DEVELOPMENT OF A BIOFIDELIC DUMMY FOR CAR-PEDESTRIAN ACCIDENT STUDIES

T.J. Huang, J. McDonald, M. Artis, N. Rangarajan, T. Shams, R.P. White Jr., D. Beach, R. Campbell Jr.
GESAC, Inc., USA
A. Akiyama, S. Yoshida
Honda R&D Co., Ltd. Tochigi R&D Center, Japan
H. Ishikawa, A. Konosu
Japan Automobile Research Institute, Japan

Abstract

A 50 percentile adult male, pedestrian dummy, called Polar I, has been developed. During this development effort, the focus was on achieving fidelity with currently available anthropometrical and human kinematic data. This paper discusses the biomechanical requirements that were established for the dummy and computer modeling that was performed to determine the design parameters for the principal components. Accordingly, the paper discusses the design, fabrication and testing of the components. A preliminary series of crash tests was conducted to evaluated the responses of the dummy. Results from these crash tests with the dummy are discussed. Based on these results, modifications to the initial dummy design were made and the refined dummy was performed in a second series of tests. Also, the results from the second series of tests are discussed.

IMPROVING PEDESTRIAN SAFETY is a major consideration in crash injury protection and research, since pedestrian fatalities and injuries in traffic accidents occur world-wide each year (Ishikawa, 1991). In Japan, pedestrian fatalities account for about 30% of the total traffic fatalities. A reduction of 50% in pedestrian fatalities occurred between the years of 1970 and 1979, but that trend has reversed and such fatalities have been again gradually increasing.

Reducing the severity of pedestrian fatalities and injuries can be accomplished by several different approaches. Improvement of vehicle design and construction is among those approaches. At the present time, there are three principal methods of evaluating the level of protection offered by existing and new vehicle designs: component testing, computer simulation, and full-scale testing. Component testing provides a flexible framework to examine interaction of specific parts of the dummy with vehicle panels or components under different initial conditions. The EEVC has established guidelines for performing impact tests with the head, upper leg, and upper/lower legform (Harris, 1991 and Cesari et al. , 1996). Using component or subsystem testing, the performance of a specific vehicle panel can be evaluated by impacting a specific dummy component against the panel at different locations and impact velocities. But with component tests, it is difficult to obtain an integrated picture of the change in response of the whole body to changes in design of a specific vehicle. Computer simulations are gradually becoming a powerful tool in evaluating the interaction of a pedestrian model with a vehicle (Yang and Lovsund, 1997). However, their usefulness, at the present time, lies in performing parametric studies on well validated models. There is difficulty in developing realistic models without supporting test data and the material models are still evolving in complexity. Thus we believe that there is a sound basis for pursuing the development of a pedestrian dummy.

Testing with conventional full-scale dummies have not produced completely successful results. Harris (1989) pointed out some problems in these tests, such as likelihood of damage to dummy components, difficulty in assessing different phases of impact, and uncertain repeatability. Therefore, there was a need to develop a robust and repeatable pedestrian dummy which can perform in a biofidelic manner.

A new pedestrian dummy, called Polar I (Figures 1), has been developed by GESAC, HONDA R&D, and JARI. Dummy development focused on achieving fidelity with currently available anthropometrical and human kinematic data. Polar I is representative of a 50th percentile adult American male and is based on the advanced frontal crash test dummy, known as Thor, developed by GESAC for the National Highway Traffic Safety Administration (White et al., 1996 and Rangarajan et al., 1998). The selection of a 50th percentile male size was motivated mainly by reason of practicality. The Thor dummy, which is a 50th percentile adult male dummy, provided a convenient platform for making modifications. In addition, the most reliable anthropometric and biomechanical data were available for a 50th percentile adult male, and the kinematic targets were developed for this size.

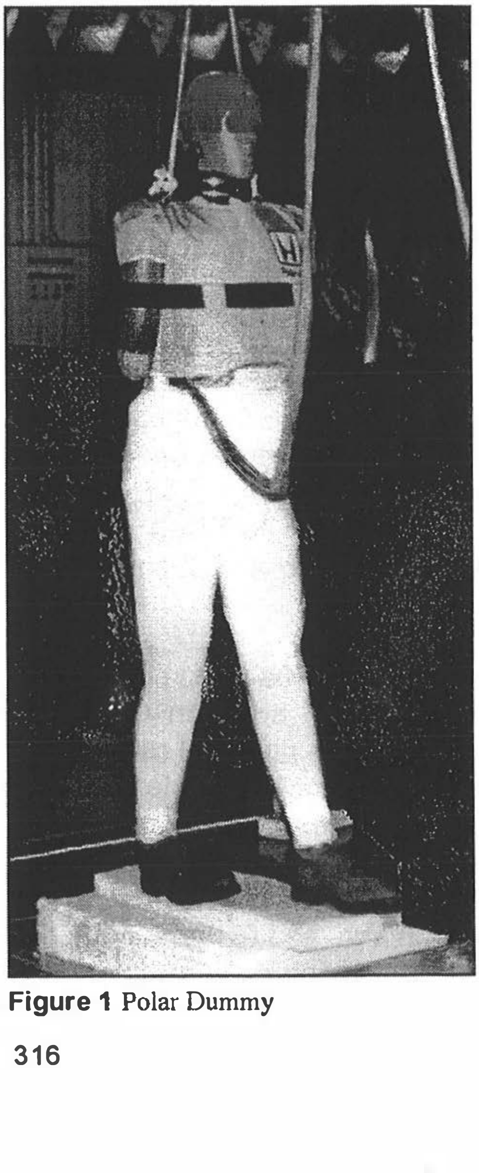


Figure 1 Polar Dummy

Modifications to the thorax, spine, knee and lower leg were made in order to meet biomechanical requirements for pedestrian-vehicle impacts. The first series of full-scale tests were conducted at JARI. The results were encouraging and have been presented at the 1999 SAE conference (Akiyama et al., 1999).

The first version of Polar I provided reasonably biofidelic head motion (both displacement and velocity) at the higher impact speed of 40 kph, but the head displacement was less than the human values at the lower impact speeds. Additional modifications were required to improve performance at both 40 kph and 32 kph. This paper summarizes the results from the first series of tests. It then presents results of computer simulations performed to improve the dummy design and then describes the modifications made to the dummy. It presents the results of a second series of tests using the modified dummy and concludes with discussion of the results and possible future work. In this paper, the first version of the dummy is identified as Polar I.1 and the modified version as Polar I.2.

Design Criterion

The design criteria for the new pedestrian dummy is discussed in this section. The objective of the initial phase of the pedestrian dummy design was to develop a dummy that would be capable of responding kinematically in a biofidelic manner. The primary requirement was that the trajectories of four landmarks on the dummy, namely, the head CG, pelvis CG, knee and ankle, would be similar to the corresponding trajectories observed in Post Mortem Human Subject (PMHS) tests with a similar vehicle.

Ishikawa et al. (1993) obtained a set of trajectories for the motion of these landmarks from ten PMHS tests conducted at three impact speeds, namely, 40 kph, 32 kph, and 25 kph. Based on those data, trajectories for the four landmark points were normalized according to the height of the PMHS and combined to establish a set of trajectory corridors. It was concluded that there was no significant variation in the displacements with impact speed. Thus a single corridor was defined for each of the four locations for all three impact speeds. The highest priority among the four trajectories was given to meeting the corridor for the head trajectory. A secondary biofidelity requirement was defined by the corridors for the resultant head velocity. In this case, corridors were defined for each impact speed through differentiating the Y (lateral) and Z (vertical) components of the displacement obtained from the digitization of the high speed film. No normalization was performed in the calculation of the velocity corridors. Figure 2 shows the corridors for the trajectories of the head, pelvis, knee and ankle. Figures 3 through 5 show the corridors for the head resultant velocity at 25 kph, 32 kph, and 40 kph.

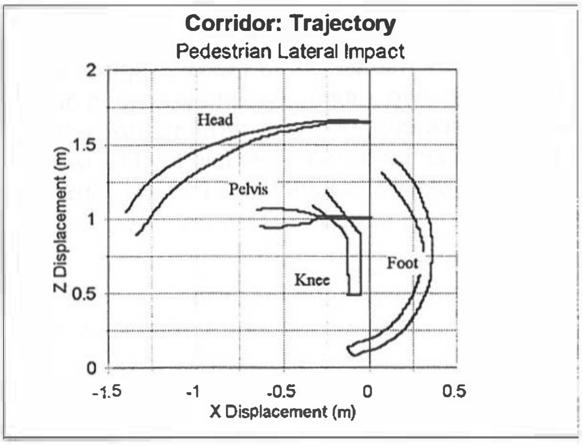


Figure 2. Corridors of human trajectories for lateral impact pedestrians

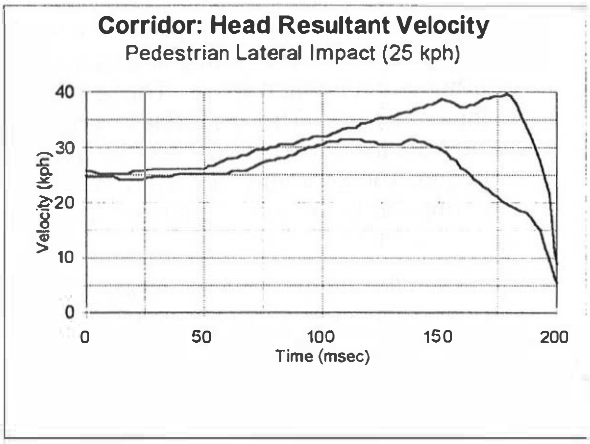
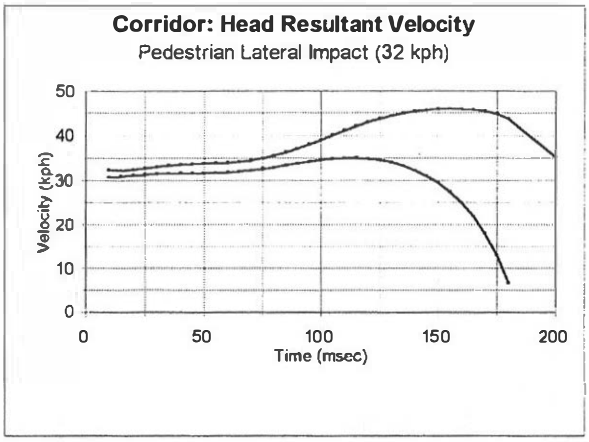


Figure 3. Corridor for head resultant velocity at 25 kph Impact speed



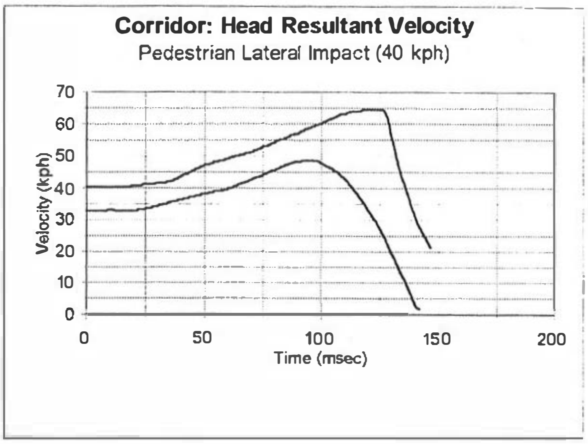


Figure 4. Corridor for head resultant velocity at 32 kph Impact speed

Figure 5. Corridor for head resultant velocity at 40 kph Impact speed

Polar I.1 Design and Development

The first version of the pedestrian dummy, Polar I.1, was based on Thor, the NHTSA advanced frontal crash test dummy. The major modifications are shown as follows:

- The ribcage of the Thor dummy was maintained since it had reasonable human anthropometry. The outer jacket was modified to increase the outside contour to correspond to anthropometric data for the 50th percentile male published in Robbins (1985). The jacket consisted of thin, high abrasion resistant, Cordura on the outside, a Rubatex liner on the inside, and a moderately stiff, open cell foam sandwiched in between. The jacket materials were selected to provide appropriate durability and human-like contact stiffness upon impact.
- The pitch change mechanisms situated at the neck and the T12/L1 location were replaced by metal blocks. The lumbar spine was oriented in the erect posture relative to the thoracic spine.
- Computer modeling [Akiyama, 1999] had suggested that the pedestrian dummy would require a spine which was more compliant in lateral flexion than was feasible with the Thor spine. The Thor spine consisted of two flexible components, one in the middle of the thoracic spine, and another in the lumbar spine. These flexible joints contained two cables placed laterally relative to the center line. The two cables were replaced with a single cable running through the center. Apart from the change in cables, the geometry and material in the thoracic flexible joint were not changed. The geometry of the lumbar spine was changed from a rectangular section to a circular section, and the material changed from Urethane to Neoprene of equivalent durometer (Shore 75A).
- Based on flexion tests on the newly designed flexible components in the thoracic spine and the lumbar spine, it was determined that the joint stiffness was in the range estimated by the computer models.
- The Thor abdomen consists of a small upper abdomen and a larger lower abdomen, with a third wedge shaped piece inserted in-between when the dummy is placed in an erect posture. For the pedestrian dummy, the wedge shaped piece was combined with the lower abdomen to produce a two segment abdomen. The stiffness of the foam inserts were unchanged.
- The pelvis and pelvis skin were kept the same as in Thor. The pelvis skin had been molded using material with the approximate stiffness of human flesh in the buttock area.
- The Hybrid III femur was used in the Polar I.1 dummy. Though the Thor dummy can be used either as a standing dummy or as a seated dummy, the femur ball used in Hybrid III has been maintained and is inserted into the acetabular cup in the pelvis. The upper leg skin consisted of three sections. The topmost section covers the femur flange assembly and makes contact with

the pelvis skin, while the middle section was kept the same as in Hybrid III, and the bottom section served to cover the knee and mesh with the lower leg skin.

- The Hybrid III slider knee was simplified to include only rotational freedom and made smaller. It was also decided to try to design a knee that would have some compliance to lateral bending and shearing loads. A Neoprene cylinder was designed to fit with the regular Hybrid III knee at the proximal end of the new joint and with the lower leg at the distal end. The center of rotation of the compliant element was about 100 mm below the center of the knee. The required compliance in bending and shear were obtained from Kajzer (1997). The size and material properties that would be required to fulfil these requirements were then estimated.
- A new tibia was designed such that it fit the new, compliant knee element, connect properly to the Hybrid III ankle joint and would have the correct mass and anthropometric characteristics. The lower leg skin was also completely redesigned. The stiffness and damping characteristics of the flesh around the knee and lower leg were estimated from our computer modeling. To provide the appropriate damping, Confor foam was used around the tibia.

Review of the First Full-Scale Test Series

The dummy was set up for testing in approximately the same configuration that was used for the PMHS tests and described by Ishikawa (1993). The dummy was aligned on a platform in an upright position and oriented so that it would be impacted laterally by the vehicle front. The legs were placed in a walking position, with the impacted leg placed forward at about 10 cm from vertical, and the opposite leg placed rearward also at about 10 cm. Triaxial accelerometers were installed at the C.G. of the head, thorax and pelvis, and a uniaxial accelerometer on the tibia. These sensors corresponded to those used in the earlier PMHS tests. The kinematics was recorded on high speed film.

As indicated previously, the major design goal for the new dummy during the first phase was to match head kinematics. Table 1 shows the comparison between results from the first series of tests with Polar 1.1 and the PMHS corridors for the head.

Table 1. Comparison of the first series of tests with Polar 1.1 and corridors for the head motion

Impact Speed	25 kph		32 kph		40 kph	
	Corridors	Tests	Corridors	Tests	Corridors	Tests
Final Head X Displacement (m)	-1.40 to -1.25	-0.97	-1.40 to -1.25	-1.12 to -1.05	-1.40 to -1.25	-1.20 to -1.14
Peak Head Velocity (kph)	30 to 39	41	35 to 45	48 to 53	48 to 64	54 to 58
Time at Peak Velocity (msec)	170 to 180	115	150 to 170	100 to 110	120 to 130	85 to 95

According to Table 1, the horizontal travel of the head fell short of the required human corridors at all three speeds. The displacement of the head showed much greater sensitivity to impact velocity than seen in The PMHS tests. The smallest discrepancy between human and dummy head displacements was seen for the 40 kph impact test, where the difference was about 0.15 m, while the largest discrepancy was for the 25 kph impact, where the difference was about 0.4 m. The motions of the pelvis, knee, and ankle markers were close to the corridors for the 32 kph and 40 kph tests.

When the results of the resultant head velocity are compared with the PMHS corridors, it is found that the peak magnitude is in the expected range though it is at the high end for the 25 kph and 32 kph tests, and at the low end for the 40 kph test. The time at which peak occurs is early for the 25 kph and 32 kph tests and close to the expected range for the 40 kph test. The variations in head displacement and velocity for the those tests were less than 10% Therefore, the results indicated a good degree of repeatability.

Examination of the high speed film indicated that the lower leg of Polar I.1 did not react as quickly to the impact as seen in the PMHS tests, specially at the lower impact speeds. Also, from the film, it appeared that there was greater lateral bending in the dummy knee than in the PMHS knee, though this has not been quantified. The results indicated that the knee was softer than the desired stiffness of the human knee. Nevertheless the overall kinematics observed in the film showed similarity with the PMHS motion, in that the dummy rotated about the pelvis near the hood edge and stayed in contact with the hood up to the time of contact of the head with the hood.

Results from testing indicated that with some modifications to the current Polar I.1 design, better agreement with human response could be attained. It was proposed that the modifications would mainly deal with the initial contact phase. This would include increasing the stiffness of the knee joint in lateral bending and increasing the stiffness of the lower leg contact with the bumper. It was also proposed to soften two spine joints in order to improve the lateral bending of the upper torso during the second contact phase when the upper body makes contact with the vehicle hood. In order to estimate the magnitude of these modifications, computer simulations were used and are discussed in the next section.

Computer Modeling for Design Modification

The pedestrian model was developed using the *DYNAMAN* program (Shams et al, 1993), which is a software package for the simulation of human body dynamics during vehicle crash or other abrupt acceleration events. A model of the Polar I.1 dummy was developed and validated against the results of the first series of impact tests. The necessary geometrical and inertial characteristics were measured from the Polar I.1 dummy. The characteristics of the principal joints (neck, upper thoracic spine joint, lumbar joint, and knee) had also been measured, as were the force-deflection functions of the flesh/skin of lower leg, upper leg, and pelvis. This allowed us to have a base model which could be modified to seek a better agreement with the trajectories defined in the biomechanical corridors.

As indicated in the previous section, the proposed modifications focused on knee stiffness, lower leg, upper leg, and pelvis stiffness, and the lumbar and upper thoracic joint stiffness. A series of simulations were conducted, where these parameters were varied to find the direction in which design should be directed to improve the kinematic response of the dummy and make it behave in a more biofidelic manner. Table 2 summarizes the simulation sensitivity study.

Table 2 Summary of the sensitivity study on selected pedestrian dummy components

Component	Variation	Effect on head trajectory	Effect on head velocity
Upper thoracic Jt.	decrease stiffness 50%	0-8 mm moves closer to corridor	reduces 0-1 kph contact velocity
Lumbar Jt.	decrease stiffness 50%	0-12 mm moves closer to corridor	reduces 0-0.5 kph .
Pelvis skin	increase stiffness 50%	0-15 mm moves closer to corridor	reduces 0-0.3 kph
	decrease damping 50%	0-12 mm moves closer to corridor	increases 0-0.3 kph
Upper leg	increase stiffness 50%	0-10 mm moves closer to corridor	increases 0-1 kph
	decrease damping 50%	0-10 mm moves closer to corridor	increases 0-0.5 kph
Lower leg	increase stiffness 50%	0-30 mm moves closer to corridor	reduces 0.3-0.5 kph
	decrease damping 50%	30-65 mm moves closer to corridor	reduces 0.5-1.8 kph
Flexible knee jt.	increase stiffness 50%	0-30 mm moves closer to corridor	reduces 0-0.7 kph
	move up location 10 mm	0-20 mm moves closer to corridor	reduces 0-1.1 kph

From the above table, the following conclusions were made about the effect of the modifications on dummy response:

- For the head velocity, the major contributing factors are the stiffness of the upper thoracic joint and the lumbar joint. For example, according to the simulations, reducing the stiffness of the upper thoracic joint by 50% will increase by about 5-10 msec the time the head stays in the air.
- For the head trajectory, the major factors are the overall properties of the lower body segments. Especially the damping component of the lower leg and the stiffness and location of the flexible knee joint will play important roles for the head trajectory. Also the stiffness of the upper leg and pelvis skin have makes a small contribution.

The simulation model was then exercised by combining the modifications suggested by the sensitivity studies on the individual input parameters. These modifications were reduced damping in the lower leg, increased stiffness in the upper leg and pelvis skin, reduced stiffness in the upper thoracic spine joint and the lumbar joint, and increased stiffness in the flexible knee joint and also moving it up 10 mm (0.4 in). Since we were focusing on the higher speed impact cases in this initial phase of the project, the new model was used at impact speeds of 32 kph and 40kph.

Design Modifications for Polar I.2 Dummy

As indicated in the previous section, computer simulations indicated that modifications to a number of components in the Polar I.1 dummy would improve the dummy's kinematic performance. Among the major components that needed to be modified were the pelvis skin, the femur skin, and the lower leg skin. For the pelvis and femur skins, increased stiffness was desired. In order to do so, both skins were remolded to obtain higher nominal hardness (10A to 20A). The lower leg skin was designed according to the parameters used in the computer model which produced the closest agreement with the human corridors. An important factor in the leg impact response was the effective damping in the vehicle lower leg contact. Damping in the lower leg had been realized by using a layer of Confor foam beneath the skin. The simulations indicated that the damping should be reduced, and the easiest way of reducing damping was to reduce the thickness of the Confor foam.

The other important modification was to increase stiffness in the flexible knee joint and decrease stiffness in the thoracic and lumbar joints, though the latter had a smaller effect on the kinematics. According to the basic theory of strength of materials, the stiffness is approximately proportional to the length cubed of the component if the material and the cross section did not change. Initially, it was proposed to increase the length of both thoracic and lumbar joints to reduce their stiffness. However, other sections of the spine would have to be redesigned to meet the anthropomorphic landmark locations in the dummy when we made those changes. Since there was not enough space for the longer joints, the alternative way was to decrease the hardness of the materials in both lumbar and upper thoracic joints (75A to 65A) and only have a small increase in the length of the lumbar joint. The new modified spine is shown in Figure 6.

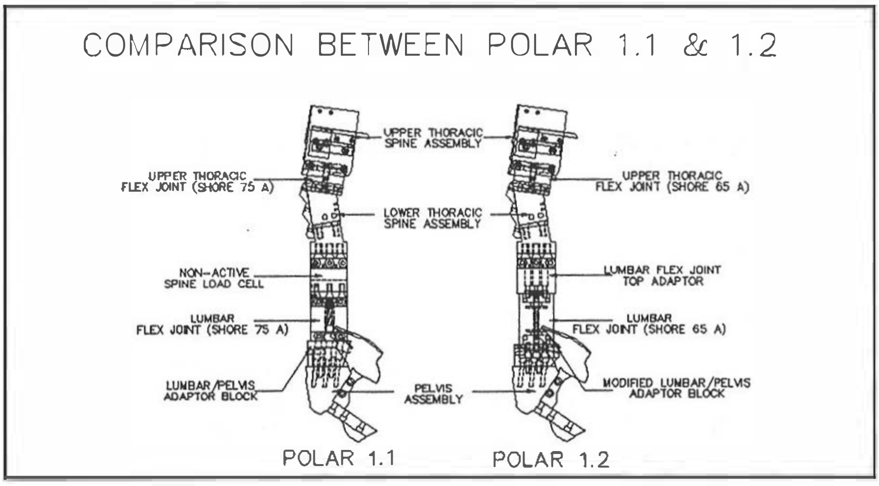


Figure 6. Comparison of spine design between Polar 1.1 and Polar 1.2

For the flexible knee joint, the modification was made by both reducing the length of the joint and by using a higher durometer material (85A urethane). This change also allowed the joint to be located closer to the center of rotation of the knee in flexion. As a result, the stiffness of the joint was increased and the center of rotation of the joint was moved up. The new lower leg design is shown in Figure 7.

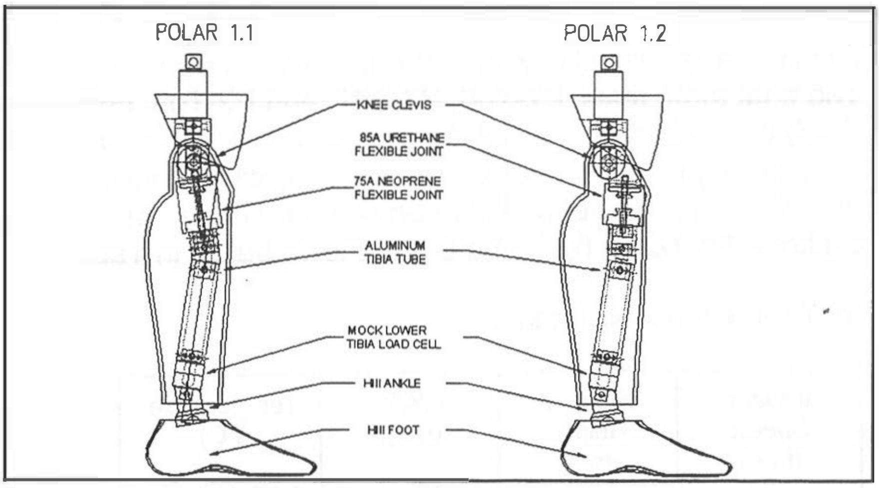


Figure 7. Comparison of tibia design between Polar 1.1 and Polar 1.2

There were two additional modifications that resulted in the improvement of the overall anthropometry of the dummy. One was a reduction in the weight of the pelvis bone. This would bring the weight of the pelvis closer to that of the human pelvis. The other was the removal of the Hybrid III upper femur ballast ring and making the femur shaft size uniform. This would provide the correct flesh thickness at the upper femur.

In order to ensure that the modifications were producing correct results, component tests were performed to determine the approximate characteristics of the skin/flesh covering of the pedestrian dummy. Fixtures were designed for holding the components rigidly, so that they could be impacted by a linear impactor. Two different impact surfaces were used. One impactor had a 7.6 cm diameter circular face representing a smaller loading area, while the second had a rectangular face with sides of 7.6 x 15.9 cm which represented a large loading area. The small impactor was used to simulate the contact of the bumper with the lower leg, while the larger impactor was used to simulate the impact of the hood edge with the upper leg and pelvis.

Another set of component tests were designed to examine the dynamic response of the flexible joints. Test fixtures were designed to perform these tests which included the lateral flexion of the lumbar joint, both under concentrated loading and with indirect loading on the pelvis and the flexion of the newly designed knee joint. The tests were conducted mainly to obtain approximate data on the dynamic characteristics of the particular component which would be useful in refining our computer model.

Results and Discussion on the Second Full-Scale Test Series

The Polar I.2 dummy was set up for testing at JARI in the same configuration that was used for the first series of tests. Eight impact tests were performed in the second series at impact speeds of 32 kph and 40 kph. The higher impact speeds were of greater interest during the first phase of this project and corresponded to the impact speeds at which the PMHS was tested. A fully constituted vehicle front was placed on the Hyge sled. The vehicle front was equivalent to that used in the PMHS tests and

consisted of the complete bumper, grill, hood edge, hood and windshield assembly. The first five tests were used to check the influence of the individual modifications made in Polar I.2. The final three tests, P2-T06, P2-T07, and P2-T08, constituted the actual test runs and were conducted with all the modified parts in place. Only the older version of the lumbar joint was kept in the dummy, since there was no significant difference in the kinematic response between using it and the modified version.
The initial conditions for Tests 6, 7, and 8 are shown below in Table 3.

Table 3. Initial conditions for second test series

Test #	Impact Speed (kph)	Bumper Height (mm)	WAD (mm)	Temperature (°C)
P2-T06	40.0	383	1878	24
P2-T07	31.9	383	1803	26
P2-T08	31.5	383	1793	26

The kinematics of the dummy were again captured by digitizing the high speed film of the events. The resultant velocity was computed by differentiating the digitized displacements. The comparison of the trajectories in the X-Z plane obtained from the pedestrian dummy tests with the PMHS corridors are provided in Figures 8 and 9. They represent the results for the two test impact speeds of 32 kph, and 40 kph respectively. Figures 10 and 11 show the comparison of the head resultant velocity with the human corridors for these two speeds. Figure 12 shows the frame-by-frame pictures for dummy motion at 40 kph impact speed. The results from the computer simulations are also overlaid on those graphs.

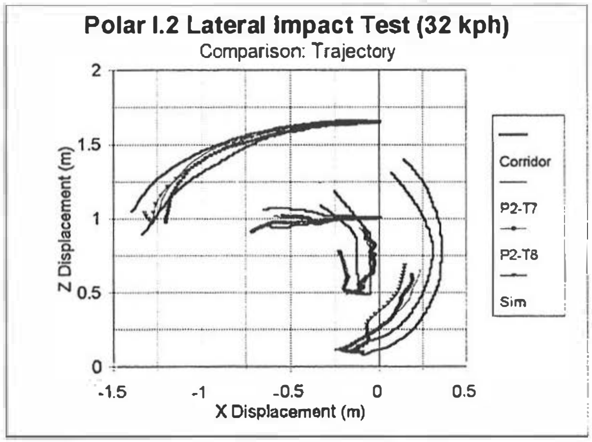


Figure 8. Comparison of trajectory at 32 kph test and simulation

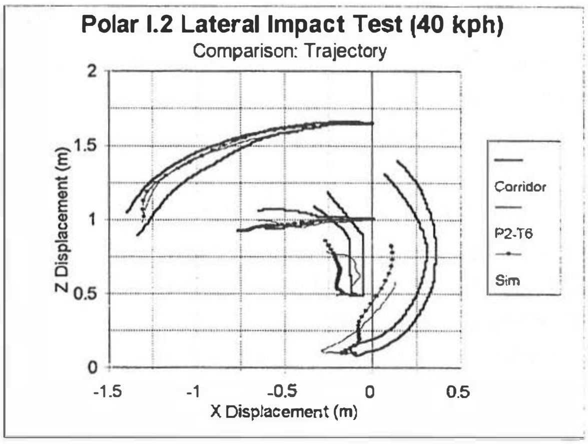


Figure 9. Comparison of trajectory at 40 kph test and simulation

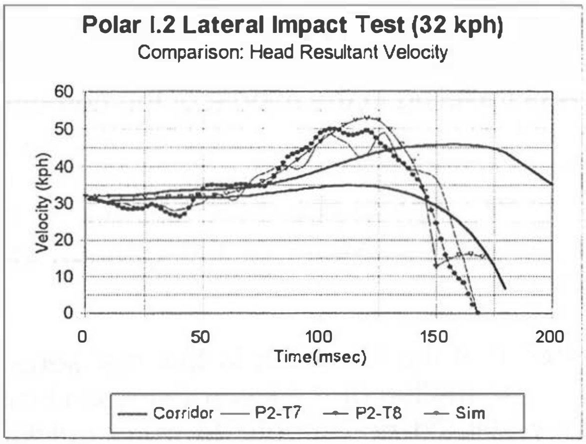


Figure 10. Comparison of head velocity at 32 kph test and simulation

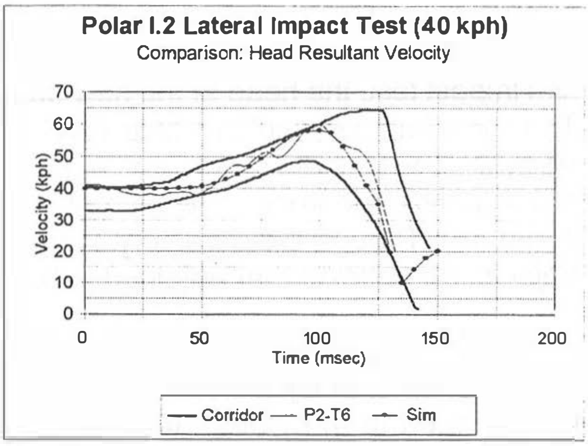


Figure 11. Comparison of head velocity at 40 kph test and simulation

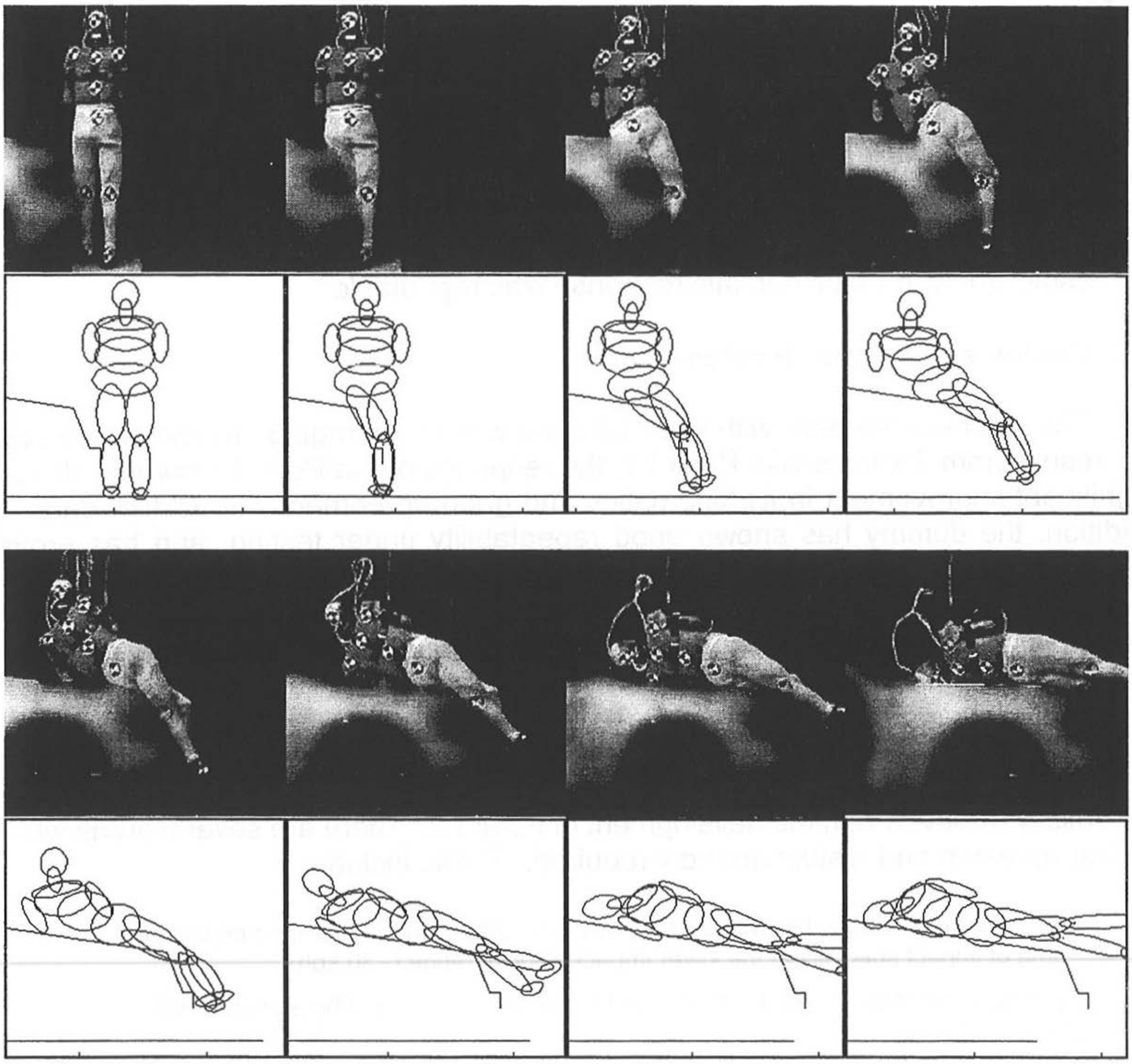


Figure 12. Frame-by-frame pictures for Polar dummy motion with comparison to DYNAMAN model (40 kph impact speed; 20 msec each frame)

From the results shown above, it is seen that the horizontal travel of the head had now moved closer to the expected human response at both speeds. Especially for the 40 kph impact test, the head of the new dummy was traveling in the middle of the corridor. The same improvement in results can been seen in the magnitude of the resultant head velocity. The time at which peak occurs is still earlier than the PMHS tests. The motion of the pelvis, the knee, and the ankle, also improved and were close to the human corridors. Though the trajectory of the foot still did not move inside the corridor, the trajectory paralleled that obtained in human tests.

Examining the high speed film, it was seen that the lower leg in this test series reacted more quickly than the first test series. The motion of the lower leg was close to that seen in the PMHS tests although they still did not appear to react quickly enough. It indicated that the knee design modifications were in the right direction though still had not achieved optimal response. The Polar I.2 kinematics observed in the film shows similarity with the PMHS motion in the rotation of the dummy about the pelvis during the periods from the starting contact up to the contact of the head with the hood.

As in the first series, the tests showed that the Polar I.2 dummy components were durable during the impact. During the tests series, the knee joint, the lumbar joint, and upper thoracic joint did not show any visible damage. The knee and lower leg skins also held up well under impact, as did the Confor foam placed beneath the leg skin. For the second series, only the 32 kph test was repeated. The variations in head displacement and velocity for this configuration were 2% and 10%, respectively. Again, the results showed that kinematic response was repeatable.

Conclusion and Future Development

The results of the tests with Polar I.2 were very encouraging. In comparison with the results from the tests with Polar I.1, the response of the Polar I.2 dummy showed significant improvement in its kinematics and good agreement with PMHS data. In addition, the dummy has shown good repeatability under testing, and has proven durable over ten tests conducted during the first test series and eight tests conducted during the second test series. The DYNAMAN simulation model matched quite well with the final test results and showed that appropriate simulation procedures could be effectively used in the design of the dummy.

The goal of this pedestrian dummy development was to ensure that the dummy would have the correct kinematics when impacted by a vehicle. This goal was essentially achieved with the development of Polar I.2. There are several areas where further research and testing are now required. These include:

- Refinement of dummy kinematics to improve the magnitude of the head impact velocity and the time of impact specially at the lower impact velocity range (~30 kph).
- Examination of the biofidelity of the kinematics when impacted by a vehicle with a significantly different profile.
- Inclusion of appropriate instrumentation to assess injury of critical body components. These would include the head, neck, spine, chest, upper leg, lower leg , and the knee.
- Examination of various response variables, such as loads, accelerations, and displacements, generated within specific body components by using the above instrumentation. Comparison of

these responses with available human data.

- Scaling of the 50th percentile adult male size to size representative of most vulnerable pedestrians.

References

Akiyama, A., Yoshida, S., Matsuhashi, T., Rangarajan, N., Shams, T., Ishikawa, H.,and Konosu, A. (1999) Development of Simulation Model and Pedestrian Dummy. SAE Conference, March, 1999, Detroit, MI.

Cesari, D., Fontaine, H. And Lassare, S. (1996) The Validity of the Proposed European Pedestrian Protection Procedure and its Expected Benefits. 15th International Conference on ESV.

Harris, J. (1989) A Study of Test Methods to Evaluate Pedestrian Protection for Cars. 12th ESV.

Harris, J. (1991) Proposals for Test Methods to Evaluate Pedestrian Protection for Cars. 13th International Conference on ESV.

Ishikawa, H., Kajzer, J.,and Schroeder, G. (1993) Computer Simulation of the Impact Response of the Human Body in Car Pedestrian Accidents. 37th SAE Stapp Car Crash Conference.

Ishikawa, H., Yamazaki, K., Ono, K., and Sasaki, A. (1991) Current Situation of Pedestrian Accident and Research into Pedestrian Protection in Japan. 13th International Conference on ESV.

Kajzer, J., Schroeder, G., Ishikawa, H., Matsui, Y.,and Bosch, U. (1997) Shearing and Bending Effects at the Knee Joint at High Speed Lateral Loading. 41th SAE Stapp Car Crash Conference.

Rangarajan, N., et al. (1998) Design Criteria, Design, and Performance of the Thor Advanced Frontal Crash Test Dummy Thorax and Abdomen Assemblies. 16th ESV Conference.

Robbins, D. (1983). Development of anthropometrically based design specifications for an advanced adult anthropometric dummy family. Volume 2: Anthropometric specifications for mid-sized male dummy. Report No: UMTRI 83-53-2. UMTRI, Ann Arbor.

Shams, T., Weerappuli, D.,Sharma, D.,Nurse, R.,and Rangarajan, N. (1993) *DYNAMAN User's Manual*. Report No: GESAC-92-08, AL/CF-TR-1993-0076

White, R.P., Rangarajan, N., and Haffner, M. (1996) Development of the Thor Advanced Frontal Crash Test Dummy. SAFE Conference, 1996.

Yang, J. and Lovsund, P. (1997) Development and Validation of a Human-Body Mathematical Model for Simulation of Car-Pedestrian Collisions. IRCOBI.