

PEDESTRIAN RECONSTRUCTION USING MULTIBODY MADYMO SIMULATION AND THE POLAR-II DUMMY: A COMPARISON OF HEAD KINEMATICS

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ABSTRACT

The aim of this study was to reconstruct three pedestrian collisions with multi-body simulations using the computer program MADYMO and the Polar-II dummy. In this paper, we compare the head kinematics of the computer simulation and the Polar-II test with reference to the vehicle-pedestrian contacts in the actual cases. We also discuss aspects of the reconstructions made using these different tools, especially findings on the velocity trajectory of the head. The cases selected for reconstruction were ones in which the pedestrian's height and weight were close to the 50th percentile adult human male, and where the accident investigation provided good estimates of impact speed and complete injury data. The cases were investigated to estimate the speed of the vehicle at impact and the position of the pedestrian relative to the vehicle. Contact points between the vehicle and pedestrian were recorded. From this information MADYMO simulations were made to estimate the kinematics of the pedestrian during the collision. We then reconstructed each case using the Polar-II full-scale pedestrian dummy. Results showed that some aspects of the head kinematics were in good agreement but, generally, Polar-II head impact angles were steeper and the head impact location was more forward than the location suggested by the simulations and the cases themselves. Leg kinematics were noticeably different, with the Polar-II legs remaining engaged with the front of the vehicle for a longer period of the collision. In contrast to the simulations, the Polar-II legs were in some instances still engaged as the head struck the vehicle.

INTRODUCTION

Subsystem pedestrian tests form the basis of regulation and consumer tests related to pedestrian safety (for a reference, see EEVC, 2002). From a vehicle development point of view, subsystem tests are useful for certain aspects of passive safety development and in the improvement of the vehicle

design against the benchmark of regulatory standards. They are of more limited value for rigorous testing of advanced active and passive safety devices and do not reveal unintended interactions between aspects of vehicle design. Therefore, a valid pedestrian dummy would provide an important and useful tool to study the interaction between the vehicle and the human body in a collision.

For example, it would be counterproductive if the velocity of the head were increased on impact by designing a vehicle to protect the knee from a rupture to the medial ligament (a relatively rare occurrence). As such, interactions between contacts in pedestrian collisions are important. Also, some devices that are being developed to protect pedestrians use sensing to trigger them (Fredriksson et al., 2001) and must also bear the load of the torso as well as the head in the collision. The development and refinement of such safety interventions will benefit from an adequate pedestrian dummy. Computer simulation can reveal many important interactions in pedestrian tests, and simulation is being used more-or-less successfully to reconstruct actual pedestrian crashes (eg. Konosu, 2002; Depriester et al., 2005; Yang, 2003; Yang et al., 2005; Anderson et al, 2002; Anderson et al., 2003). These simulations are difficult to validate, but the performance of the model against PMHS tests and a correspondence between contact points in the actual case and in the simulation can provide a guide. Usually, the pattern of contact between pedestrian and vehicle can be explained with such simulations and so we have tended to view such tools as reliable when used carefully. However, these tools do not negate the value of an adequate pedestrian dummy for testing the design of vehicles.

Polar-II is a pedestrian dummy developed by Honda R&D Ltd., in conjunction with GESAC Inc. The development of this dummy is described in Akiyama et al. (2001). Experience with the use and evaluation of this dummy is being used to guide the

development of an SAE pedestrian dummy standard.

Ultimately, the requirement of any simulation or test tool is the same – to represent a pedestrian in a collision, to allow the measurement of the response of the structure being hit, and a measure of the risk of injury that the impact produces. Obviously, there should be some relationship between the results of tests with a pedestrian surrogate and the consequences in an actual accident. And given the parallel roles of sub-system tests and any future work in which a pedestrian dummy might be used, we are interested in examining how the results of sub-system tests compare with the results of dummy tests, and how each of these compare with injuries actually suffered in accidents. We have previously reported on the ability of the subsystem tests to discriminate injurious pedestrian impacts (Anderson et al., 2002 and 2003).

Some recent papers have reported on the performance of the Polar-II dummy in simulated pedestrian collisions. Kerrigan et al (2005a; 2005b) compare the kinematics of the dummy with PMHS tests in collisions with a small sedan (Kerrigan et al., 2005a) and with a sports utility vehicle (Kerrigan et al., 2005b). While Kerrigan et al. concluded that the biofidelity of the Polar-II was good overall, the comparisons showed some trends:

- The wrap-around-distance for the head strike was 15- 20% shorter in Polar-II tests on the small sedan. This difference was smaller in the SUV tests - around 5-10%.
- In sedan tests, the head velocity profile of Polar-II did not match the cadaver velocity profiles: The dummy head achieved higher peak speeds but the speed of the head was lower on impact than the cadaver head speeds. In SUV tests, the velocity profiles matched more closely.
- The velocity of the Polar-II head exhibited a larger vertical component on impact in all tests
- In sedan tests, the head of the Polar-II struck the vehicle surface earlier than the PMHS subjects. The average timing of head strike in PMHS tests was 140 ms after first contact, and 126-131 ms in Polar-II tests. In SUV tests, timing was almost identical.

In 2003, we had an opportunity to replicate, with Polar-II, reconstructions of crashes that we had investigated at the scene and reconstructed using our multi-body pedestrian model and subsystem impact laboratory. These cases were well documented with good injury data and so they were useful candidate cases to reconstruct with Polar-II,

the output of which could be compared with the injury.

In this paper, we compare the kinematics of Polar-II with our multi-body simulations (in MADYMO) and the evidence of contact in the crash. We intend to report more fully on the comparison of the kinetics of the Polar-II collision and the injuries in these cases in a subsequent publication.

AIM

The aim of this study was to compare the head kinematics of actual pedestrian collisions with reconstruction using MADYMO multi-body simulation, and from Polar-II reconstructions.

MATERIALS AND METHODS

Accident data

The three cases used for this study were pedestrian accidents investigated by the Centre for Automotive Safety Research (formerly known as the Road Accident Research Unit). The cases had been studied as part of a research program that includes the study of brain injuries in automotive accidents and studies that were designed to characterize injuries to pedestrians more generally. This program has collected data on over 500 pedestrian accidents since the late 1970s.

We selected cases for this study using the following criteria:

- The size and weight of the pedestrian were close to the 50th percentile human male. This was to ensure that the Polar-II dummy could adequately represent the stature of the pedestrian in the reconstruction.
- The physical evidence (dents and scrapes on the car, injuries to the pedestrian) clearly revealed the kinematic trajectory of the pedestrian. This was to ensure that the MADYMO simulation could be verified, and hence the head impact speed in the sub-system test and the initial position and trajectory of the Polar-II dummy.
- The vehicle was the substantial cause of any head injury suffered by the pedestrian.
- The speed of the vehicle could be estimated. This was used as an initial condition in the MADYMO simulation and the Polar-II test.

The accidents are summarized in Table 1.

Table 1 Details of cases reconstructed for this study

Case	Vehicle Details			Pedestrian details			
	Year	Model	Impact Speed ¹	Age	Sex	Weight	Height
Case 1	1992	Ford Fairmont	33 km/h	52	M	75 kg	178 cm
Case 2	1973	Holden Torana	55 km/h	75	M	75 kg	175 cm
Case 3	1983	Holden VK Commodore	60 km/h	35	M	81 kg	178 cm

¹Speed used in the simulation and the Polar-II test

In cases we investigate, the scene of the accident is surveyed, and the lengths of any skid-marks left by the vehicle are measured, and the location of the impact point and final position of the pedestrian, scuff marks on the road, debris, and any other feature of relevance are noted. The speed of the striking vehicle is estimated from the evidence left by the braking vehicle and the trajectory of the pedestrian.

If the pedestrian is fatally injured, a member of the crash investigation team records injuries at autopsy, and their height, weight, and the dimensions of various body segments are measured.

In cases where the pedestrian's injuries are not lethal, the pedestrian is interviewed and asked to describe their injuries and the circumstances of the collision. Further information on the pedestrian's injuries is obtained from their hospital medical record. The South Australian Trauma Registry is also consulted in cases where data on the pedestrian's injuries are not complete.

The crash investigators inspect the striking vehicle for signs of contact with the pedestrian, such as dents, scratches and scuffs on the surface of the vehicle. The location of the head contact is identified by a dent in a panel or cracks in the windscreen, and often by the presence of hair on the contact area. The location of each contact is measured from defined datum points, replicable in the laboratory later. In the three cases reported here, these records were used to check the simulation of the collision with the MADYMO model and the Polar-II.

The following sections give an overview of the simulation, and Polar-II reconstructions and the methods used to evaluate the results.

Computer simulation

Each of the three cases was simulated by computer using a MADYMO model that represents the 50th percentile human male. (Adjustments were made to the model to reflect actual anthropometry using a tool based on GEBOD; Baughman et al., 1983) The model was described by Garrett (1996; 1998), and has been used for simulating accidents from data collected during accident investigation (Anderson

et al., 2000; Anderson et al., 2002; Anderson et al., 2003).

The model as a whole has been validated using the results of cadaver tests (Garret, 1998). Recently, the neck of the model has been improved to better represent the response of the neck in frontal and lateral directions reported by Thunnissen et al. (1995) and Wismans et al. (1986).

Implementation of the model in the simulation of the accidents

Vehicles identical to the make, model and series of those involved in the cases were obtained, and the geometry of the cars were measured using a digital theodolite using a process we have described before (Anderson et al., 2003) and the measured geometry was used as a basis of the vehicle model in MADYMO. The geometry was then approximated by a series of planes, elliptical cylinders, and ellipsoids. Contact stiffnesses for the vehicle were based on Ishikawa et al. (1993).

In setting the initial posture of the pedestrian, we ignored both the walking velocity and the velocity of the limbs during locomotion. The orientation of the pedestrian can often be estimated either from statements from the pedestrian themselves or from drivers, witnesses, and/or marks on the body. The impression of the bumper or other component often indicates the orientation of the pedestrian, and the alignment of marks often indicated the position of limbs and torso as they were struck. Sometimes, it is not possible to determine the exact posture of the pedestrian, so simulations are made that cover the possible range of postures in the accident, or using postures covering a human gait cycle (Anderson et al., 2005). However, for this study, after performing simulations representing the gait cycle, a single simulation was designed that was subjectively judged by the authors to represent the accident most closely, based on the match between contact locations and marks left on the vehicle. This was necessary, as the Polar-II reconstruction would be set up to match the initial conditions set in the simulation. Variations in head impact conditions due to changes in gait are described in Anderson et al. (2005).

Polar-II reconstructions

The tests were conducted at the Japan Automobile Research Institute (JARI) in Tsukuba, Japan and at the Honda R&D crash test facility in Tochigi, Japan. We are very grateful to the staff of both organisations in making their facilities available and performing the tests on our behalf, and providing data from each test.

In each test, the dummy was set in a posture that matched the initial position of the pedestrian in the simulation. Data on joint angles and segment positions relative to the front of vehicle were provided to the test engineers. Because the dummy was designed to be struck on the left-hand side, the dummy positioning was the mirror image of the crash in two cases where the pedestrian was struck on the right.

Coordinated high speed film, shot in the three principal orthogonal planes, provided estimates of the velocity of the dummy and its component parts, and 44 channels of data were collected on loads and accelerations to various parts of the dummy.

The Polar-II head trajectory was calculated from video analyses of the test: the displacement of the centre-of-gravity and the vehicle was tracked using high speed video which was taken from three orthogonal views giving the three components of displacement. The velocity of the head and the vehicle was estimated using a Simpson's rule method and then subjected to centred five-point smoothing. The vehicle velocity was then subtracted from the Polar-II head velocity to produce an estimate of the time varying velocity of the dummy head relative to the vehicle. Corresponding data from the simulations were extracted from the model results.

We report the head velocity data in two ways: head speed versus time and head speed versus the angle of the relative velocity to the horizontal. Typical figures are shown in Figure 1 and Figure 2. The annotations in Figure 2 correspond to typical phases in the trajectory of the head: (a) as the car strikes, the relative velocity is equal to the velocity of the car. The relative speed of the head is nearly constant, and only the angle of the velocity is changing for a period after the initial contact. (b) As the upper body of the pedestrian is put under tension, the head accelerates rapidly. After this acceleration, the centre of gravity of the head moves in a circular motion toward the upper surface of the car, slowing slightly just before contact (c). This point is marked on the plot with an "o". After the initial contact the head rapidly loses all vertical speed, and hence the velocity's

locus rapidly returns to the horizontal before the head rebounds. The angular position of the impact point in Figure 2 reveals the contribution of horizontal and vertical components in the impact velocity.

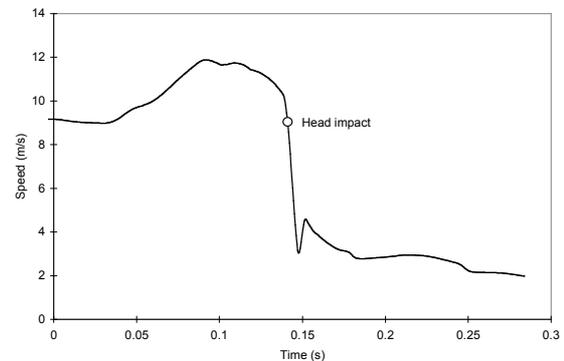


Figure 1 An example of head speed over the duration of a pedestrian impact.

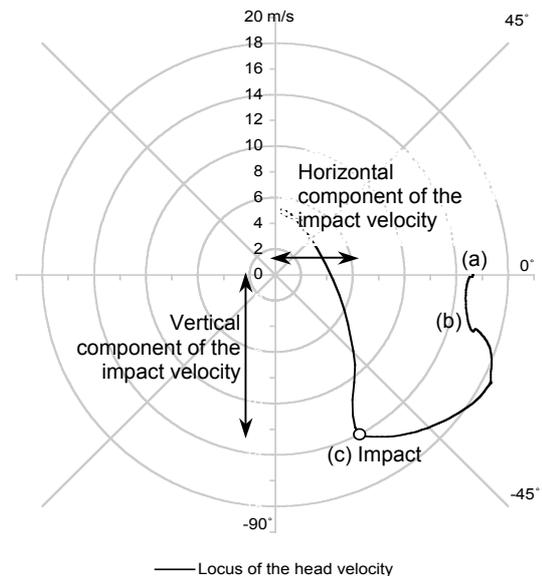


Figure 2 The locus (speed and angle) of the velocity of a pedestrian's head in a collision with a car.

Finally, we can compare the trajectory of the head relative to the vehicle produced by the simulation with the trajectory of the Polar-II head. A common way to present this is a plot of the vertical position against the horizontal position of the head. Trajectory data in Polar-II tests were calculated relative to the vehicle using the system described by Kerrigan et al. (2005a and b) with one difference – the origin of the vehicle coordinate system was centred on the ground, with the horizontal origin aligned with the most forward point on the vehicle. We wanted to ensure that trajectories were comparable with respect to the vehicle, reflecting actual head impact locations. Therefore, small differences between the

simulation and the Polar-II, in the initial horizontal position of the head relative to the vehicle, were accounted for.

RESULTS

Case 1: Case number PED043

The pedestrian was near the centre line of the road when he stepped backwards into the path of a vehicle travelling in the right-hand (inner) lane of a two-lane road. The pedestrian was struck by the front right-hand headlight of the vehicle and was thrown onto the bonnet, striking his head near the back of the bonnet before being thrown to the road by the impact.

The pedestrian died as a result of the collision. He experienced loss of consciousness at the scene, paramedics rating his loss of consciousness with a Glasgow Coma Score of 4-5/15. His airway and circulatory systems were also compromised. His most significant injuries were:

- A fracture to the right parietal bone and the base of the skull (open and closed),
- An extradural and subdural haematoma and other brain haemorrhages and contusions,
- A splenic laceration,
- Fractured ribs to his right side (5-7), and
- An open 30 mm laceration to the right hip and contusions to the right ankle.

The position on the road at which the pedestrian was standing when struck was identified from the presence of a scuff-mark that was caused by the twisting and sliding of the sole of the pedestrian's shoe as the vehicle struck his leg. The distance that the pedestrian was thrown implies an impact speed of approximately 33 km/h. The damage to the right front of the vehicle (Figure 5) suggests that it was these structures that caused the wounds to the pedestrian's thigh and hip. The significant depression in the right trailing edge of the bonnet was a result of the impact between the bonnet and the head of the pedestrian.

MADYMO simulation: An Australian 1992 Ford Fairmont was obtained for the physical reconstruction of this collision. The car was measured to obtain the geometry of the vehicle for the MADYMO simulation (Figure 3). The initial position of the pedestrian is shown in Figure 4.

Rather than simulations representing the gait cycle, two simulations were designed to represent a pedestrian taking a step backwards (left foot down and right foot down). The kinematics of the collision in these two simulations showed a significant involvement of the pedestrian's right arm in the collision. To see what effect this may

have had on the head impact velocity, two further simulations were run. In these simulations, the right arm of the pedestrian was raised slightly and positioned forward of the trunk of the body to minimise its involvement in the kinematics as the collision progressed. There was little effect on the head impact velocity, however, and so the right arm was raised slightly in the final simulation and in the Polar-II test to avoid any complications arising from arm involvement.

Polar-II reconstruction: The initial dummy position is shown in Figure 4. The position was set to match the initial position of the MADYMO simulation. The dummy was struck at 33 km/h

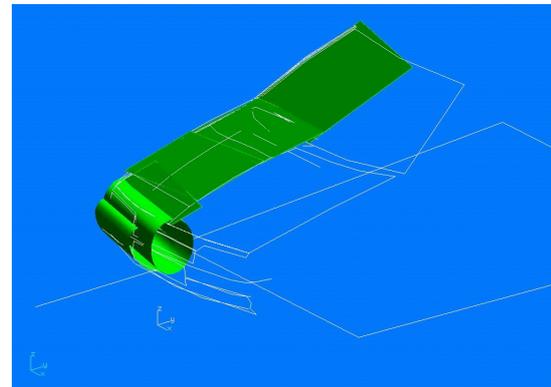


Figure 3 Geometry of the vehicle in Case 1 (shown in white). The approximation of this geometry for the simulation is shown by the shaded geometric entities.

MADYMO and Polar-II results: The results of simulation and the Polar-II test are shown in Figure 5 through Figure 7. Figure 5 compares the damage caused in the actual collision with that produced in the Polar-II test. Figure 6 shows three graphs that summarise the kinematics of the head and Figure 7 shows comparisons of the positions of the simulation and Polar-II at two time points during the collision.

Several things are notable about Figure 6.

- The head impact speed in the MADYMO simulation was higher than that recorded in the Polar-II test: 12.5 m/s (138 ms after first leg contact) compared with 5 m/s (144 ms after first leg contact). The impact speed of the vehicle was 9.2 m/s.
- The difference in the head impact velocity contains differences in both the horizontal and the vertical components of the velocity.
- The angle of the head impact in the Polar-II test was slightly beyond the vertical, meaning that the head velocity has a small component toward the front of the car. Examination of the video reveals that the neck was in extension on head impact, and it appears that the tension in

the neck decelerated and rotated the head prior to impact.

- The Polar-II head trajectory and velocity were similar to the simulation for the first 100 ms. At 80 ms (Figure 7) it is apparent that, apart from a difference in the amount of sliding over the vehicle surface, the position of the dummy and the model are similar. By 120 ms, differences are becoming apparent: the dummy appears less flexible through the torso, and the neck and head appear to have realigned with the torso, something that happens only just before impact in the simulation. The difference in the amount of sliding is increasingly obvious, with the knees of the Polar-II still forward of the leading edge of the vehicle.
- The Polar-II head impact location was about 200 mm forward of the simulation head impact location, although a comparison between the damage with the case vehicle (Figure 5) shows that the location was slightly rear of the actual case impact location. Damage to the leading edge was less in the Polar-II test than in the actual case.

Case 2: Case number H032

Description: The vehicle was travelling in a westerly direction on a three-lane road in the left (outer) lane. The pedestrian was crossing the road in a southerly direction. The driver said that he was travelling at no more than 55 km/hr when a vehicle following about 10 metres behind in the right hand lane distracted him. He looked in his right side rear view mirror, and it was at that point that the windscreen of his vehicle shattered. At no time prior to the accident did he see the pedestrian and did not take any evasive action.

The pedestrian died as a result of the collision. Reported movements indicate that the pedestrian would have been hit on his left side and his injuries were consistent with this. There were lacerations and bruises to the left aspect of both legs and on the left arm. The leg injuries indicate that the legs were apart at impact, with the right leg leading. The bruise on the outside of the left knee was at the same height as the front edge of the bonnet, which was noticeably dented to the left of the centre line. The head of the left femur was displaced into the acetabulum indicating a very forceful impact at that location.

Injuries to the pedestrian and damage to the vehicle indicate that the pedestrian was struck by the left front of the car and was thrown up over the bonnet, and his head struck the left side of the windscreen. As there was laceration and bruising to the occiput, he might have rotated slightly away from the car during the vault. His head also hit the dash

underlying the windscreen, where a dent was noticeable. We estimate, from the projection distance, that the impact speed was consistent with the comments of the driver: 55 km/h.

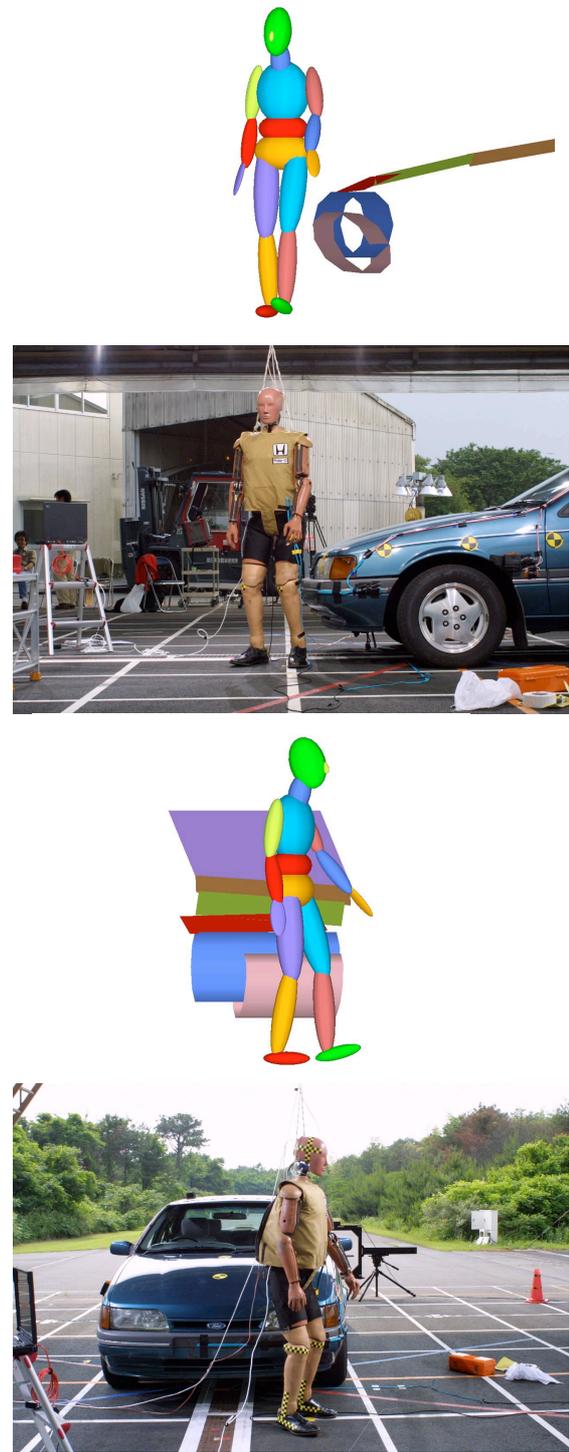


Figure 4 Positioning of computer simulation model and Polar-II dummy in Case 1



(a)



(b)

Figure 5 Damage to (a) the leading edge caused by the actual collision (*top*) and the Polar-II test (*bottom*), and (b) the trailing edge from the head impact in the actual case (*top*) and the Polar-II reconstruction (*bottom*) in Case 1.

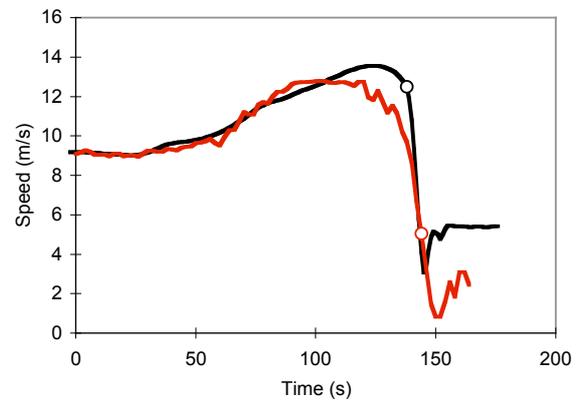
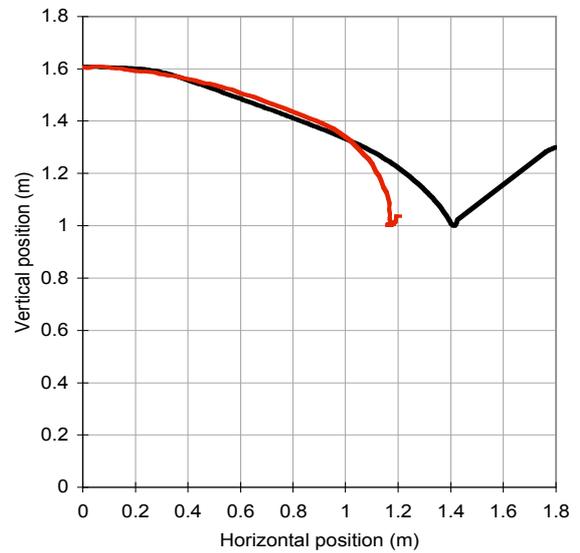
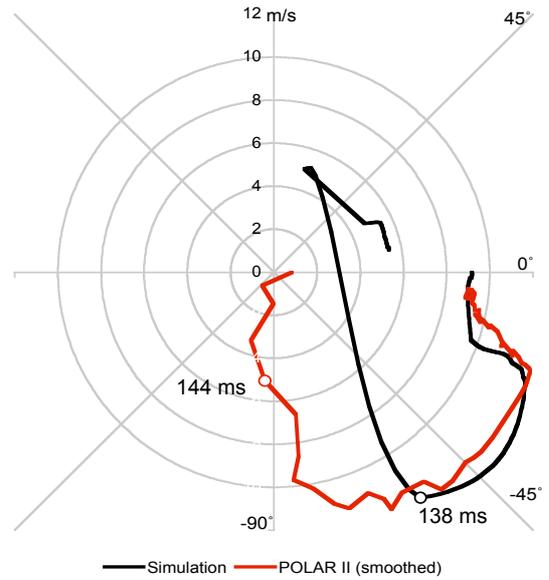
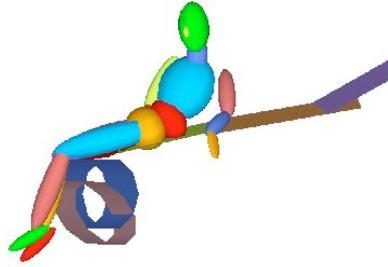
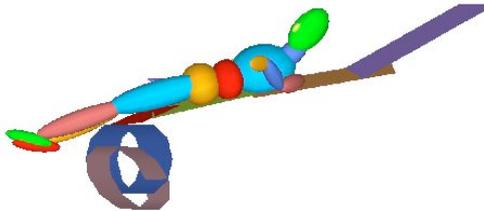


Figure 6 (*top to bottom*) radial head velocity trajectory, head position trajectory and head velocity history for Case 1. Polar-II data are red and simulation data are black. The hollow circles represent data points associated with head impact.



(a)



(b)

Figure 7 A comparison between the MADYMO simulation and the Polar-II test at (a) 80 ms and (b) 120 ms.

MADYMO simulation: A 1973 Holden Torana was obtained for the physical reconstruction of this collision. The car was measured to obtain the geometry of the vehicle for the simulation. The geometry was represented by a series of planes and elliptical cylinders, as illustrated in Figure 8.

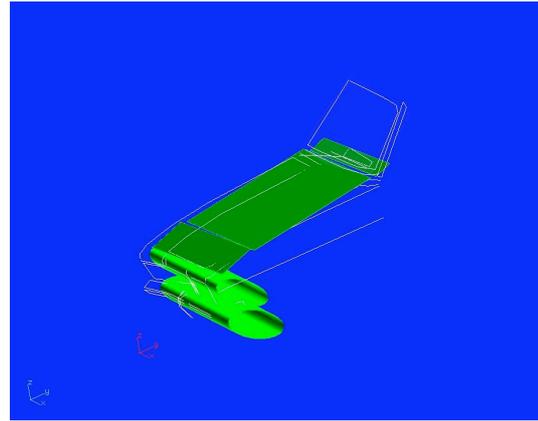


Figure 8 Geometry of the vehicle in Case 2 (shown in white). The approximation of this geometry for the simulation is shown by the shaded geometric entities.

Polar-II reconstruction: The initial dummy position is shown in Figure 9. The position was set to match the initial position of the MADYMO simulation.

Comparison of MADYMO and Polar-II results: The results of simulation and the Polar-II test are shown in Figure 10 through Figure 12.

Several things are notable about Figure 11.

- The head speed at impact and the timing of the impact were almost identical in the Polar-II test (13.8 m/s at 100 ms) and the simulation (14.0 m/s at 103 ms).
- There were, however, differences in the components of the velocity. The Polar-II head velocity was slightly beyond vertical at impact. The radial plot of the simulation shows that the head impact velocity in the simulation included about 6 m/s in the horizontal direction.
- The Polar-II head impact location was about 400 mm forward of the simulation head impact point and the actual head impact point in the case. The Polar-II head struck the bonnet whereas the head of the pedestrian struck the windscreen and dash (Figure 10).
- The damage to the leading edge was slightly greater in the Polar-II test compared to the damage caused to the case vehicle.

Similarly to Case 1, there was significantly more sliding in the simulation than in the Polar-II test. Figure 7 shows that the Polar-II appears to become hooked on the leading edge of the vehicle – at head contact, the legs have moved over the leading edge only slightly. Unlike most modern passenger vehicles, this vehicle has a very prominent and stiff leading edge, and so this may represent an extreme case for the dummy.

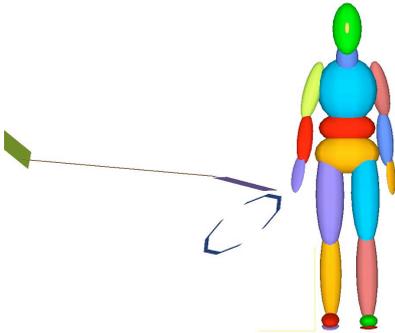


Figure 9 Positioning of computer simulation model and Polar-II dummy in Case 2.

Case 3: Case number PED056

Description: The vehicle was travelling north in the right side of a wide lane and moved to the left because another vehicle in front was turning right into a petrol station. The driver of the vehicle did

not see the pedestrian who was crossing the road from east to west, and the vehicle struck the pedestrian on its front left-hand side of the vehicle. The pedestrian was flipped up onto the bonnet, striking the windscreen before falling to the roadway.

The pedestrian was transported by ambulance to a hospital because of his injuries. He remained conscious after the accident. His most significant injuries were

- An open fracture to his left tibia and fibula - the 3 cm puncture site was 36-39 cm from ground level.
- Grazes to the left aspect of the head, behind the left ear and extending down lateral aspect of neck
- Grazing to the left shoulder, the left hand, both elbows and both knees.

The pedestrian had a clear recollection of events and from his interview we could place his initial position in an area that meant that the car had not commenced braking when he was struck. The subsequent skid marks left by the vehicle indicated that the car was travelling at 60 km/h on impact.

MADYMO simulation: An Australian 1983 Holden VH Commodore was obtained for the physical reconstruction of this collision. The car was measured to obtain the geometry of the vehicle for the MADYMO simulation (Figure 13). The initial position of the pedestrian is shown in Figure 14.

The pedestrian gave a detailed description of the collision, and described how his left arm slid over the bonnet before his head struck the windscreen. He described how his left forearm and hand subsequently struck the broken windscreen above his head. Each of the initial simulations produced slightly different head impact locations, and several also produced heavy impacts between the left elbow and the bonnet. The simulation that best reflected the pedestrian's description of the collision, and the head impact point in the case, was modified so that the left arm slid over the bonnet, rather than digging into it, while maintaining the correct head impact location. In this simulation, the left arm of the pedestrian went on to strike the windscreen in a manner consistent with the pedestrian's description and with the secondary damage to the windscreen.



(a)



(b)

Figure 10 Damage to (a) the leading edge caused by the actual collision (*top*) and the Polar-II test (*bottom*), and (b) the trailing edge from the head impact in the actual case (*top*) and the Polar-II reconstruction (*bottom*) in Case 2.

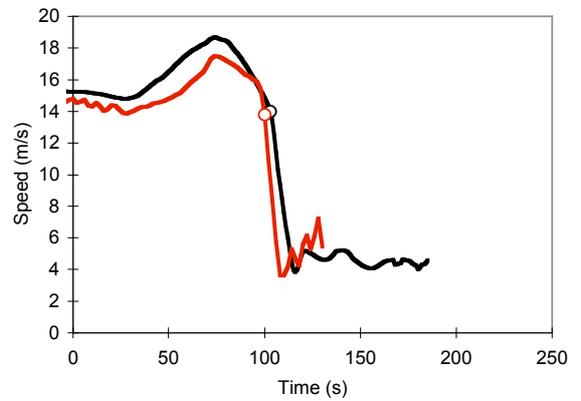
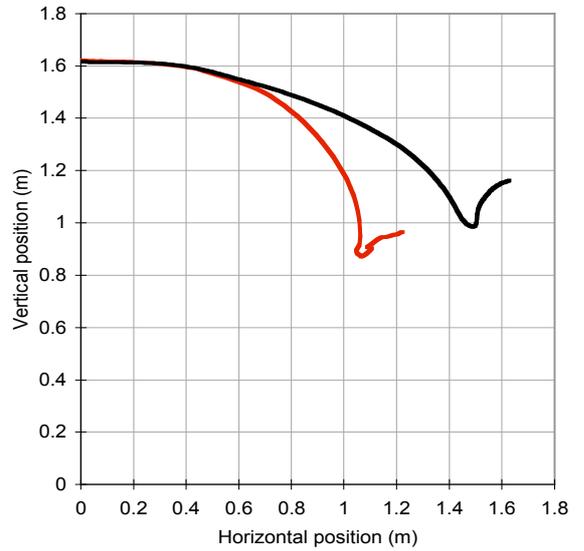
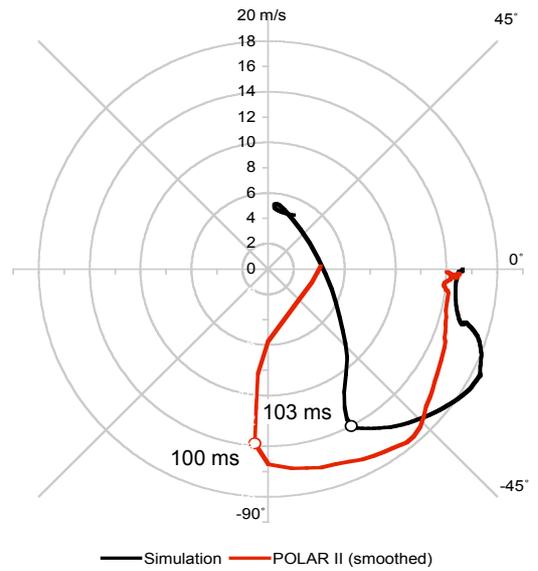
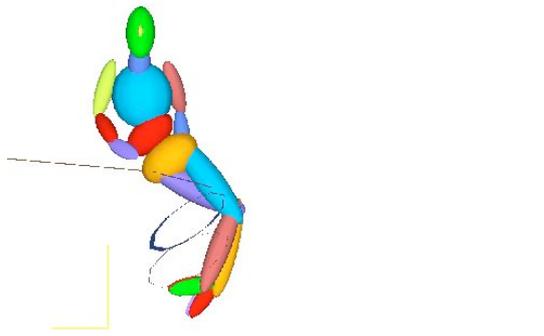
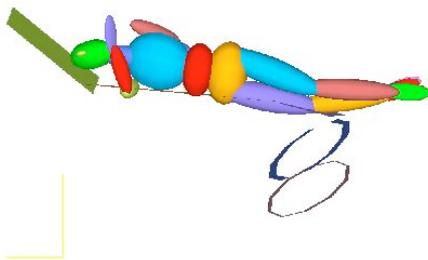


Figure 11 (*top to bottom*) Case 2 radial head velocity trajectory; head position trajectory and head velocity history. Polar-II data are red and simulation data are black. The hollow circles represent data points associated with head impact.



(a)



(b)

Figure 12 A comparison between the MADYMO simulation and the Polar-II reconstruction of Case 2 at (a) 40 ms and (b) 100 ms.

Polar-II reconstruction: The initial dummy position is shown in Figure 14. The position was set to match the initial position of the MADYMO simulation.

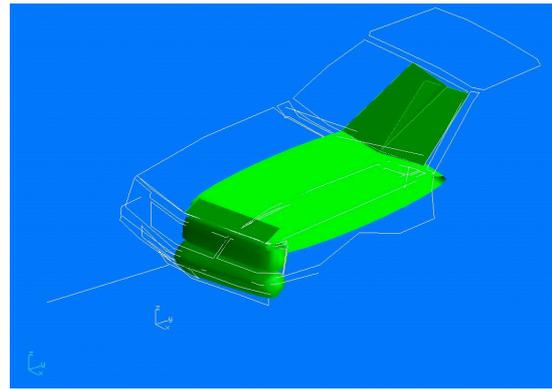


Figure 13 Geometry of the vehicle in Case 3 (shown in white). The approximation of this geometry for the simulation is shown by the shaded geometric entities.

MADYMO and Polar-II results for Case 3:

Figure 15 to Figure 17 compare results of the simulation with the Polar-II test. The Polar-II test and the simulation show a pattern of similarities and differences consistent with the previous two cases. It may be noted that:

- The location of the Polar-II head strike was forward of the location in the actual case (Figure 15) and in the simulation (Figure 17).
- In early stages of the collision, the Polar-II kinematics and the simulation kinematics are similar. After 40 ms there are small differences in the amount of sliding over the bonnet, but the upper body positions are clearly similar (Figure 1 (a)). However, at 100 ms, differences in the leg kinematics have produced large differences in displacements. The simulation head impact has already occurred (Figure 16 (b)).
- The simulation head velocity reaches a higher peak level than the Polar-II (Figure 17). An examination of the components of the head velocity reveals that this difference is due to a difference in the horizontal velocity of the head. In the simulation, the head accelerates to the rear of the vehicle and then it is accelerated forward just before head impact. In the Polar-II test, the head does not significantly accelerate toward the rear of the car at any stage. This difference appears to be largely due to the differences in the amount of sliding between the lower body of the simulation pedestrian and the Polar-II.
- The head impact velocity of the Polar-II is less than in the simulation: 15.2 m/s versus 19.1 m/s. This is due to differences in the horizontal component of the velocity mentioned above, and the radial velocity plot shows this difference to be more than 8 m/s.

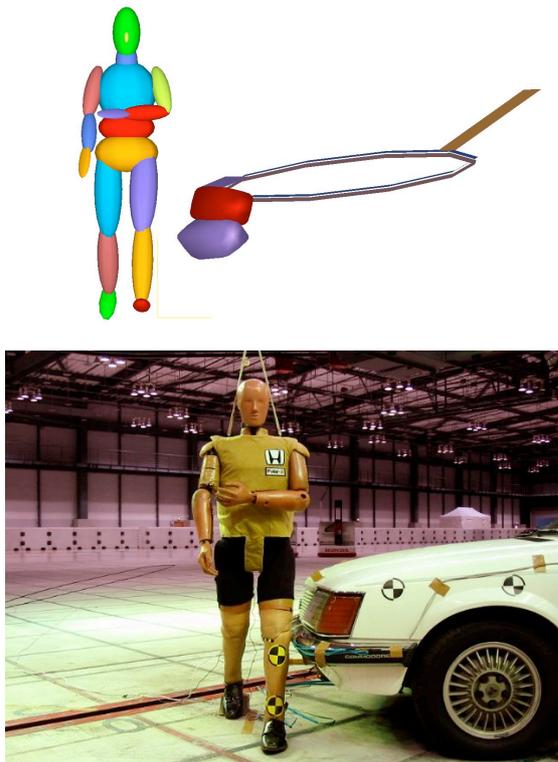


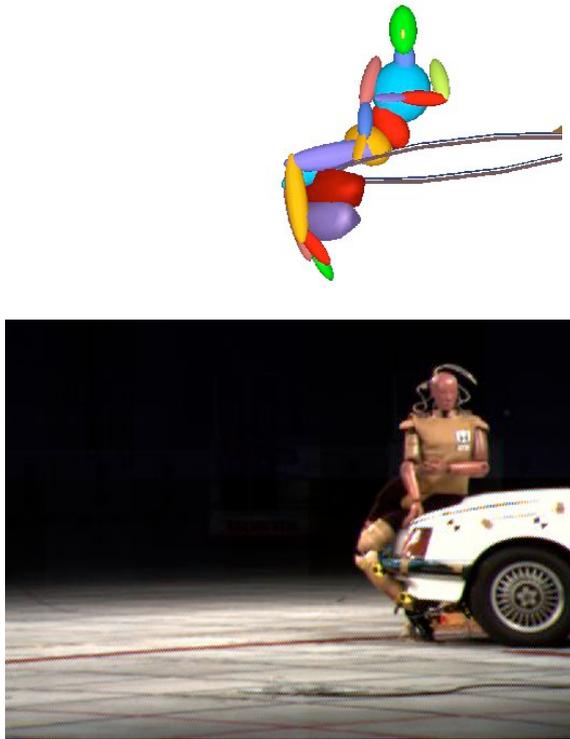
Figure 14 Positioning of computer simulation model and Polar-II dummy in Case 3.



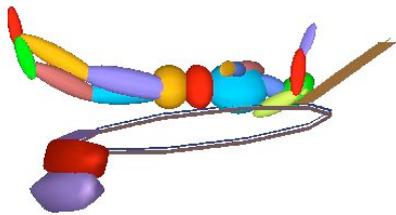
Figure 15 Damage to (a) the leading edge caused by the actual collision (top) and the Polar-II test (bottom), and (b) the trailing edge from the head impact in the actual case (top) and the Polar-II reconstruction (bottom) in Case 3.

DISCUSSION

The purpose of this paper has been to present a comparison of the head kinematics in reconstructions of pedestrian crashes using a multi-body model of a pedestrian and reconstructions using the Polar-II pedestrian dummy. As we are mainly comparing the performance of two surrogates of actual crashes, in some respects the approach is somewhat less direct than the PMHS comparisons reported by Kerrigan et al. (2005a; 2005b). However, the reconstructions were of actual collisions, so we could relate various aspects of the performance to the evidence from the actual case. Furthermore, given the extensive use of multi-body simulations to study pedestrian kinematics, understanding the differences in the response of the Polar-II with simulation models may help to improve both pedestrian dummies and simulation techniques.



(a)



(b)

Figure 1 A comparison between the MADYMO simulation and the Polar-II reconstructions of Case 3 at (a) 40 ms and (b) 100 ms.

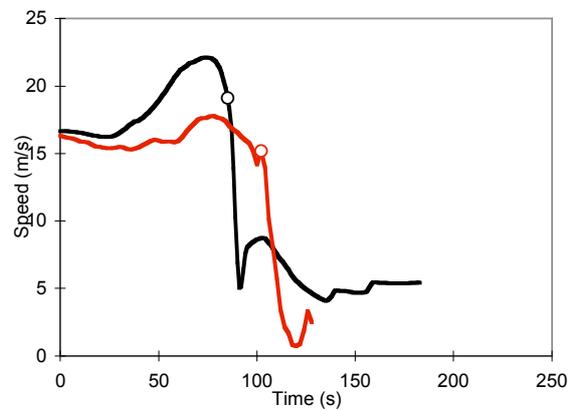
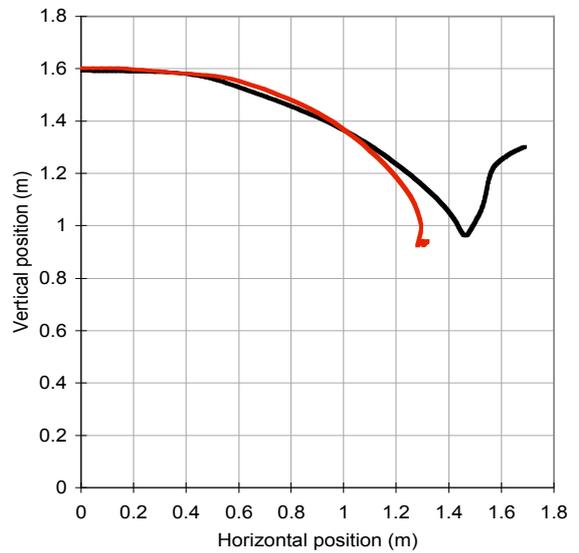
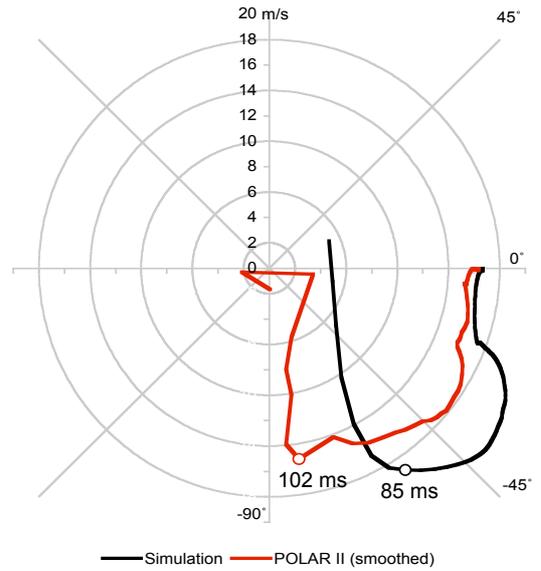


Figure 17 (top to bottom) radial head velocity trajectory; head position trajectory and head velocity history. Polar-II data are red and simulation data are black. The hollow circles represent data points associated with head impact.

In each case, we based our simulations on the physical evidence left after the crash and we could reproduce patterns of contact between the pedestrian and the vehicle in the simulation. The Polar-II reconstructions were conducted with the same make and model of vehicle, and were set up to match the initial conditions chosen for the simulation. This allowed us to compare the kinematics of the Polar-II with our simulation model, and allowed us to compare contact points produced by each surrogate with contacts in the actual case.

There were discrepancies in the head kinematics between the simulation and the Polar-II tests. Consistent across all three Polar-II tests were the following:

- Negligible horizontal velocity component in the head impact velocity, and
- Wrap-around-distances to head impact 200-400 mm shorter than the simulation results.

Both phenomena appear to be related to differences in the amount of sliding of the dummy/pedestrian model over the vehicle. There was noticeably less sliding of the Polar-II than in the simulation.

Kerrigan et al. (2005a) also noted differences in sliding between Polar-II and PMHS tests. Those authors suggested that non-biofidelic pelvic responses and different mass distribution in the dummy might contribute to the phenomenon. It should be noted that the vehicles used in the reconstructions in this paper are not contemporary designs and they might be considered relatively aggressive, and so it is possible that the apparent snagging of the dummy on the bumper/leading edge and the lack of sliding may have been worse than previously observed. In Cases 2 and 3, the radial plots suggest that this snagging might be characterised by a distinctive head velocity trajectory: an initial period of nearly vertical acceleration, followed by a period of almost horizontal deceleration relative to the car, until the horizontal component of the velocity is close to zero. The relatively steep impact velocities are also noticeable in other evaluations of Polar-II (Kerrigan et al., 2005a; Kerrigan et al., 2005b and Akiyama et al., 2001).

When we compared the Polar-II impact locations with the actual cases, the differences appeared to be greatest for the vehicle with the most aggressive leading edge (Case 2) and least with the vehicle with the least aggressive leading edge (Case 1). We suspect that the more aggressive leading edges might have caused the dummy to snag on the vehicle. This, with the pelvic response discussed by Kerrigan et al. (2005a) might explain in whole, or partly, the lack of sliding over the vehicle that was observed.

The vertical component of the impact velocity was similar in the Polar-II tests and the MADYMO simulations of Cases 2 and 3. The smaller vertical component of the velocity in Case 1 appears to be because of the oblique contact between the torso and bonnet, which appeared to rapidly decelerate the head through tension and a resistive moment in the neck.

One other aspect of the kinematics that might have affected the head velocity, and which was notably different between the Polar-II tests and simulations, was the kinematics of the legs. The legs in the MADYMO model did not remain in contact with the leading edge as long as the legs of the Polar-II, and the contact with the bumper and leading edge imparted greater kinetic energy to the legs in the simulation. We have not yet investigated the kinematics in detail, except to note that the kinematics of the legs in the simulation of PMHS tests (detailed in Ishikawa et al., 1991) fitted displacement corridors. It is possible that the greater excursion of the legs may have been partly due to the greater sliding of the pedestrian over the vehicle, the lower legs coming into greater contact with the leading edge in the simulation compared to the Polar-II tests.

In summary, the differences in the kinematics of the head of the computer model and the Polar-II seem to arise mainly as a consequence of the differences in the relative motion that occurs with respect to the vehicle, and possibly also to differences in torso/head/neck behaviour (as observed in Case 1). The behaviour of the model and/or Polar-II in these areas might be a focus of further validation and refinement.

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