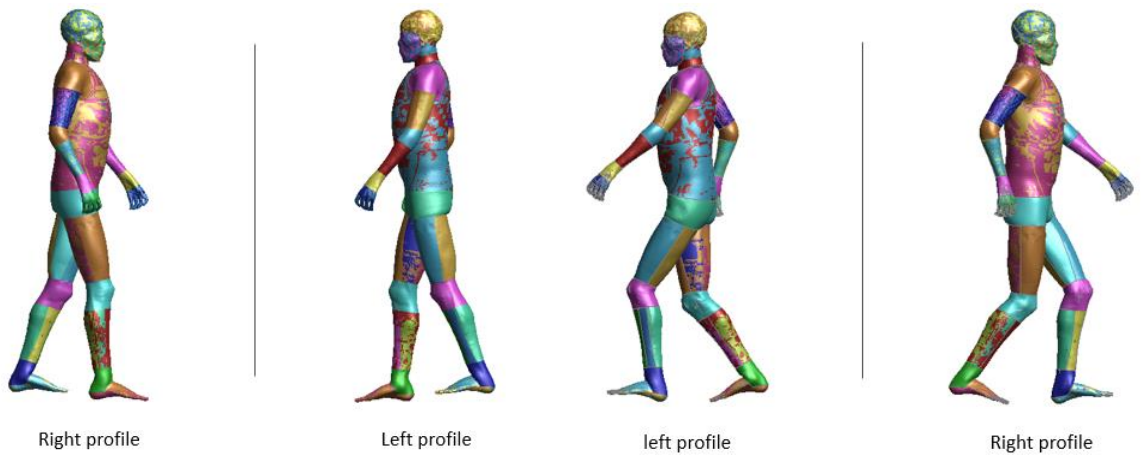


Figure 6 Throw distance measurement [5].

2 Analyses set up

The 50th percentile male Total Human Model for Safety (THUMS) was used to perform the throw distance analyses. Positioning tool created by JSOL [7] was utilised to position the human model to the desired stance i.e. walking and running stances, as illustrated in Figure 7. Five different pedestrian stances were investigated in this study:

- Standing facing the car - SF
- Standing sideways (left side impact) - SS
- Walking (left side impact, right food forward) - WLR
- Waking (right side impact, right foot forward) - WRR
- Running (left side impact, left foot forward) – RLL



Pedestrian walking posture　　　　Pedestrian running posture

Figure 7: THUMS stances

Previous research has reported that ordinary pedestrian walking speeds vary between 1.1 - 1.6 m/s for women and 1.2 – 1.8 m/s for men, and running speeds between 2.0 - 3.7 m/s and 2.6 – 4.6 m/s for women and men respectively [8]. Based on this data, the walking speed was chosen as 1.3 m/s and running as 3.0 m/s for the purpose of the analyses. In both walking and running stances the pedestrian was slightly off the ground.

The Toyota Yaris car model, validated in the front impact against the rigid wall [9], was used to investigate all impact cases. Three car impact velocities were considered: 20, 30 and 40 km/h.

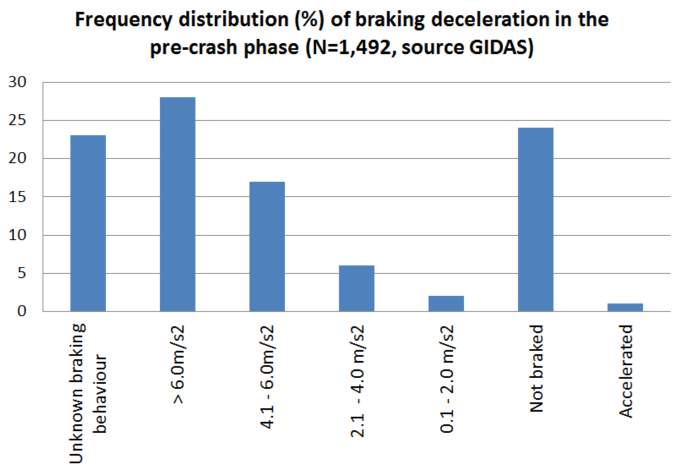


Figure 8: Frequency distribution of braking deceleration in the pre-crash phase [10]

In order to include the most common vehicle behaviour upon impact, the driver's most likely attitude was considered. Previous research produced by GIDAS [10], drivers usually brake prior to impact (50% with 22% cases unknown), as suggested in Figure 8. Consequently, the vehicle braking pattern is modelled using a LOAD_BODY card with a 0.6'g' deceleration pattern applied at the moment of collision. The applied deceleration corresponds to emergency braking which was applied after the first contact with the pedestrian to ensure the correct speed at collision. The full matrix of performed analyses is shown in Table 1.

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Table 1 Pedestrian/car collision cases

Pedestrian stance	SF	SS	WLR	WRR	RLL
Impact speed (km/h)	20	20	20	20	20
	30	30	30	30	30
	40	40	40	40	40

Friction coefficient between the ground and the pedestrian/car was set up with an arbitrary value 0.7 to represent a dry road [3] [2]. The road was assumed to do not undergo any deformation and therefore was modelled as a rigid wall.

Depending on the impact velocity, the termination time was set to 2.5 – 4.0s to enable for the pedestrian to rest on the ground. The plot output interval was set to 0.05s, which enabled for sufficient number of plots to measure and capture the post impact pedestrian behaviour.

3 RESULTS

3.1 THUMS 4.01 TRAJECTORY

As mentioned, the pedestrian post-impact trajectory is influenced by many factors from which the following parameters play major role: car geometry, impact velocity as well as the stance. In all the analyses shown in this research the car geometry is kept constant, therefore this factor does not change.

Figure 9 Pedestrian wrap around trajectory

Figure 9 shows the 20 km/h WRR analysis which resulted in a wrap trajectory. As the car and pedestrian get into contact, the pedestrian body wraps around front end of the vehicle. The vehicle's momentum is transferred to the body and the car velocity is reduced due to braking. The two bodies then separate as the velocity of the vehicle becomes lower than the human body. The pedestrian rotates around it's centre of gravity until it lands on the ground. In the analysis, the pedestrian legs contact the ground as first, which is in good agreement to the findings of police experts [5].

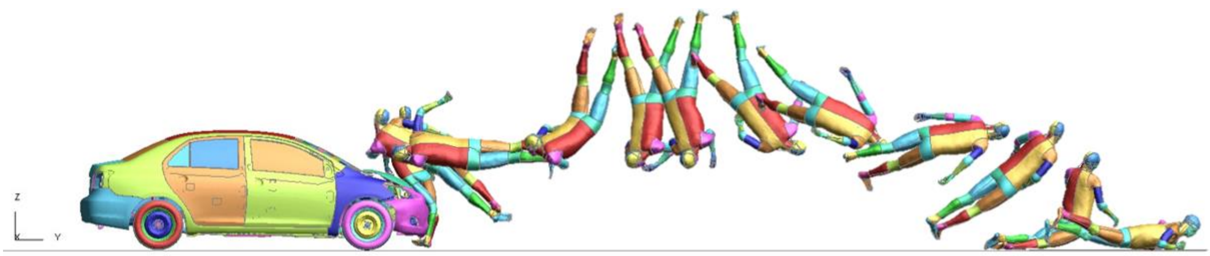
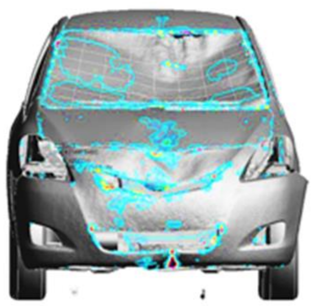
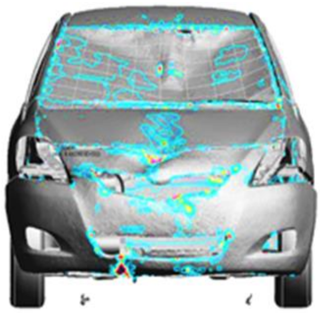
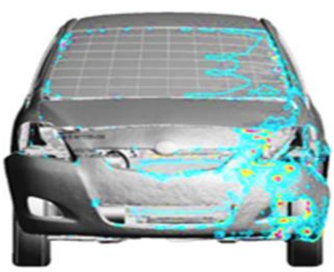
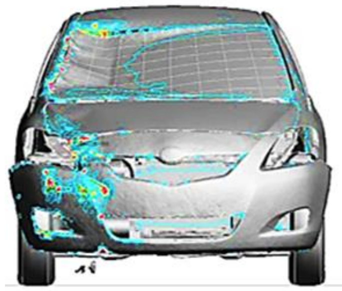


Figure 10 Pedestrian somer sault trajectory

A pedestrian trajectory for WRR 40 km/h collision is illustrated in Figure 10. The trajectory can be categorised as a somersault. The contact between the car and pedestrian is characterised by initial wrap around followed by significant body rotation due to the vehicle momentum transferred to the pedestrian. Higher impact velocity causes the pedestrian to be projected into the air in the direction of the car motion. Due to higher rise in the air, the pedestrian rotates post impact causing almost full body rotation before contacting with the ground. In this scenario, the pedestrian rotated approximately 300^{o}. The first body parts in contact with the ground were the lower extremities. Depending on the car velocity, a somersault trajectory may lead to the pedestrian to impact the ground with the upper body part (torso) and head.

In both cases showed in Figure 9 and Figure 10, the pedestrian post impact trajectory was in good agreement to the behaviour described in literature [5] [4].

Table 2: Comparison of vehicle damage due to head impact (real-life vs THUMS impacting Toyota Yaris)

West Midlands Police Dataset		Computer model prediction Pedestrian hit left foot first	Computer model prediction Pedestrian hit right foot first
(36mph)			
(40mph)			
(30mph)			

The pedestrian head impact location was compared against selected real-life accidents, illustrated in Table 2. It can be observed that for the impact speeds above 46km/h that the pedestrian hits the windscreen in a comparable location. The pictures shown in Table 2 suggest that the THUMS kinematic responses are realistic.

3.2 VALIDATION OF PEDESTRAIN THROW DISTANCE

The throw distance was measured using the pedestrian CG's displacement, as recorded by West Midlands Police (WMP) [5]. The THUMS 4.01 throw distance is measured by calculating the maximum displacement of the human model CG (node 89021890) in the plane parallel to ground.

In order to stabilise the model at higher velocities and avoid negative volumes, all the THUMS solid element formulations was altered from fully integrated to under-integrated with a stiffness based hourglass control set to 0.05.

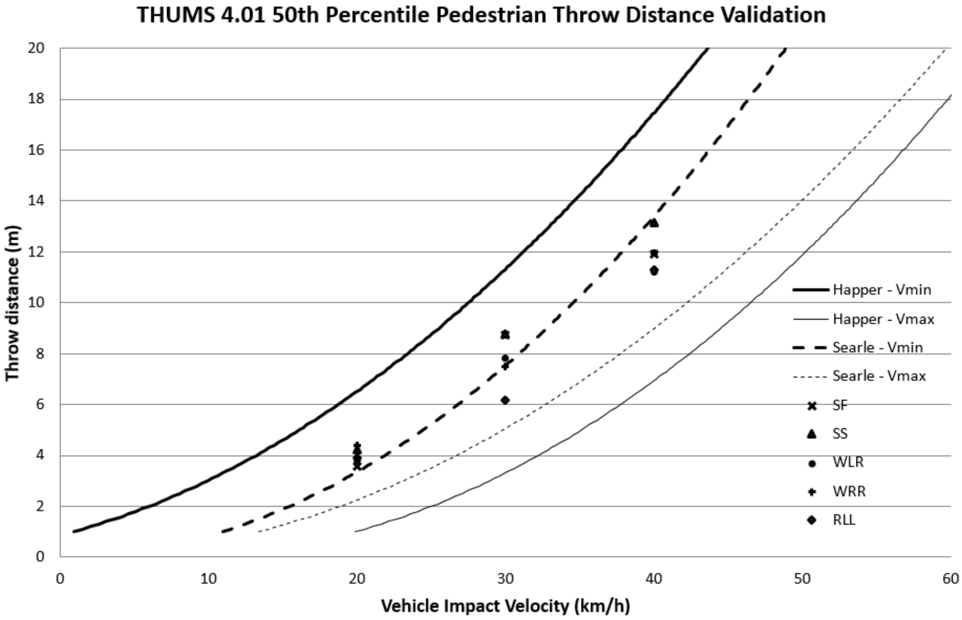


Figure 11: THUMS model throw distance vs. velocity

From the data presented in Figure 11, it can be observed that the THUMS human model throw distance predictions are in good agreements with the real-life responses observed by Happer as the responses fall within the corridor.

Regarding the Searle's corridor, for speeds less than 40km/h, the throw distances fall outside the corridor, while at higher impact velocities the computer predictions agree with the Searle's theoretical envelope. It can be noticed however that the pedestrian kinematics reflect Searle's equations, as depicted in Figure 12 and Figure 13.

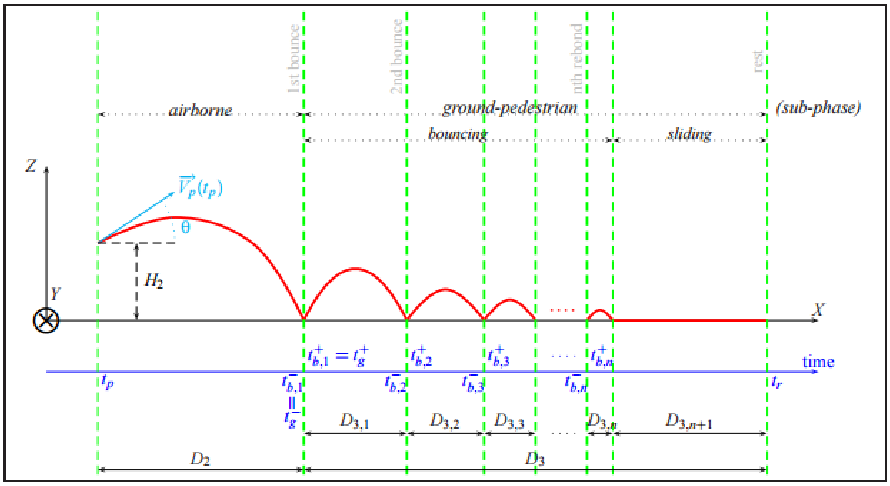


Figure 12: Theoretical kinematics computed from Searle's equations

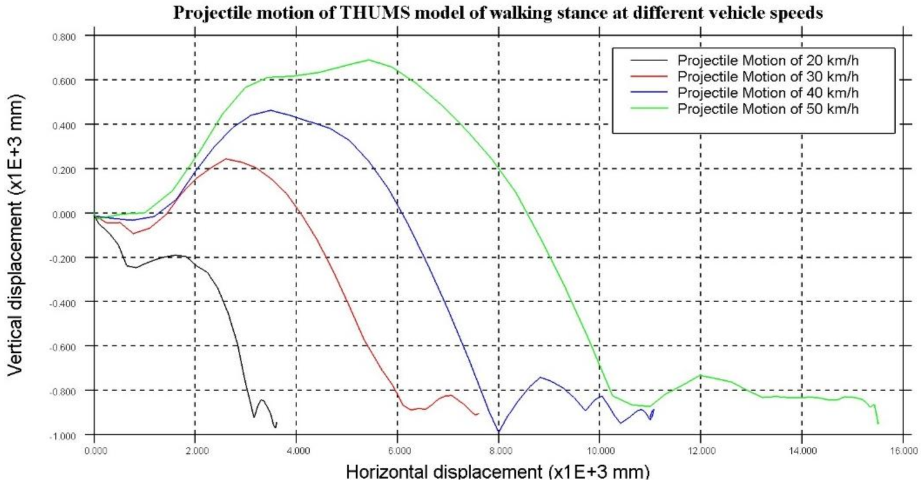


Figure 13: Projected motion with walking stance

Looking at the Searle's equations (3) (4), it can be noticed that the vehicle stiffness and compliance are not considered, as well as the pedestrian anthropometry and walking speed. As the Searle's equations relate to the motion in one plane, it can be suggested that at lower speeds, the difference in relative motions between the pedestrian and the vehicle is greatest, while at higher speeds, the vehicle velocity is much higher than the pedestrian crossing speed. Consequently, the pedestrian throw distance responses are more similar at higher speeds than lower speeds.

During a vehicle to pedestrian impact, the entire kinetic energy is also transferred to the pedestrian who then deforms the structure. Because of the vehicle architecture, the deformation energy capability is capped, unlike the impact kinetic energy. Consequently, at lower speeds, the deformation energy may have more influence on the pedestrian relative to the vehicle impact energy, while at higher velocities, the kinetic energy, velocity squared, is much greater than the capped deformation energy. Consequently, at higher speeds, the impact scenario involves mainly momentum transfer which is exactly what the Searle's equations relate to and which is replicated using THUMS. This statement would lead to conclude that the THUMS throw distance at lower speeds would be smaller than the Searle predictions, as the system is conservative, i.e. the energy remains constant during the whole accident. The rebound kinetic energy would be expected to be lower than the initial vehicle impact kinetic energy, as the deformation energy would generate a loss. This would consequently generate a lower exit speed from the bonnet, hence would yield to lower throw distance than Searle's equations. However, the results suggest otherwise, as illustrated in Figure 11. It can be proposed that at lower velocities, the pedestrians may wrap longer on the bonnet, suggesting the vehicle styling could play a role at lower speeds; this parameter is not included in the Searle's model [5].

As discussed, the throw distance computation is a complex problem which would require more research to investigate the specific effects of pedestrian crossing speed, vehicle speed, shape and stiffness. As the THUMS human model meets the Happer real-life accident corridors (Figure 12), as well as the Searle's throw kinematics (Figure 13), it can be proposed that, in this specific study where the vehicle is braking straight after the collision, the THUMS human model is a good candidate to compute in a believable manner the pedestrian throw distance.

4 CONCLUSIONS

Pedestrian kinematics and throw distances have been computed using THUMS 4.01 by replicating various accident scenarios based on a Toyota Yaris FEA computer model travelling at various speeds (20km/h, 30km/h, and 40km/h) and braking at 0.6'g' immediately after contacting the pedestrian. The pedestrian was static, walking or running across the vehicle

prior to collision. In this accident configuration, it was observed that the THUMS 4.01 model responses complied with Happer's throw distance/ velocity regression model. It was also observed that THUMS also met the Searle's corridors for velocities greater or equal than 40km/h, as well as the predicted flight behaviour.
It can be concluded that, in this specific accident scenario, human models can be used as an accident investigation tool for pedestrian kinematics assessment, provided that geometry and vehicle stiffness can be obtained as well as stance and crossing speeds during the accident event.

5 FURTHER WORK

Following this study, it would be beneficial to investigate more accident scenarios, like changing the vehicle braking behaviour as well as changing the vehicle class to investigate whether the THUMS model still performs within real-life corridor responses.

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