DEVELOPMENT AND APPLICATION OF THE NEW PEDESTRIAN DUMMY

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ABSTRACT

A new pedestrian dummy, called "POLAR" has been recently developed. It can be used as a tool not only for the investigation of the mechanism of pedestrian accidents, but also for the assessment of vehicle aggressiveness to pedestrians. This dummy is modified from "THOR", new generation occupant dummy, in its body structure to reproduce human body kinematics in the event of collision with a vehicle more precisely.

Its knee has a human-like structure, with condyles which shape is similar to that of human knee, meniscus, cruciate ligaments and collateral ligaments. Tibias of Polar are made of urethane which bending characteristic is that of human tibia. These features not only make the lateral bending and shearing responses of the leg and knee more human-like but also the whole body kinematics more human-like.

The dummy is installed with the on-board data acquisition system (DAS) which allows conducting a full-scale test without any connection to the ground, which may affect the kinematics of the dummy. It also makes it possible to measure more data channels and to assess more kinds of pedestrian injuries.

Certification tests of the leg proved that the bending and shearing characteristics of the leg were almost in the corridors derived from PMHS leg impact tests. And full scale certification tests indicated that the dummy can well reproduce the kinematics of a pedestrian in the event of a collision with a vehicle.

Full scale tests with various shapes of vehicles were conducted. Kinematics of the dummy and measured values were compared, and the result proved the possibility of the dummy in assessing the effect of vehicle shape on pedestrian injuries.

INTRODUCTION

Reducing pedestrian fatalities and serious injuries is a major concern in crash safety research. Recent accident statistics indicate that pedestrian fatalities account for almost 10% of all traffic related fatalities in Europe, 13% in the U.S., and almost 30% in Japan, among the

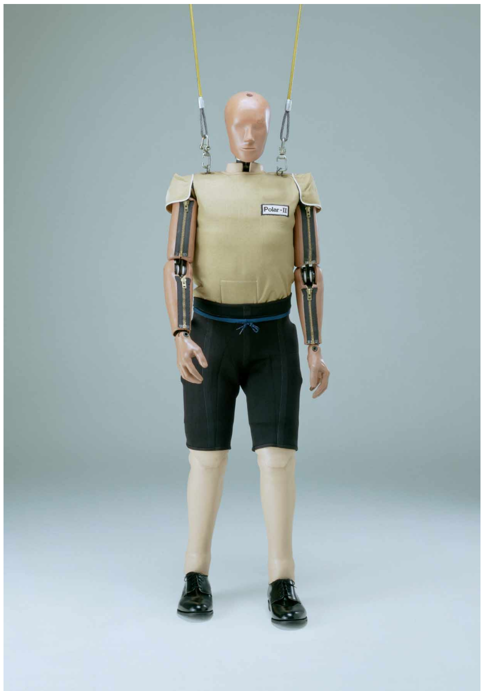

Figure 1 POLAR Dummy

advanced, industrialized nations [Jarret, 1998; Otte, 1999; Ishikawa, 1991]. The fraction of pedestrian fatalities and serious injuries are significantly higher in less developed countries where there has been a constantly increasing vehicle population [Chawla, 1998].

Mitigation of pedestrian injuries has been attempted at different levels such as improvement of road conditions and education of motorists and pedestrians. But along with several kinds of efforts, a great deal of effort has been spent in improving the design of the vehicle to make it less aggressive during an impact with a pedestrian [Sakurai, 1994].

There are three main methods for evaluating the level of protection offered to pedestrians: 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. Using component or sub-system testing, the performance of a specific vehicle panel can be evaluated. But with component tests, it is difficult to obtain an integrated picture of the response of the whole. Changes in the components which come into contact earlier, such as the bumper, may effect how the rest of the body will interact with the vehicle [Edwards, 1999; Sakurai, 1994]. Computer simulations are gradually becoming a powerful tool in evaluating the interaction of a pedestrian model with a vehicle [Yang, 1997]. However, their usefulness, at the present time, lies in performing parametric studies on well-validated models.

The new pedestrian dummy, called Polar (Figure 1), has been developed by GESAC, HONDA Research & Development and the Japan Automobile Research Institute (JARI). The development of the new dummy proceeded in two phases.

During Phase I, a dummy was designed and manufactured that would move in a biofidelic manner during lateral impact with a vehicle. The dummy at the end of Phase I, was known as Polar I. The results from an extensive series of sled tests indicated that the trajectory goals were essentially met, specially for the head. Description of the dummy and the results from the tests series are given in [Huang, 1999] and [Akiyama, 1999].

Following the successful results from the Phase I testing, it was decided to proceed with Phase II development, where the principal objectives were two-fold. The first was to further improve the kinematics of the dummy, especially the head impact velocity at lower impact speeds. And the second was to develop instrumentation that would provide adequate injury assessment capabilities. The dummy that evolved from the Phase II development efforts, known as Polar, is the focus of this paper.

PHASE I DEVELOPMENT

Design Requirement

The basic requirement during the first phase of Polar development was to produce a dummy that would move in a biofidelic manner during a lateral impact.

Accident statistics indicate that the majority of pedestrians involved in accidents are adults. Accordingly, the size selected for the dummy corresponded to a 50th percentile American male representing adult pedestrians, since a base dummy, which has most advanced biomechanical futures, of this size was already available and PMHS kinematics data were available for this size. Ishikawa, et al [1993] had developed a set of corridors for four trajectories: the head C.G., pelvis C.G., knee and ankle, based on results of tests with PMHS. These tests were carried out at impact speeds of 40, 32, and 25 km/h. The trajectories described the motion of these landmarks in the impact plane. Based on further analyses, it was determined that the trajectories were essentially independent of impact velocity. Additional requirements were developed for the time-histories of the head resultant velocities. At each impact velocity, corridors were derived based on the trajectory time histories that had been digitized from the high-speed video images. During the first phase of Polar development, the goal was to make the dummy move within the PMHS corridors at the different impact speeds. Priority was given to achieving biofidelity in the head trajectory and head velocity at 40 km/h. During this phase, instrumentation was not considered.

Summary of Polar I Features

The design and development of Polar I has been described in [Akiyama, 1999; Huang, 1999]. The basic structure of the dummy was adopted from the Advanced Frontal Dummy developed for the National Highway Traffic Safety Administration (NHTSA) known as Thor [White, 1996; Rangarajan, 1998]. Here, the main features of Polar I will be briefly summarized.

The major new features of the Polar I dummy were:

1. The lateral stiffness of the two spinal flexible joints were significantly lowered by replacing the two steel cables with a single, central one and also by lowering the durometer of the Urethane material used for molding the components. The length of the lumbar flexible joint was also increased to allow for greater bending capability.
2. A compliant element was introduced just below the knee joint to allow the lower leg to bend and shear relative to the femur during impact with the bumper.
3. The skin/flesh around the knee and tibia was modified to produce the requisite stiffness and damping during impact.

During the Phase I development effort, the initial selection of the properties of the flexible joints in the spine and the force-deflection characteristics of the skin/flesh around the pelvis, knee, and lower leg were guided by modeling done using computer simulations. The initial simulations are conducted at JARI using a Madymo model, from which target stiffness of the two flexible joints in the spine were derived [Akiyama, I 999]. Further simulations using Dynaman were conducted to identify appropriate stiffness for the knee joint and the skin stiffness. Details of the modeling are given in [Huang, 1999].

As mentioned earlier, instrumentation on the dummy was not a requirement during the Phase I development, but triaxial accelerometers were used at the head and thorax C. G. locations . The trajectory and velocity data obtained from the tests used for comparing with PMHS data were all gathered from digitizing high-speed video.

PHASE II DEVELOPMENT

Design Requirement

Good kinematics correspondence with PMHS data was achieved at the end of the Phase I effort, especially at the 40 km/h impact speed. There were two overall goals for the Phase II development. One was to further improve the kinematics of the dummy so that it met the trajectory and velocity requirements of the head at the lower impact speed of 32 km/h. The second objective was to add proper instrumentation so that the dummy could be used to assess the likelihood of principal injuries seen in the field.

The main performance requirements on Polar were on its response at impact speeds of 40 km/h and 32 km/h. These requirements were the same as in Phase I. An additional requirement was that the dummy should be durable and suffer no major damage at the higher impact speed of 50 km/h. No biomechanical data are available for quantifying the human response at this impact speed. It was assumed that the dummy should behave in a manner that could be extrapolated from its responses at 32 km/h and 40 km/h.

The second objective during Phase II development was to introduce sufficient instrumentation to make the dummy a useful tool for injury assessment. Injury measures for the head, chest, and neck, were based on standard instrumentation consisting of accelerometers at the head and chest C.G.s and load cells at the upper and lower neck. Injury to the knee was measured according to the procedure described by Kajzer [1997]. This involved measuring shear loads and moments acting at the knee, as well as, displacement and bending of the tibia relative to the femur. To enable such measurements, multi-axis femur and tibia load cells were included in the design. For estimating angles and displacements, linear and angular accelerometers were added to both the femur and proximal tibia. Measurement systems were also designed to assess the amount of lateral deflection produced at the ribcage and abdomen.

Design and Development of POLAR

Knee Design - The most important design feature in Polar was a human-like knee. The motivation for moving to a human-like design was the expectation that if the general contact geometry between the femur and tibia and the resistance of the four knee ligaments were represented, then the dummy should produce a human-like response during lateral impact.

The Polar knee was designed based on a shape digitized from the physical knee model. The geometry was simplified so that the femur condyles were represented as elliptical cylinders with left/right symmetry. The meniscus was molded from Urethane and was made thicker than the human counterpart to provide durability but with stiffness comparable with the human meniscus.

Each of the four knee ligaments is composed of a combination of steel spring, rubber tube, and steel cable. The stiffness of the spring and rubber tube combination provide the compliance of the ligaments which were based on literature values [Yang, 1995]. The average stiffness was selected so that the force and elongation at the point of rupture in the human ligament would be comparable to the force and elongation in the mechanical system. The origin and attachment points of the MCL and LCL were similar to the human knee but had to be modified for the ACL and PCL, in order to provide an adequate pathway for the cables connecting the femur to the tibia. For simplicity, the LCL and MCL have similar geometry and properties, and the ACL and PCL also have similar geometry and properties. Figure 2 shows a frontal and side view of the new knee assembly with attached load cells on the femur and tibia ends.

Figure 2 Knee Structure

The new knee structure was tested in a test setup which was a simplified version of the original lateral impact tests performed by Kajzer [1997, 1999] to obtain the dynamic response of the knee in shear and bending. There was general agreement in both the magnitude, timing, and duration of the force time history for both shear and bending tests at impact speeds of 4.7 m/s and 9.5 m/s. The impact speeds were reduced from the values used in the Kajzer tests (5.5 m/s and 11.1 m/s) to compensate for a heavier impactor mass, so that the total impact energy would be the same for the two test configurations. For the bending tests, the peak force obtained was about 15% higher than the PMHS results, but closer to the target response than obtained with other mechanical knees.

Knee Injury Assessment - A preliminary procedure was developed to estimate the parameters of interest for assessing knee injury. Five axis load cells (Fx, Fy, Fz, Mx, My) are placed just above the knee in the femur, and below the knee in the upper tibia. In order to account for the rotation of the tibia relative to the femur, uniaxial angular accelerometers are placed above and below the knee. Uniaxial linear accelerometers are also placed on the femur and tibia to provide a means of estimating translational motion of the tibia relative to the femur, during the early portion of the impact.

Tibia Design - A new deformable tibia was also included in the design. It was felt that some deformation was required during the impact with the bumper in order to properly manage the crash energy and transmit the appropriate level of force to the upper leg and pelvis. Thus a deformable tibia with human-like deformation characteristics, was thought to increase the biofidelity of the initial vehicle impact with the lower leg and knee.

The biomechanical requirements for a deformable tibia were :

1. It should have static loading response in lateral loading similar to that of cadaver tibias as given in Yamada [1970].
2. It should have dynamic loading response similar to that seen in tibia lateral impact tests as described by Nyquist et al [1985].

In addition to the biomechanical requirements, a design requirement was added that the deformable tibia should be reusable to make the tibia easier to certify and also easier to maintain. However, the effect of fracture would have secondary influence on the final kinematics. A number of computer simulations were performed with a deformable element that could undergo ultimate fracture. It appeared that there would be only limited influence on the final body trajectory, once the energy absorbed in the deformation is accounted for.

The main design features of the deformable tibia are:

- The tibia is a hollow rod made of hard Urethane (75D), with a rod of Kevlar/nylon inserted in the middle.
- The two ends of the tibia have a tapered design to relieve stress concentration and resemble human tibia.
- The ends of the tibia were reinforced with internal and external steel rings bonded to the Urethane.
- The left and right tibias are symmetrical and interchangeable.

The features of the new tibia are shown in Figure 4. Static and dynamic tests were performed on the tibia and good agreement was found for the static loading conditions and fair agreement for the dynamic impact. A rigid, aluminum tibia of a similar shape, was also designed as a backup design, in case the flexible tibia showed durability problems. More details on the design and its biofidelity is given in [Artis, 2000].

Instrumentation for Thorax and Abdomen - In order to assess the likelihood of injury in the lower ribcage and in the abdomen, measurement systems were added to measure lateral deflections in these regions. The deflection in the ribcage is measured using a modified version of the Crux system used in the Thor dummy. The end of the Crux unit was attached to a lateral point on the 4th rib and. The system is capable of measuring up to 90 mm of deflection in the lateral direction.

The lateral deflection in the abdomen is measured using a high-speed. string potentiometer (Space Age Control. Model 160-0321VR). This is aligned in the local Y direction using a pulley system that guides the string from the potentiometer housing. Deflections up to 100 mm can be measured using this system.

Shoulder Design- It was known that the resistance of the shoulder in fore-aft rotation (adduction-abduction) was relatively stiff as compared to a human. It was hoped that decreasing the stiffness of the shoulder in this motion, would help in softening the contact of the head with the hood. In order to decrease the stiffness of the shoulder during its contact with the hood, the effective moment arm of the main shoulder block was increased to allow for greater rotation. The modification made in the shoulder geometry is shown in Figure 5.

Instrumentation - A number of sensor channels were included for measurement in the Polar design. The sensors were selected to provide the dynamic information necessary to estimate typical injury parameters.

It was recognized that cabling required to connect the sensors on the pedestrian dummy to an external data acquisition system could interfere with the motion of the. Dummy. For future testing with Polar, an on-board DAS is being planned. With such a system, it is expected that the number of channels will be increased significantly for the final version of Polar. At the time of the first round of testing with Polar, a small, prototype, on-board DAS system with 8 channels was put into the dummy.

CERTIFICATION TESTS

First Series

A series of seven tests were conducted at JARI to evaluate the response of Polar under lateral impact. The front of an intermediate sized vehicle was placed on a HyGe sled. Impact speeds were at 32 km/h and 40 km/h. The vehicle was similar to that used in the PMHS tests performed earlier.

The height of the hood leading edge (bonnet) was 145 mm and the height of the center of the bumper was 383 mm. A total of seven tests were performed. The test matrix is described in the following Table 1. It shows the various combinations of Polar design features that were made available for this test series. Both a stub arm that was used with Polar I and a normal full arm was used. Tests with the full arm had the hands tied at the front at the wrist. The table also shows the wrap around distance (WAD) measured in each test.

From this test series, following results were obtained.

1. The configuration with full arm, modified shoulder and flexible tibia provided most biofidelic kinematics, including head velocity at both impact speeds.
2. For the 40 km/h impact tests, the dummy motion was in the corridor for both trajectory and head velocity.
3. For the 32 km/h impact tests, the trajectory was within the corridor. The magnitude of the peak velocity is now in within the corridor but occurs about 20msec too early.
4. The dummy kinematics for the 50 km/h test appears to be reasonable.

Second Series

Following the first test series, it was decided that some more modification should be made to improve the kinematics of the dummy, especially the head velocity at 32 km/h.

Computer simulations Using Dynaman and also Madymo were conducted to find the effective parameters on the head velocity. The results indicated that following modification would be improve the head velocity.

1. Decreasing the lateral Stiffness of the lumber joint.
2. Increasing the lateral motion range of the shoulder joint.
3. Raising the positions of the lumber and thoracic joints.

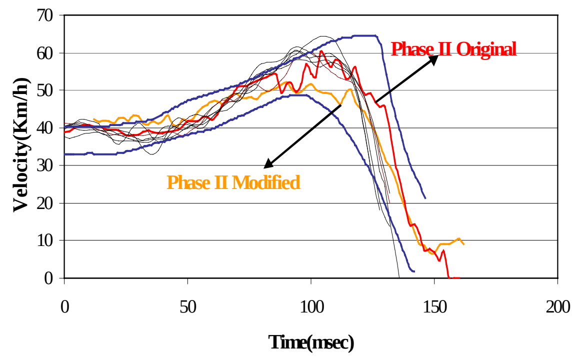

Figure 3 Resultant Head Velocity at 40 km/h

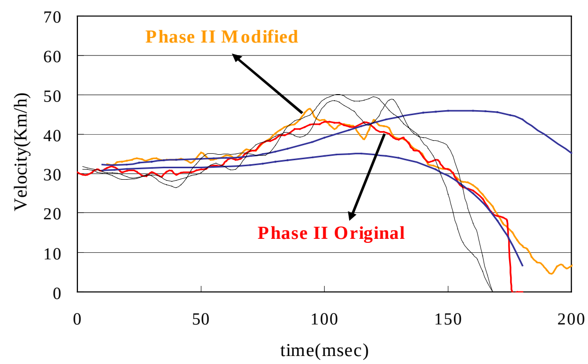

Figure 4 Resultant Head Velocity at 32 km/h

Table.1 Test Matrix

Test No.	1	2	3	4	5	6	7
Tibia	Flexible	<-	<-	Rigid	<-	Flexible	<-
Shoulder	Rigid	Spring	<-	<-	<-	<-	<-
Arm	Stub	<-	Full-Arm	<-	<-	<-	<-
Impact velocity (km/h)	40	32	<-	<-	40	<-	50
WAD (mm)	1866	1785	1846	1916	1946	1846	1846

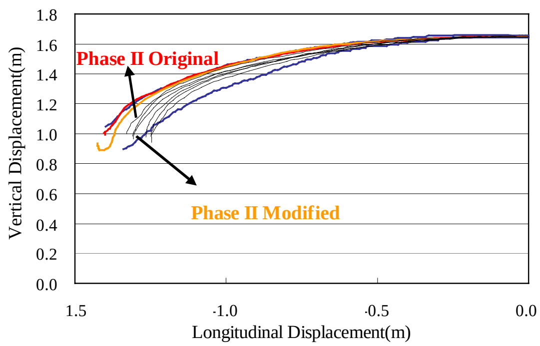

Figure 5 Head Trajectory at 40 km/h

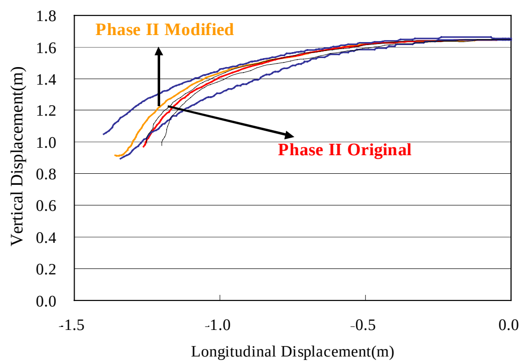

Figure 6 Head Trajectory at 32 km/h

These modifications were made and the certification tests were conducted again.

Figures 3 to 6 show the head velocities and trajectories together with the results of first test series and phase I tests. Blue lines indicate the corridors made from PMHS tests. Thin black lines are results of phase I test and red lines are phase II original (first series) tests. And orange lines indicate the modified (second series) test results.

Head Velocity - The mostly emphasized improvement of the kinematics in the phase II development is head velocity at 32 km/h. In phase I tests, peak value of the head velocity is much higher than the corridor and occurs earlier. In phase II, peak value has decreased and now is enough within the corridor. However, the timing of peak value is still about 20 ms earlier than the corridor. And even with the modified phase II dummy, the peak timing is not so much modified comparing with phase II original result.

In the phase I, head velocity was almost within the corridor at the impact velocity of 40 km/h. The phase II results indicate that the head velocity at 40 km/h impact is improved and well within the corridor.

Head Trajectory – Head trajectories were well within the corridor at both 40 and 32 km/h in the phase. It was concerned that the modification of lumber and thoracic joint might cause the elongation of head trajectory and it might go out of the corridor. Figure 5 shows that the elongation occurred at 40 km/h, but the trajectory is still in the corridor. At 32 km/h, elongation can be also seen but it is not so significant and the trajectory is well within the corridor.

From the second test series, following results were obtained.

1. Head trajectories are well within the corridor at both 40 and 32 km/h.
2. Head velocity at 40 km/h is also within the corridor.
3. Head velocity at 32 km/h has been much modified from the phase I result. The peak value is in the corridor, but the time of the peak value is still earlier than the corridor even in the modified phase II series.

Although a small problem is remaining in the kinematics at low speed impact, it is decided that the development of the dummy is finalized for the time being. It is because;

1. Kinematics of the dummy at 40 km/h well satisfies the requirement and proved the dummy can be used at the speed.
2. The trajectory and peak value of the head is within the corridor. It means that by full scale test using this dummy, head contact point, angle and velocity can be determined.
3. 50 km/h test result proved that the dummy is enough durable and the kinematics is reasonable up to this speed.

Table 2 Front Geometry of Test Vehicles (mm)

Vehicle No.	1	2	3	4	5	6
Bumper Height	665	661	548	599	488	508
Hood Egde Height	822	766	737	1015	665	634
Bumer Lead	148	72	89	84	149	128
Hood Length	937	822	806	214	690	993

FULL SCALE TEST

As a next step in the study of the pedestrian dummy, full-scale tests using this new pedestrian dummy with several mass production vehicles were conducted. The kinematics and injury related measurements were compared vehicle by vehicle.

Objectives

Objectives of this test series are;

1. To confirm that the body structures and measurement systems of Polar are effective and durable with another types of vehicles than that were used for the certification tests.
2. To see the effect of body shape or characteristics on the trajectory and injury of pedestrians.

For these objectives, different types of the vehicles were selected for the tests.

Tested Vehicles

The vehicles used in the test series are listed in table 2.

Vehicle 1 is a kind of SUVs that has a high bumper and high hood edge. Vehicle 2 has a rather special shape that the bumper is high as vehicle 1, but the hood edge is not so high. Vehicle 3 is also a kind of SUVs, but it has ordinary bumper and hood edge height and short and slanted engine hood. Vehicle 4 belongs to the special category of mini vehicle that has an engine of 660cc displacement. Its front shape is nearly vertical and has a very short hood. Vehicle 5 is a ordinary passenger vehicle. It was designed with considerations for pedestrian safety, i.e., with energy absorbing structures for both head and leg protection. Vehicle 6 is also a ordinary passenger vehicle with a similar shape as vehicle 5. However no special consideration for pedestrian safety was taken in designing it.

Test Condition

The tests were conducted in the similar condition as that of the certification test series. Test velocity was 40km/h. The dummy was suspended from the roof in the walking posture, and released prior to the impact. However, real vehicles are used instead of cut body on the sled that was used in the certification tests. Dummy left leg, which is impacted side leg, was backward positioned while it was foreword positioned in the certification tests. It is because to observe the motion of the impacted side leg more clearly from the backside of the dummy.

The dummy was released 100 ms prior to the impact to ensure its whole weight are loaded to the legs in the event of impact. Automatic brake system was installed to the vehicles, which was activated 300 ms after the impact, and stopped the vehicle

Test Results

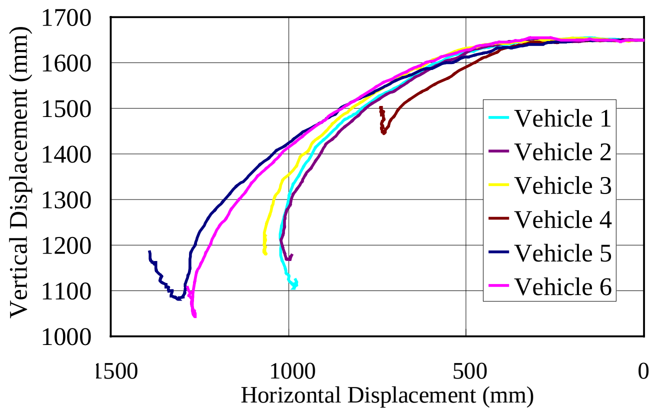

Figure 7 Trajectories of Head C.G.

Kinematics of pedestrian head – Figure 7 shows the trajectories of head C.Gs Vehicles 1 to 3 are SUVS, and pedestrian head flies in almost the same trajectory in the tests with them. The height of head contact point for Vehicle 1 is the lowest although its hood is highest. It's because in vehicle 1, head contacted to the hood surface, while head to the windscreen which slope is steeper than that of hood in vehicles 2 and 3. The inclination of the windscreen made the head contact points higher.

Vehicles 5 and 6 are ordinary passenger vehicles, and head trajectories for them are almost the same., and horizontal displacements are about 300mm longer than that of SUVs

Vehicle 4 has a very short nose and the head collided to the windscreen. So the horizontal travel of the head is very short and the impact angle is small.

Table 3 WAD of head contact point

Vehicle No.	1	2	3	4	5	6
WAD(mm)	1750	1760	1790	1750	1960	1840

Table 3 shows the WAD of head contact point and the ratio of WAD and the stature of the dummy. It indicates that with vehicles that have high hood, the ratios of WAD to height are almost 1. But in case of vehicle 5 and 6, which have rather low hood, WADs are 100 to

200mm longer than that of high hood vehicles.

This result indicates that with low hood, pedestrian body hardly be stopped at hood edge and it slides relatively freely rearward. Consequently, WAD of head contact point becomes longer.

Figure 8 shows the resultant head velocities relative to the vehicle body. Stars on the velocity curves indicate head contact times and velocities. And in Table 4, maximum head velocities and the velocities at the time of head contacts to the hood or windscreen are listed.

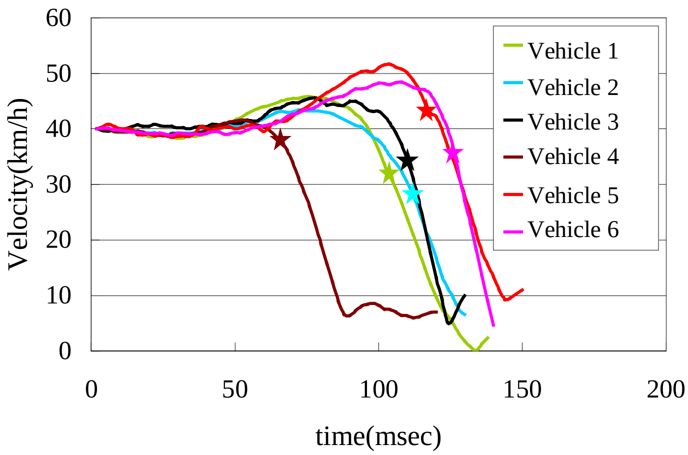

Figure 8 Head Resultant Velocity

Table 4 Maximum and Contact Head Velocity

Vehicle No.	1	2	3	4	5	6
Maximum Velocity	45.8	43.4	45.6	41.6	51.6	48.4
Contact Velocity	31.4	28.0	34.3	38.6	42.1	36.4

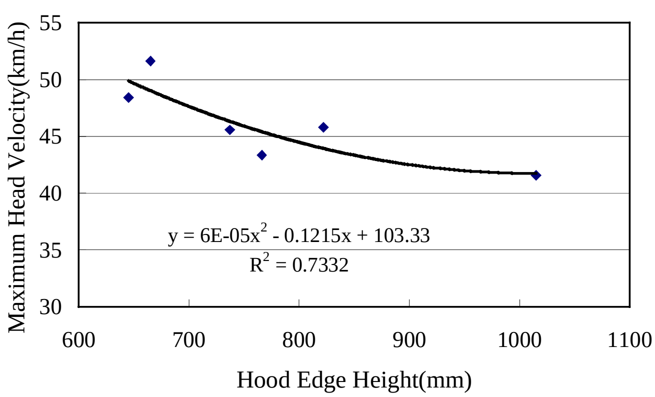

Figure 9 Hood Edge Height and Maximum Head Velocity

Head velocity time histories can be classify into three groups as same as head trajectories, Vehicle 1 to 3, Vehicle 5 and 6, and Vehicle 4. Figure 9 indicates the relationship between maximum head velocities and hood edge height. Obviously, there is a clear correlation between them. When pedestrian is hit by a vehicle with low hood edge, maximum head velocity is high On the contrary, with high hood edge, maximum head velocity falls down.

Seeing them by categories, Vehicle 4 has short hood and nearly vertical windscreen. The upper body of the dummy does not incline so much before the head contacts the windscreen. The head velocity does not increase nor decrease so much and head collides to the windscreen at nearly the vehicle impact velocity.

Vehicles with low hood, such as vehicle 5 and 6, impacts the rather lower part of pedestrian. It causes relatively high rotation velocity of the body and consequently, high head velocity. Maximum velocities are about 50km/h for this group, it means more than 20% higher than vehicle velocity. However, after the upper body contact, head velocity rapidly decreases and contact velocity falls to around 40km/h, which is same as vehicle velocity, or lower.

In case of vehicles with high hood, like vehicle 1 to 3, maximum velocities are a little higher than vehicle velocity, but lower enough comparing with low hood group. Its because impact point to the body is relatively near the C.G., so rotation velocity is lower. After the peak value occurs, the upper body of the dummy contacts the hood. It decelerates the head velocity and head contact velocities are lower enough than vehicle velocity.

Lower extremity - To measure injuries of lower extremity, Polar is installed with load cells at upper and lower tibia, and femur, accelerometer in pelvis, linear and angular accelerometers at upper and lower knee to measure linear and angular displacement of knee. However, knee displacement measurement by accelerometers did not work well in this test series due to the problem of data processing system. So linear displacements were not analyzed and angular displacements were measured by high-speed video analysis.

- Bending Moment

Figure 10 and Figure 11 indicate the relationships between maximum bending moment and hood edge height. Figure indicates the bending moments at upper tibia and Figure is at femur. Minus value here means that leg is bent to rearward. So the lower the value in this graph, the larger the moment is.

Similar trends can be seen in both femur and upper tibia, i.e., bending moment is the largest when the hood edge height is about 750mm. But the correlation with the hood edge height is much higher in the femur bending moment than in upper tibia.

When the hood edge is low, hood edge does not hit the femur but the hood surface does. Hood surface is rather soft structure comparing the hood edge, so the bending moment at the femur is not so high. When the hood edge height is around 750mm, it hits the around the middle of the femur. It causes the very high bending moment at the femur. If the hood edge rises higher than this value, it hits the pelvis area instead of the femur. Consequently, the bending moment at the middle of the femur falls again, but the load to the pelvis area rises. If a vehicle of this kind of body shape hits a pedestrian, injury may occur at the pelvis instead of the femur.

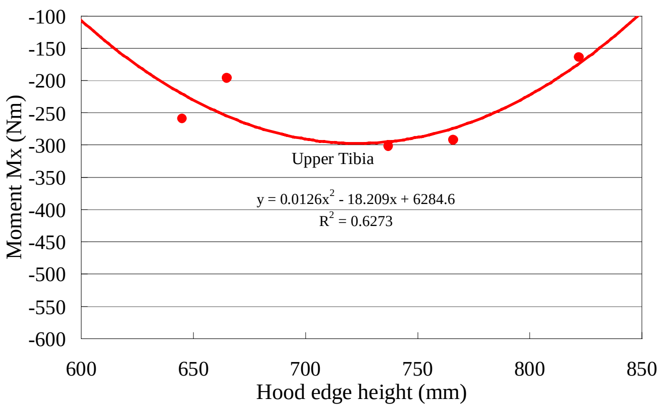

Figure 10 Hood Edge Height and Upper Tibia Bending Moment

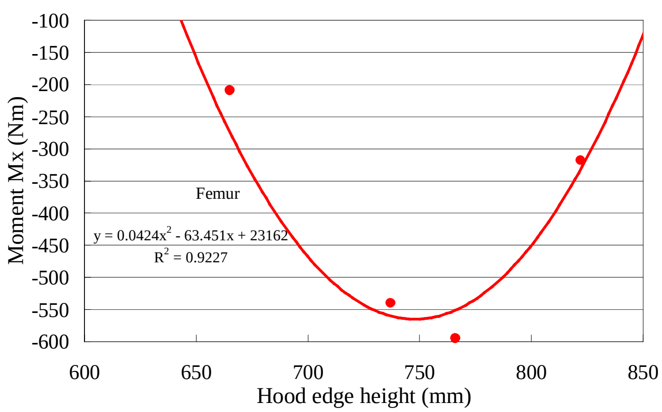

Figure 11 Hood Edge Height and Femur Bending Moment

- Shearing Force

Shearing force at the femur also has a correlation with the hood edge height. Figure 12 shows the relationship between them. Upper line indicates positive peak value, i.e., the load is applied to the upper part of the femur. And lower line indicates the negative peak value, i.e., the force is mainly applied to the lower part of the femur.

It is very interesting that the differences between positive and negative peak are almost the same value of about 1.5kN. However ratios of the positive and negative values are different vehicle by vehicle. The mechanism of this trend is not clear now, but basically, positive value occurs by the impact from the hood edge and negative value is by the bumper. Usually, the hood edge height and the bumper height are related, i.e., a vehicle with a high hood edge has the tendency to have a relatively high bumper. But the distances between them are not the same. Further study will be needed in this area.

Upper tibia force has a correlation with bumper height. Figure 13 shows the relationship between the bumper height and upper tibia force. It indicates that the bumper height and upper tibia force have a nearly linear correlation. The upper tibia force rises with the height of the bumper, i.e., with a higher bumper, upper tibia shearing force is higher.

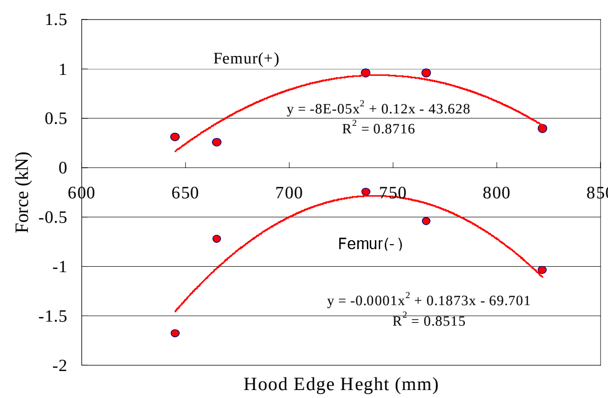

Figure 12 Hood Edge Height and Femur Shearing Force

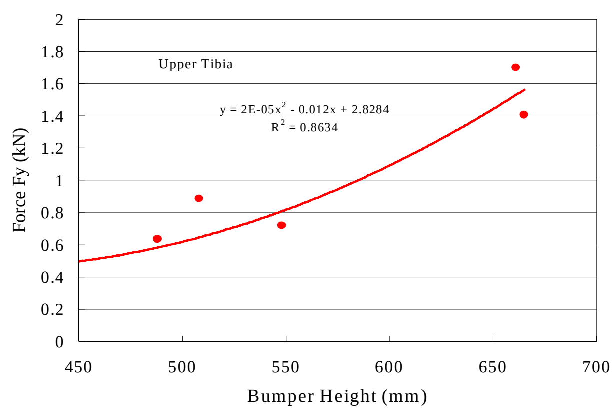

Figure 13 Bumper Height and Upper Tibia Shearing Force

- Knee Bending Angle

In the impact test with the pedestrian dummy, knee bending angles indicate rather large values. One reason is that the dummy has flexible tibia and the bending of the tibia is included in the angle measured by high-speed video analysis. And another is that the dummy has upper body and it causes a large bending of femur comparing with the leg-form impactor test. However, comparing these values, the analysis of relation between knee bending angle and vehicle body shape can be conducted.

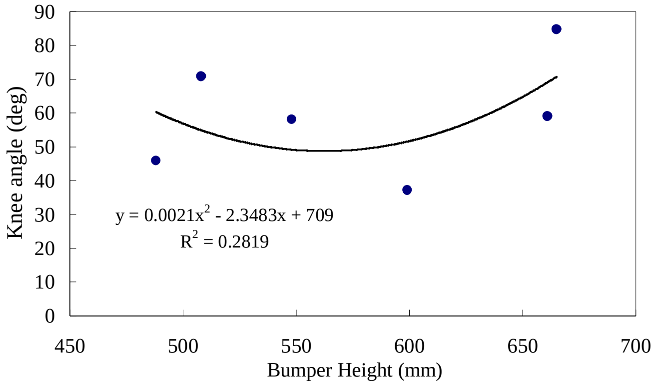

Figure 14 Bumper Height and Knee Bending Angle

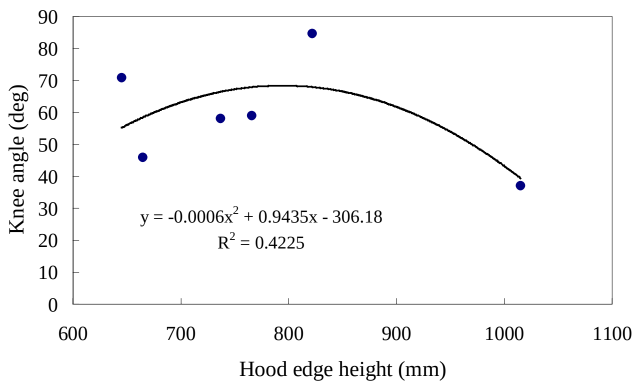

Figure 15 Hood Edge Height and Knee Bending Angle

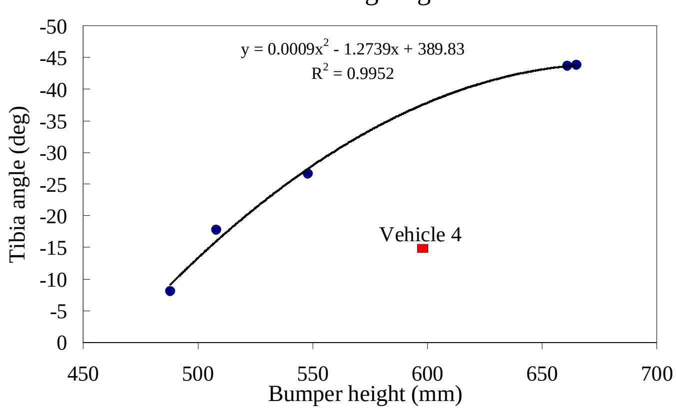

Figure 16 Bumper Height and Tibia Angle

Figure 14 shows the relationship between knee bending angle hood edge height, and figure 15 shows the relationship with bumper height. It seems that no clear relation can be seen in these graphs. However, focusing on the tibia angles, correlation with bumper height can be seen. Figure 16 shows this relation. Maximum tibia angle significantly rises with the bumper height. This corresponds with the result that upper tibia shearing force is higher with higher bumper. In this graph, Vehicle 4 is excluded from the analysis because it has the very special shape.

Pedestrian Friendly Body

Vehicle 5 has the pedestrian friendly body structure such as leg protection bumper, head protection hood hinge, etc. As described up to here, kinematics of the dummy and measurement value of the transducers are much influenced by vehicle shape. But Vehicle 6 is of similar shape as Vehicle 5 and no special consideration was taken in designing it. So comparing these two vehicles, effectiveness of the pedestrian safety measure was verified.

In Table 5 measured values of Vehicles 5 and 6 are listed. The value hatched with yellow means it is higher than that of the other vehicle. In tests with both Vehicles 5 and 6, the dummy head collides into windscreen that has no special feature, so no head injury related value (HIC, maximum acceleration, etc) is listed here.

All the values related to leg and femur injuries are lower in Vehicle 5. It indicates the effectiveness of pedestrian friendly body structure for lower extremity injuries. However, maximum head velocity in Vehicle 5 test is higher than in Vehicle 6. Vehicles 5 and 6 are of similar shape. But they are not exactly same, and head velocity is much affected by body shape. So it can not say directly that the leg protection features have the opposite effect for the head velocity. Further study on the effect of body shape on the head velocity in characteristics is needed.

Table 5 Measured Values for Vehicle 5 and 6

		Vehicle 5	Vehicle 6
Head Velocity(km/	Peak	52.6	48.4
	Contact	42.1	36.4
Bending Moment (N-m)	Femur	209	-
	Upper Tibia	196	259
	Lower Tibia	115	-
Shearing Force (kN)	Femur	0252/-0.72	0.306/-1.679
	Upper Tibia	0.634	0.887
	Lower Tibia	1.112	-
Knee Bending Angle		46	71
Acceleration (G)	Lower Femur	81	275.1
	Upper Tibia	61.5	136.4

CONCLUSIONS

The following are conclusions obtained from this study.

1.The certification tests results show that new pedestrian dummy, POLAR, can well reproduce the kinematics of a pedestrian in the event of a collision with a vehicle.
2. The dummy had no damage at 50 km/h test, which proved its durability up to the speed.
3. The newly designed biofidelic knee and tibia performed properly in the tests and were durable at up to 50 km/h.
4. Full scale tests with the vehicles of various kinds of body shape proved the possibility of the dummy in assessing the effect of vehicle shape and characteristics on pedestrian injuries.

DISCUSSION

The new pedestrian dummy "POLAR" has been developed. It has biofidelic knee structure and flexible tibia which were proved to have good agreements with Kajzer's test results of PMHS's knee structures. [Artis, 2000] It indicates that this leg structure can be not only used in a dummy but also a base for a new test device assessing aggressiveness of vehicle front structure.

The series of certification tests were conducted and it was proved that the kinematics of the dummy shows good agreement with that of PMHSs at 32 and 40 km/h collision. The dummy is durable up to 50 km/h collision and is seems the kinematics is fairly good at this velocity. It means that the dummy can be used at the velocity range from about 30 km/h up to 50 km/h.

Full scale test series with various kinds of vehicles indicates that the dummy can be used in tests with various shapes of vehicles. The kinematics and measured values show some correlation with body shape. It indicates the effectiveness of the dummy in assessing the total performance of vehicles in pedestrian protection.

However, the correlation between measured values, such as bending moments, accelerations, etc, and pedestrian injury level is not clear for the time being. Further studies in this area is needed to make the dummy more effective in study of pedestrian protection and development of pedestrian safety vehicles.

Polar is equipped with on-board DAS. But the system is a prototype at this stage. Finalizing and validation of the system is to be conducted.

FUTURE WORK

1. Studies to make the measured values correlated with pedestrian injuries and to establish injury criteria will be needed.
2. Studies on the injury mechanism of pedestrians using this dummy should be conducted to improve the pedestrian safety performance of vehicles.
3. Although component test results indicates that the leg of the dummy is enough biofidelic, knee bending angles in the full scale test series seems rather large. This fact should be checked and some more modification might be made if necessary.
4. Instrumentation including DAS is not finalized at this moment. Completing the system and certification should be conducted.

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