DEVELOPMENT OF PERFORMANCE SPECIFICATIONS FOR A PEDESTRIAN RESEARCH DUMMY

Jeff Crandall
K. Wiley
Doug Longhitano
A. Akiyama
SAE Pedestrian Dummy Task Group
Paper 05-0389

ABSTRACT

Existing test procedures assessing vehicle interactions with a pedestrian have generally been limited to subsystem impactors. The complex kinematics of vehicle-pedestrian impacts necessitates test surrogates that possess whole-body response capabilities. This paper reports on the activities of an international task group working to develop a recommended practice for pedestrian dummy performance. The objective of the task group was to develop a performance standard for a research dummy based on existing technology. Potential applications include the study of pedestrian kinematics, injury prediction, and the evaluation of countermeasures including active systems. Specifications focus on the 50th percentile male for primarily lateral impacts in the range of 30 km/h to 50 km/h. Development of the specifications included a detailed review of the literature and evaluation of existing dummies including the Hybrid III and the POLAR II. Based on these studies, biofidelity priority was given to whole body kinematics, as well as head, knee, leg, and thoracic impact response. Biofidelity requirements for whole-body kinematics were developed from cadaveric impacts with a late model vehicle. The specification also includes component response corridors for the head, leg, knee, and chest. In addition to the biofidelity evaluation, testing at facilities around the world was performed to evaluate durability, usability, and repeatability of existing dummy technology.

INTRODUCTION

Worldwide, pedestrian crashes constitute the most frequent cause of traffic-related fatalities. Improving vehicle design to make automobiles less aggressive to pedestrians during impact is an essential component of reducing the frequency and the severity of pedestrian injuries. Assessing the level of protection offered by existing and future vehicles will likely be accomplished by a multi-dimensional evaluation including full-scale tests, subsystem tests, and computer modeling.

Currently, the primary evaluation tool for assessing potential pedestrian protection is subsystem test procedures. Through an evolution of procedures within the European Enhanced Vehicle-Safety Committee (EEVC) Working Groups 10 and 17, experimental test devices have been developed that represent the head, thigh-pelvis, and lower extremity (EEVC 2002). Pedestrian protection test procedures have also been discussed or developed in ISO and IHRA activities with the resulting procedures similar to those of the EEVC. In Europe and Japan, pedestrian protection regulations will be introduced based on the EEVC procedures and IHRA activities. Given the complexity of pedestrian kinematics during vehicle impact, subsystem test procedures alone, however, are likely insufficient to evaluate the comprehensive level of protection potentially afforded by vehicle countermeasures. The interrelationship of response between successive contacts of body regions is strongly determined by the pedestrian and vehicular geometry, the impact speed, the orientation of the pedestrian, and the response of previously contacted structures. In addition, subsystem tests are not effective for evaluating active safety systems such as pedestrian airbags or pop-up hood systems. These countermeasures usually include sensors that detect pedestrian contact with the vehicle that cannot be evaluated by subsystem testing. To study and assess the vast array of vehicle-pedestrian interactions, test surrogates that possess whole-body response capabilities, such as a pedestrian dummy, are necessary. Historically, testing with full-scale dummies has been hindered by both biofidelity and durability of the anthropometric test devices. Some of the problems encountered include propensity to damage dummy components, difficulty in assessing phases of impact, and uncertainty of repeatability (Harris, 1989). Recently, attempts have been made to develop improved pedestrian dummies including modifications to the H-III (Hattori et. al, 2000), a modified side impact dummy (Frederikson 2001), and the Polar II (Huang et al., 1999; Akiyama et al., 2001). However, these dummies were independently designed and used primarily by the developing organizations without independent assessment or review by a broader international community working on pedestrian safety.

OBJECTIVES

The SAE Pedestrian Dummy Task Group (SAE PDTG) was established to develop performance, as opposed to design, specifications for pedestrian research dummies based on existing dummy technology. While the objective of the group was not to develop or specify a physical device, the task group realized it was necessary to have a physical representation of such a dummy in order to assess the feasibility of meeting the dummy performance specifications using existing technologies.

Terms of Reference

The performance specification was developed based on several expected uses including the design of countermeasures, the evaluation of active systems (e.g., pop-up hoods and airbags), the validation of computer simulations, the study of pedestrian kinematics, the reconstruction of impacts including crash reconstruction of pedestrian kinematics, the refinement of component test parameters and procedures, and the prediction of injury probabilities for given vehicle, crash, and countermeasure combinations. In terms of requisite biofidelity for the dummy, whole-body kinematics were considered the foremost priority for the anticipated dummy applications.

While it is recognized that collisions involve pedestrians of all sizes, it was proposed that performance specifications for a 50th percentile adult male dummy be developed as a first step. This approach stems from the greater knowledge of biomechanics and existing dummy technologies for the mid-size male relative to other adult sizes and children. While not the initial objective, it was envisioned that additional performance specifications for other sizes of pedestrian dummies would be developed in the future based on accepted scaling procedures. The resulting pedestrian research dummy performance specifications for existing technology were based on studies of the following items:

1. An understanding of the frequency and severity of pedestrian injuries in order to properly prioritize instrumentation requirements
2. Anthropometry requirements including requirements for size, joint locations, mass, and mass distribution
3. Biomechanical response requirements for essential body regions such as the head, thorax, and lower extremities
4. Instrumentation compatibility to facilitate the measurement of engineering parameters known to relate causally to injury
5. Requirements for dummy durability, repeatability, and reproducibility
6. Functionality requirements including ease of use in a crash laboratory environment
7. A survey and evaluation of existing dummy and sensor technologies with particular emphasis on dummies currently used in pedestrian research programs
8. Whole-body kinematics observed in full scale test vehicle with post-mortem human surrogates

A brief overview of the studies conducted by the SAE PDTG is included in this paper.

Body Region Priorities

While numerous researchers have evaluated the frequency and severity of pedestrian injuries, there exists little consistency among the studies in terms of the inclusion criteria. Variations exist for the vehicle types, impact velocity ranges, body region breakdowns, injury coding schemes, and pedestrian demographics (e.g., age, gender, size). In order to determine body region priorities for a variety of performance specifications including instrumentation compatibility, component biofidelity, and whole body kinematics, a detailed review of available field injury studies was undertaken by the task group. The study simultaneous evaluated injury frequency, injury severity, injury cost, injury disability probabilities, and changing trends in the vehicle fleet. Given the lack of uniformity among studies, no quantitative assessment of the archival literature could be conducted. Therefore, a group of experts reviewed the available studies and somewhat subjectively prioritized the body regions (1 = most important, 10 = least important) based on such factors as the frequency of injury to the body region, the societal cost associated with the injury, and the probability of disability. The results of the rankings are shown in Figure 1. For the most part, the review confirmed well-known pedestrian injury trends (e.g., head injuries were the most frequent severe injuries) but perhaps lesser known observations (e.g., chest injuries moderately frequent and are associate with high injury cost) played essential roles in determining the body region priorities and instrumentation. While numerous studies were used to characterize the lower limb as the most frequently injured body region, an examination of the injuries within regions of the lower limb identified the leg as the most frequently injured area and the knee as the most frequently injured lower limb joint. While historically the thigh was a prominent region of injury, recent investigations have shown diminished frequency (Snedeker et al., 2003) with late model cars.

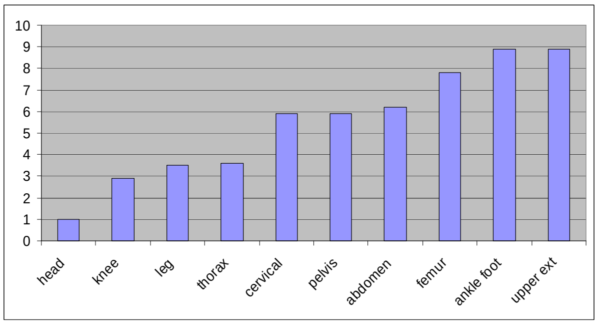

Figure 1. Body region rankings based on injury frequency, severity, cost, and disability.

METHODOLOGY AND RESULTS

Previous studies and publications were reviewed to identify response and physical parameters considered necessary for developing performance specifications for a pedestrian dummy.

Anthropometry

A target set of anthropometric specifications was determined to ensure that dummies complying with the document are, in general, representative of the 50^{th} percentile adult male. The geometric, mass, and mass distribution specifications were defined with the goal of differentiating between parameters considered to be critical for pedestrian injury studies (e.g., overall standing height and knee height) and those considered to be non-critical parameters (e.g., elbow height). The critical parameters require mandatory compliance while the non-critical factors are recommended for consideration in the design of dummies. This approach should result in dummies that are anthropometrically similar to one another, thereby facilitating the comparison of data collected with different dummies, while still not being overly design restrictive.

Defining the human anthropometry targets was complicated by the results of human studies being dependent upon the sample size and the specific subjects measured and by the fact that not all human studies contained all of the parameters needed to define a dummy (e.g., some studies with detailed dimensional data contained very limited mass distribution data). In addition, human studies with body segment data tended to use different body partition definitions making it difficult to make direct comparisons. Finally, human anthropometry data are dependent on the era and geographic location in which the data are collected. Thus, newer databases and those that included inherent geographic diversity were considered the most representative.

For the performance requirements, four primary references were used as the basis for the dummy specifications. The U.S. CAESAR data base is a recent study based on a large sample size and because of the diverse ethnicity of the U.S. was considered representative of the world population (Harrison and Robinette, 2002). The CAESAR data base provided a variety of joint locations, and three body region shape information such as circumferences etc. Other than overall mass, the CAESAR data set does not contain any body segment mass or c.g. data. The AMVO data base was used as a second source for body segment mass information.

The ManneQuin Pro V8.0 software, which is based on the 1988 Natick US Army anthropometric data base provided a complete set of parameters including overall height, joint locations, body segment masses, and body segment c.g. locations. In addition, because the software generates CAD models of the skeleton, the model could be used to identify the location of specific joints such as the C7/T1 interface. This data set could have been used as the sole source of information for this document, however the data is nearly 20 years old, and is based on a survey of U.S. Army personnel which may not be as representative of the population as a whole.

The PMHS study by Dempster (1955) provided body segment c.g. locations as a percentage of body segment length. The Dempster c.g. percentiles were combined with body segment lengths from CAESAR (or the Army data when the length was not available from CAESAR) to provide a second source for body segment c.g. locations.

A summary of the Army and AMVO mass data is found in Table 1. A summary of body region dimenstion data from CAESAR and the Army study are shown in Table 2. and target values for joint locations from CAESAR are shown in Table 3.

Table 1
Summary of body segment mass specifications

	Database	
	Army data from ManneQuin Pro V8.0	AMVO
Body Segment	Mass per dummy (kg)	Mass per dummy (kg)
Head	4.4	4.1
Neck	1.1	1.0
Upper Torso	21.5	23.7
Lower Torso	13.5	13.4
Upper arms (2)	4.0	3.5
Lower arms (2)	2.9	
Lower arms/hands (2)		4.0
Hands (2)	1.1	
Thighs (2)	19.6	17.2
Legs (2)	7.9	7.2
Feet (2)	2.0	2.0
Total	78.0	76.1

Table 2
Summary of body segment dimensions

Body Segment Dimensions	Target Value (mm)
Head Height	240
Head Breadth	154
Head Circumference	576
Head Length	200
Circumference at interscye	1008
Interscye distance	394
Hip circumference	1018
Bi-trochanteric breadth	361
Thigh Circumference	591

Table 3
Summary of joint locations

Dummy Whole Body Heights	Target Value (mm)
Top of Head	1757
T1	1519
H-Point	940
Knee	492
Ankle	73
Shoulder	1428
Elbow	1110
Wrist	851

Kinematic Response

Given the priority of whole-body kinematic biofidelity, it was considered essential to evaluate dummies under vehicle impact conditions. Kinematic response corridors based on cadaver tests were considered the most appropriate performance evaluation tool for pedestrian dummies evaluated under the same impact conditions. Since most published cadaver studies did not include the requisite combination of a late model vehicle, an identifiable vehicle model to reproduce the tests at other institutions, and multiple tests to facilitate kinematic corridors, the decision was made to focus on recent cadaver tests conducted by Kerrigan et al. (2005) with a small four-door sedan produced for sale in the US or Canadian market. While the suspension and wheels were removed to facilitate attachment to a sled system, the remainder of the vehicle fore of the b-pillar was maintained as was the total vehicle weight of 1175 kg ± 25 kg. The test impact velocity was 40 ± 2 km/h with no vehicle braking occurring until the pedestrian had ceased to be in contact with the vehicle. The pedestrian was oriented laterally with respect to the vehicle in a relatively upright mid-gait posture. The details and rationale behind the initial pedestrian orientation and impact conditions for these tests is described in Kam et al. (2005).

For assessment of pedestrian kinematics, high speed video was taken from an off board camera on the driver's side of the vehicle during the tests (Kerrigan et al., 2005). Photo targets were mounted to the cadaver head, 1st thoracic vertebra, and sacrum center. The motion of each body segment was measured by recording the location of each photo target at 4 ms intervals. The point of head strike, determined by visual examination of the video data and confirmed by head mounted accelerometers, was designated as the end of the interval of interest for computing kinematic trajectory data. Body segment velocities were calculated by differentiating the trajectory data. Since length of individual cadaveric body segments could vary, it was determined that an individual scale factor for each body segment of each cadaver was optimal for developing normalized trajectories. Corridors were developed using either the standard deviation of the recorded cadaver time-histories (e.g., head velocity) or the percentage of the pathlength traversed by the specific body region (Kerrigan et al., 2005). For pathlength corridors, it was felt that the responses shall fall within 10% and should fall within 5% corridors.

Component Response Characeristics

While the performance standard has been developed primarily for lateral pedestrian impact scenarios, it was decided that more proximal body structures (i.e., the chest and head) should have certain level of multidirectional response biofidelity. Multidirectional response is necessary to account for rotation of the pedestrian during the impact event. This rotational phenomenon is dependent upon initial orientation of the pedestrian and is described in detail by Meissner et.al. (2004). Lateral and frontal component response corridors were selected to ensure the biofidelic response characteristic of the head and thorax.

Head

Given that most existing pedestrian dummies use heads from existing frontal or side impact dummies, the decision was made to use well-established head response corridors already existing in certification, calibration, or biofidelity assessment procedures.

Frontal

The head drop test requirement for the Hybrid III (HIII) frontal dummy (FMVSS Part 572-F) was used as the biofidelity requirement for forehead impacts (Figure 2a). This requirement is based on cadaver drop tests by Hodgson and Thomas (1971). The mean peak resultant acceleration value of six forehead drop test was 250 g at 2.71 m/s, which corresponds to a free fall height of 376 mm. The requirement sets an allowable variation from the mean value of 10% (25g) (NHTSA, 2004).

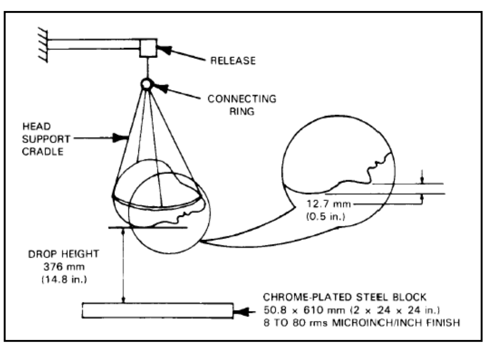

Figure 2a. Frontal head drop test.

Lateral

The head drop test requirement for the SID/HIII(FMVSS Part 572-M) was used as the biofidelity requirement for lateral head impacts (Figure 2b). This requirement was originally developed for the BioSID dummy and was also based on cadaver drop tests by Hodgson and Thomas (1975). The requirement requires the peak resultant acceleration measured at the head c.g. to lie between 100 g to 150 g when dropped from a height of 200mm onto a rigid surface (NHTSA, 2004).

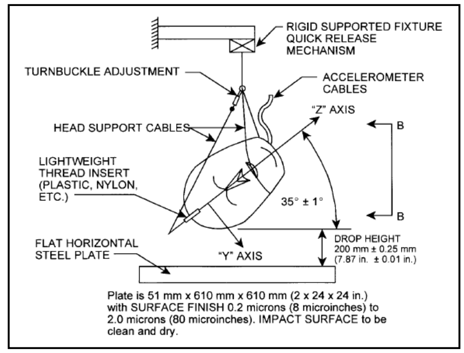

Figure 2b. Lateral head drop test.

Chest

Given that most existing pedestrian dummies used torsos from existing frontal or side impact dummies, the decision was made to use well-established chest response corridors already existing in certification, calibration, or biofidelity assessment procedures.

Frontal

For frontal response, it was decided the thoracic requirement should match the frontal pendulum requirement prescribed by Kroell (1976) for a 4.3 m/s frontal pendulum impact to the sternum.

Lateral

For lateral response, the thorax of the dummy should meet the lateral response requirements defined by ISO-9790 (ISO, 1999). This is a 4.3 m/s pendulum impact to the lateral aspect of the chest.

Lower Extremity

Unlike the more proximal body regions which experience significant rotations during the impact event, the lower limbs do not experience a significant non-lateral bending component when a pedestrian is initially struck by a laterally impacting vehicle. An assessment of pedestrian knee injury patterns (Teresinski, 2003; Bhalla et al., 2003) suggested that valgus bending was the most common failure loading mode for the knee. Pedestrian leg fractures due to bumper contact were attributed primarily to bending with shear loading of secondary importance (Teresinski, 2003). Thus, biofidelity curves were limited to valgus bending of the knee and latero-medial three-point bending of the leg.

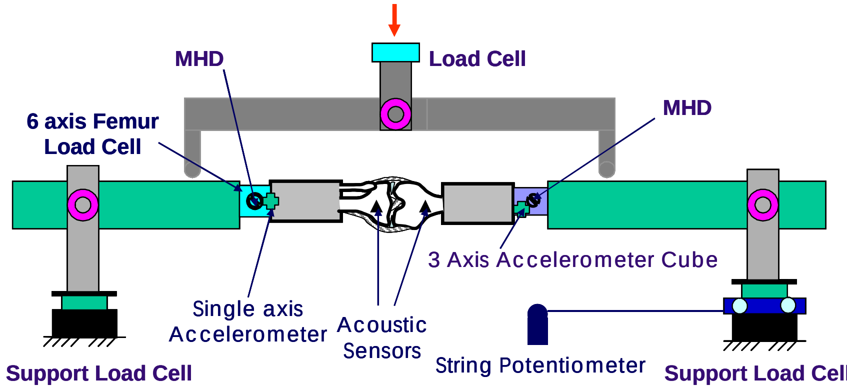

Figure 3. Schematic of the test set-up used by Bose et al. (2004) in symmetric valgus 4-point bending testing of intact human knee specimens.

Knee

The methodology and results of Bose et al. (2004) were chosen for symmetric valgus four-point bending of the knee (Figure 3). The angular velocity of the leg relative to thigh was approximately 1000º/s, determined to be a reasonable knee valgus bending rate for vehicle impacts in the range of 30 km/h to 50 km/h. Actuator and support load cells recorded the forces and moments applied to the knee specimen. Shear loads and valgus bending moments were also recorded adjacent to the knee structure using a multi-axis load cell. These forces were transferred to the knee joint using rigid body assumptions, recorded angular and linear accelerations of the segment between the load cell and knee, and inertial attributes of the segment. Ivarsson et al. (2004) scaled the inertially compensated moment-deflection responses provided by Bose et al. (2004) to the size of a 50th percentile male knee based on anthropometric femur, tibia, and patella data. A corridor was then developed around the characteristic average response using standard deviation calculations for both the independent variable (angle) and dependent variable (moment) as shown in (Figure 4).

Leg

Biofidelity requirements for leg response focused on three-point bending tests that would generate tibial bending strain rates characteristic of bumper impacts at 40 km/h. Kerrigan et al. (2003, 2004) subjected intact cadaver leg specimens to latero-medial three-point bending to failure at an approximate deflection rate of 1.5 m/s. The specimens were simply supported at a given specified distance from the proximal and distal ends such that the leg was loaded at mid-span (symmetric 3-point bending). The contact force between the impactor and specimen was determined as the sum of the normal forces measured by the three-axis load cells at the right and left supports, respectively. The maximum bending moment acting on the specimen (right under the impactor) was determined at each instant in time during loading as the average of what was calculated from the right and left side support load cell signals. Specimen deflection was determined from the impactor displacement with zero deflection defined as initial contact between the impactor and specimen. The force-deflection and moment-deflection curves from each test were geometrically scaled to the size of a 50th percentile adult male thigh and leg. Ivarsson et al. (2004) developed response corridors of dynamic latero-medial loading for the 50th percentile male leg (Figure 5).

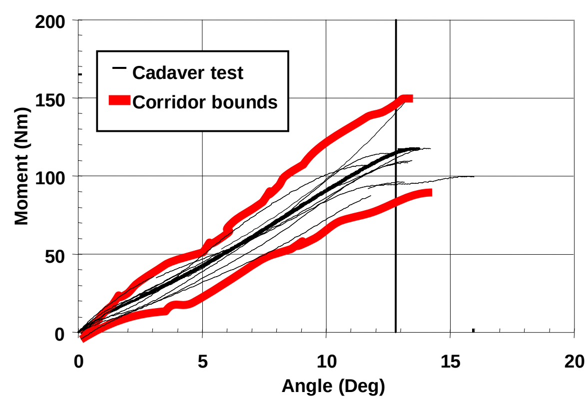

Figure 4. Moment-angle response corridor for the 50th percentile male knee subjected to dynamic 4-point valgus bending.

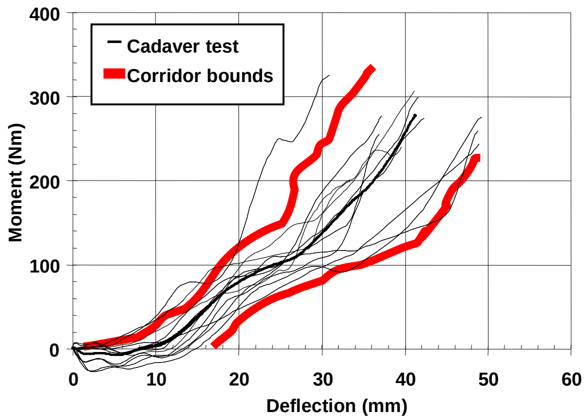

Figure 5. Moment-deflection corridor for dynamic latero-medial loading of the leg at mid-span.

While moment-angle responses were originally envisioned, inertial effects introduced complex bending modes with localized changes in deflection. Therefore, the decision was made to report a moment-deformation corridor for the mid-span position.

EVALUATION OF EXISTING TECHNOLOGY

Early in development of the pedestrian dummy recommended practice it was decided that there should be a focus on creating a practice that could be achieved using existing technology. To this end an extensive evaluation program was conducted to understand the capabilities and limitation of existing pedestrian dummy technology. These results were then used to help determine which requirements would be critical (must or shall) and which would be non-critical (recommended or should).

Test Programs

The PDTG sought involvement and participation by interested parties in the test and evaluation program for existing technology. It was requested that anyone wishing to evaluate an existing pedestrian dummy technology bring that device to the PDTG. The PDTG also solicited third party evaluations of the dummies under consideration. Two devices were submitted for evaluation, the modified Hybrid III and the Honda Polar-II, although only the latter was extensively evaluated based on interest level of the participating parties.

Five organizations participated in testing and evaluating the existing technology; DaimlerChrysler (Germany), PSA-Citroen Peugeot (France), Autoliv (Sweden), Nissan (Japan) and University of Virginia (USA). A summary of their test programs and brief synopsis of their finding is included here. Detailed summaries for each test series can be found in the documentation of the PDTG Test and Evaluation subgroup. Several organizations also contributed reports and data from pedestrian dummy testing that was not directly part of the PDTG activity.

DaimlerChrysler

The first program to test existing pedestrian dummy technology within the PDTG was conducted by DaimlerChrysler in Germany. Originally 13 tests with the Honda Polar-II were planned, but due to dummy damage and schedule delays, the test series was reduced to 8 tests (Table 4), two of which were discounted due to severe damage at 40 km/h. All tests were conducted between 30 km/h and 40 km/h in a lateral impact stance using a Mercedes E-Class vehicle. These tests showed the importance of initial positioning for achieving consistent results as well as demonstrating the influence of arm position on pedestrian kinematics.

Table 4
DaimlerChrysler Test Matrix

Arm Configuration	Speed	Comments
taped to torso	30 km/h	
bound in front	30 km/h	
bound to sides	30 km/h	
bound in front	40 km/h	Not analyzed – Severe damage
bound in front	40 km/h	Not analyzed – Severe damage
bound in front	35 km/h	
bound in front	35 km/h	
bound in front	35 km/h	

PSA Peugeot Citroen

Originally seven tests with the Polar-II were planned with five vehicles at PSA in France, but upon arrival the dummy was in poor condition and required substantive repair before testing could being. As a result of the delayed schedule only four tests were conducted as shown in Table 5. Each of these tests was conducted at 40 km/h in a lateral stance with a different vehicle type for each test. These vehicles ranged from a small car to an MPV or van. This series helps to demonstrate the usefulness of pedestrian dummies in understanding kinematic impact differences between different vehicle types

Table 5
PSA Test Matrix

Vehicle Category	Vehicle Model	Speed
Small Car	Citroen C3	40 km/h
Small Family Car	Peugeot 307	40 km/h
Large Family Car	Peugeot 407	40 km/h
Van/MPV	Peugeot 807 (Citroen C8)	40 km/h

Autoliv

Six tests were conducted with the Polar-II dummy at Autoliv in Sweden to assess the usefulness of pedestrian dummies in the development of active pedestrian protection systems such as pop-up hood and pedestrian windshield airbags (Table 6). These tests include one reference test, three active hood tests, and two airbag tests. All tests were conducted at 40 km/h in a right side lateral impact configuration with the hand tied in front and the impact leg rearward. The vehicle tested was modeled after the Saab 9-5 large sedan.

It was determined that due to the wrap around distance of the 50^{th} percentile dummy, not all desired impact locations could be contacted without modification of the test setup. In order to impact the desired head impact locations the ground level of the dummy was adjusted relative to the vehicle. For impacts to the hood structures the vehicle was raised and for contacts to the windshield area the dummy was raised.

Table 6
Autoliv Test Matrix

Purpose	Impact Location	Vertical Position
Reference Test	Hood Centerline	-95 mm
Active Hood	Hood Centerline	-95 mm
Active Hood	Above Lifter	-180 mm
Active Hood – Late Trigger	Above Lifter	-180 mm
Scuttle Bag + Active Hood	Low Windscreen Centerline	+45 mm
A-Pillar Bag + Active Hood	A-Pillar	+45 mm

Nissan

A series of 16 tests were performed by Nissan Motor Company in Japan to evaluate the Polar-II and standing Hybrid-III dummies in pedestrian and bicyclist impact scenarios. These tests looked at repeatability, variation in impact speed, variation in hand position and variation in leg position for the standing pedestrian in a lateral impact. In addition to a typical pedestrian test configuration, bicyclist tests were conducted with each dummy in front and lateral impact scenarios.

UVa

In addition to the full-scale cadaveric pedestrian tests used to create the biofidelity corridors for whole-body trajectory, the University of Virginia conducted a series of tests with the Polar II at 40 km/h. These tests were intended to replicate the cadaver test configuration and help to assess the ability of existing technology to satisfy the proposed corridors. This testing is explained in further in the section detailing whole body kinematics.

Non-PDTG Activities: VRTC, U of Adelaide

Several organizations which performed pedestrian dummy testing outside of the PDTG activity choose to participate in the task group by providing feedback, reports, and data from their testing. These organizations include the NHTSA Vehicle Research and Test Center (VRTC) in the United States and the University of Adelaide in Australia. Both of these organizations did testing to reconstruct real world crashes using the Polar-II. These two series help to demonstrate the usefulness of pedestrian dummy technology in the investigation and reconstruction of real world pedestrian crashes. They also help provide insight into the usability and durability of existing pedestrian dummies.

Durability

Given the potentially severe interaction between a pedestrian and the exterior of the vehicle or ground, it is important that a pedestrian dummy have a reasonable level of durability. For the purpose of the PDTG, it was decided that a pedestrian dummy should be able to demonstrate durability at a speed of 50 km/h, 10 km/h greater than the target impact velocity for biofidelity assessment. Testing conducted by several organizations looked at the durability performance of the Polar-II as an example of existing technology. Damage was noted in several test series dependent upon vehicle model and impact configuration.

In the first test series, conducted at DaimlerChrysler, their test engineers concluded 40 km/h impacts were too severe for the Polar-II and evaluation was limited to 35 km/h for the remainder of their test series. In these 40 km/h tests the dummy sustained broken tibia components as well as damage to some sensors and data acquisition unit components from both vehicle and ground contact. PSA found the dummy to be in poor condition upon initial inspection and made extensive repairs before beginning their test series. In their four tests at 40 km/h they found that overall durability of the dummy was good, but some improvements were need for the wiring layout to avoid sensor cable damage. Nissan also found some concern for the routing of sensor wires and encountered shoulder damage when the dummy's hands were tied behind its back. Tests at Autoliv and the University of Virginia found little concern for durability of the dummy in 40 km/h impacts. Tests conducted by other organizations also identified some minor durability concerns at 40 km/h, but generally found the damage was acceptable for the severity of impact that was experienced. In addition to the test series described, Honda R&D conducted a test at 50 km/h to confirm the whole body durability requirement prescribed in the standard. In this test there was minimal damage to the dummy and therefore it was concluded that a 50 km/h impact with a small passenger car is an achievable requirement for a pedestrian dummy.

Usability

In terms of usability, or ease of use, there was a general consensus that existing pedestrian dummies such as the Polar-II are generally easy to use with a few key exceptions. Most significant is dummy positioning. Since the Polar-II dummy cannot support its own weight in a standing position, the dummy needs to be suspended which can make it difficult to achieve a consistent initial position. Considering the importance of initial position for dummy kinematics, it was determined that the standard should include extensive positioning guidelines for the whole body kinematic test requirements. Other usability items that came up were related to the data acquisition system damage and repair of damaged dummy components. Most of the data acquisition concerns were related to integration for use in individual test labs and damaged cabling during testing. Regarding the repair of dummy components the most significant issue was the availability of replacement parts. Since the Polar-II is still a prototype device, spare parts are not always available and lead times can be long.

TEST RESULTS/REPEATABILITY

Repeatability performance of the Polar-II was evaluated in test series conducted by both the University of Virginia and DaimlerChrysler. In each of these series, one vehicle model was used for multiple tests.

During the course of the biofidelity evaluation at UVA, a series of three dummy tests was conducted with the Polar-II positioned in same initial orientation to assess the kinematic response biofidelity. Film analysis of the three tests showed that very consistent results were obtained for the head, T1, and pelvis trajectories. The head trajectory response graph is shown in Figure 6 as an example. Figure 7 and 8 demonstrate repeatability of sensor responses during repeated tests at the same impact conditions.

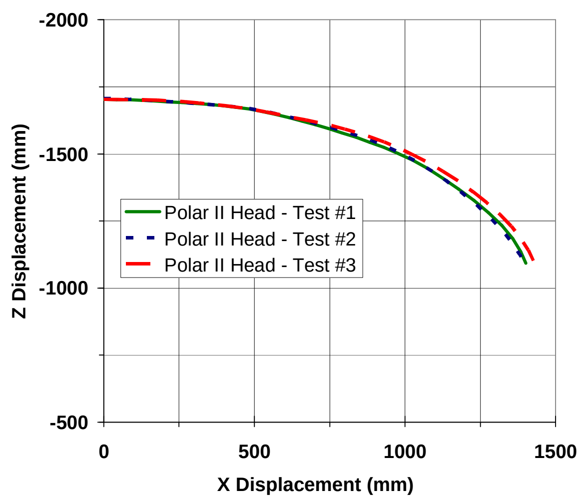

Figure 6. Polar-II head trajectory response repeatability from UVA testing

For the three tests with varied arm positions, the results of these two test series indicate that achieving a repeatable whole body trajectory is a reasonable response target for existing pedestrian dummy technology. The response, however, is dependent upon initial positioning of the dummy and can be greatly varied by changes in arm position, leg position, and orientation. Figure 9 depicts the tests conducted with variation only in the position of the upper extremities. The results indicate the sensitivity of proximal responses (e.g., the head) to more distal contacts, in this case the upper extremities. While interaction of this type would likely occur in actual pedestrian contacts with the same impact conditions, repeatability of results will require standardized procedures. Therefore, the pedestrian dummy standard will include detailed test procedures and positioning data.

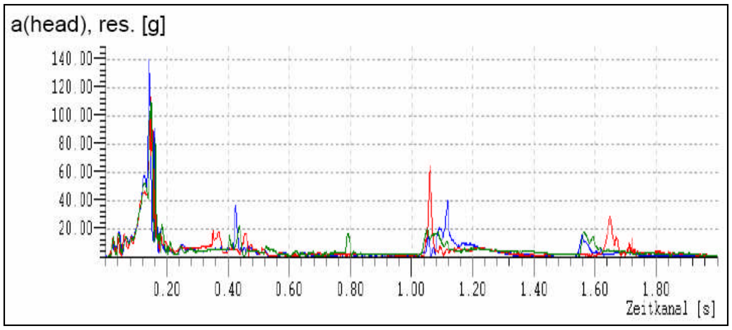

Figure 7. Polar-II head acceleration response repeatability testing at 35 km/h. (Courtesy of DaimlerChrysler).

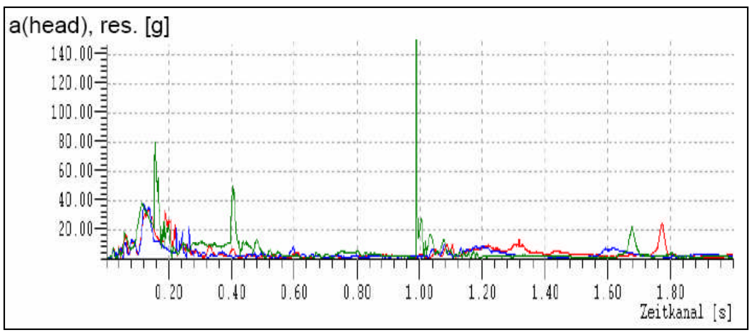

Figure 8. Polar-II head acceleration response variation with arm position changes at 30 km/h. (Courtesy of DaimlerChrysler).

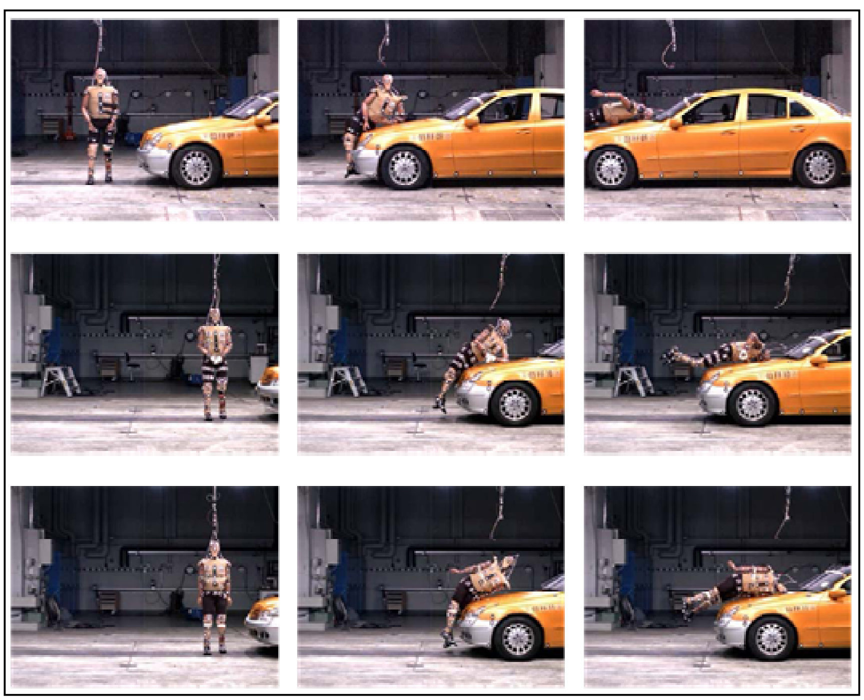

Figure 9. Polar-II whole body kinematic response variation with arm position changes at 30 km/h. (Courtesy of DaimlerChrysler).

Anthropometry

The ability of existing pedestrian dummy technologies to comply with the proposed anthropometry targets was evaluated by comparing Polar II measurements with the proposed targets. Tables 7 and 8 show the proposed target values, the Polar II measurements, and the percentage deviations.

Table 7
Comparison of body segment dimensional targets and the Polar II

Body Segment Dimensions	Target Value (mm)	Polar II (mm)	% Deviation
Head Height	240	237	1.3%
Head Breadth	154	157	-1.9%
Head Circumference	576	586	-1.7%
Head Length	200	200	0.0%
Circumference at interscye	1008	1005	0.3%
Interscye distance	394	356	10.7%
Hip circumference	1018	1038	-1.9%
Bi-trochanteric breadth	361	378	-4.5%
Thigh Circumference	591	548	7.8%

Table 8
Comparison of dummy height targets and the Polar II

Dummy Whole Body Heights	Target Value (mm)	Polar II (mm)	% Deviation
Top of Head	1757	1750	0.4%
T1	1519	1439	5.6%
H-Point	940	906	3.8%
Knee	492	489	0.6%
Ankle	73	65	12.3%
Shoulder	1428	1426	0.1%
Elbow	1110	1130	-1.8%
Wrist	851	864	-1.5%

Kinematic Response

In an effort to assess whole-body response of existing dummy designs, the Polar-II dummy was evaluated in impact conditions comparable to those used to develop the cadaver kinematic corridors (Kerrigan et al., 2005). Specifically, the pedestrian dummy was oriented to approximate the pre-impact body orientation of the cadavers. All vehicle conditions including impact speed were maintained. To facilitate body region specific response comparisons with the cadaver corridors, photo targets were affixed to the head c.g., upper spine, chest c.g., and pelvis c.g. Identical film analysis procedures were employed for the cadavers and dummies. The resulting Polar-II responses were compared with the cadaver corridors and the resulting responses are shown in Figures 10-13. Using 10% path length definitions of corridor width, all Polar-II responses with the exception of head velocity-time histories were contained in the PMHS corridor bounds. Using the standard deviation corridor for head velocity, however, the head velocity-time history did not fall within the corridor. This suggests that existing technology does comply with the majority of standard requirements although additional refinements may be necessary to satisfy all corridors.

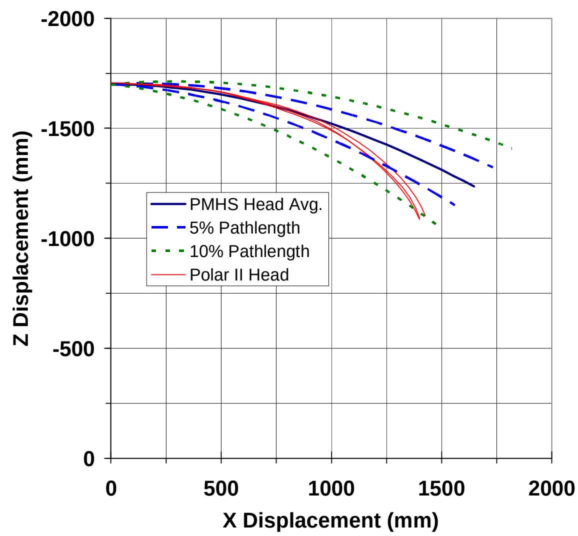

Figure 10. Polar II head response relative to cadaver corridors.

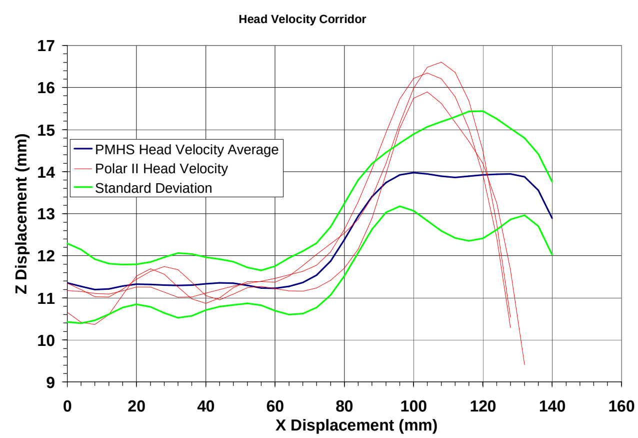

Figure 11. Polar II head velocity response relative to one standard deviation cadaver corridor.

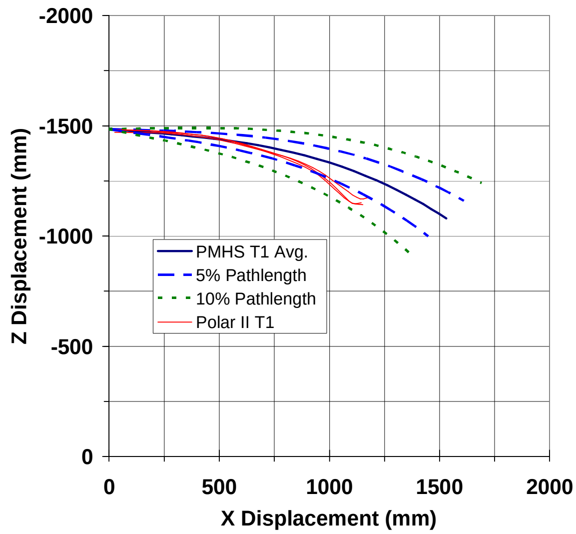

Figure 12. Polar II T1 response relative to PMHS corridors.

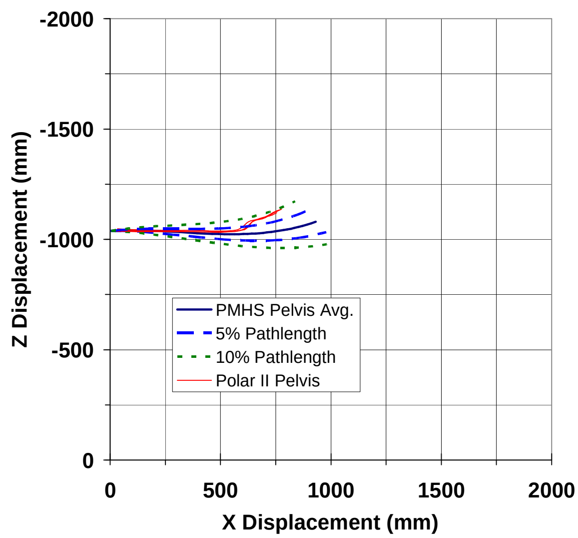

Figure 13. Polar II pelvis response relative to PMHS corridors.

The 5% corridors have also been included in the recommended practice to provide future design targets for refinement of the dummy components. In terms of satisfying the pathlength requirements, the PDTG envisions requiring (i.e., shall) compliance at the 10% corridor level while recommending (i.e., should) compliance at the 5% level.

Component Response

Head

The Hybrid III head is used for both the Hybrid III and Polar II pedestrian designs. Therefore, five frontal drop tests of the Hybrid III head were conducted in accordance with the required test procedure. Little variability was observed with minimum and maximum values of resultant head acceleration of 267 g and 270 g respectively. In addition, all resultant accelerations were within the required corridor of 225 to 275 g.

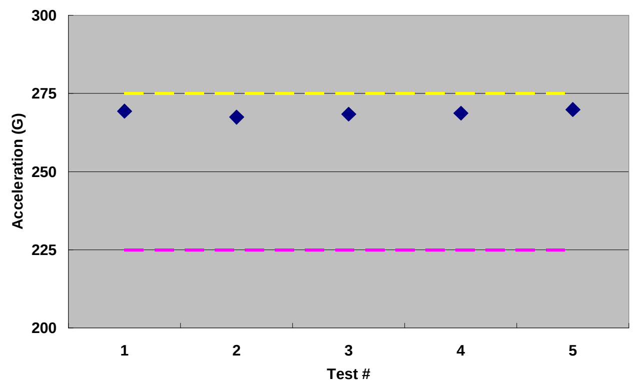

Figure 14. Frontal drop tests acceleration results and corridors.

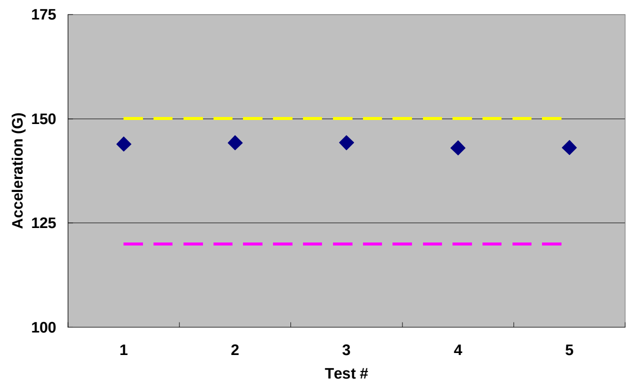

Figure 15. Lateral drop tests acceleration results and corridors.

Chest

Five 4.3 m/s pendulum tests were conducted to evaluate the Polar-II for the proposed lateral thoracic biofidelity requirement. A very repeatable response was observed in the five tests and it was demonstrated that the corridor can be achieved using current technology (Figure 16). This dummy is not configured to measure lateral spine acceleration at T1, so the ISO-9790 lateral spine acceleration-time corridor was not evaluated.

Frontal pendulum tests were not conducted using the Polar-II because this dummy is not currently instrumented to measure anterior-posterior chest deflection. However, as the Polar-II's rib structure is a modified version of the Thor dummy it is postulated that their will be some acceptable level of biofidelity in this mode.

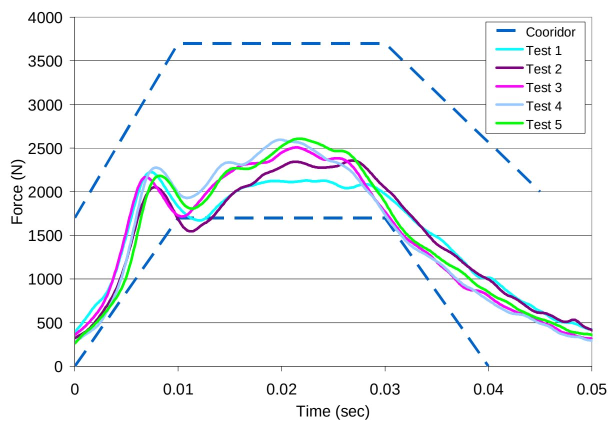

Figure 16. Lateral thoracic response biofidelity of Polar-II.

<u>Lower Extremity</u>

The Polar II lower extremity was evaluated using procedures identical to those of the PMHS tests used to develop the biofidelity corridors. A more detailed discussion of these tests can be found in Takahashi et al. (2005).

<u>Knee</u>

Three dynamic four-point bending tests of the Polar-II knee were conducted. Test results show that the moment-angle characteristics of the Polar knee are within the corridor established from PMHS test results.

<u>Leg</u>

Three replicate dynamic three-point bending tests were conducted with the Polar-II tibia. Moment-deflection and moment-angle characteristics were compared with corridors made from PMHS test results. Both characteristics almost fall within the corridors. These results show that the Polar tibia satisfies the biofidelity requirements for the leg.

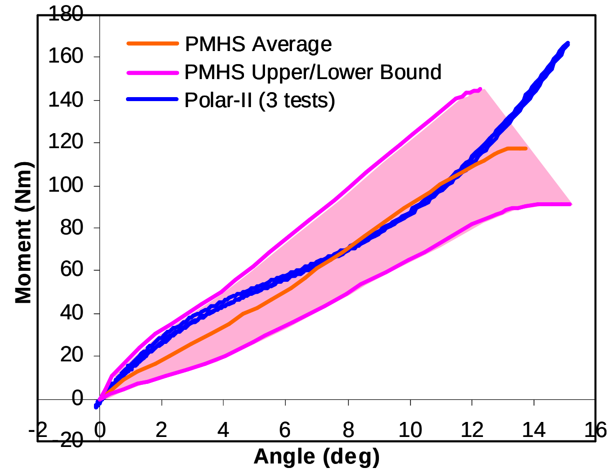

Figure 17. Moment-angle characteristics of Polar-II knee and corridors for corresponding cadaver tests.

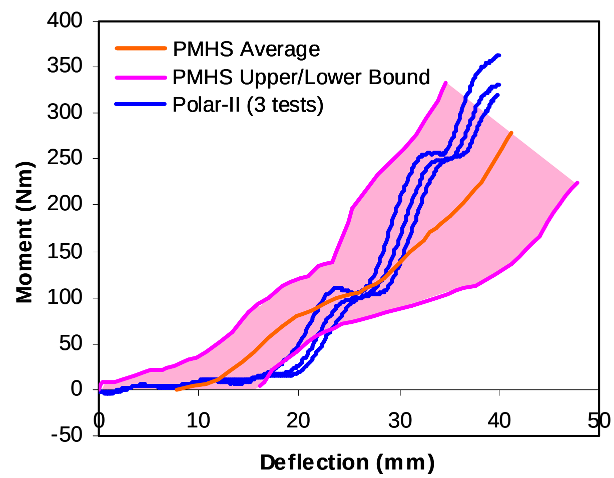

Figure 18. Moment-deflection characteristics of Polar-II leg and corridors for corresponding cadaver tests.

CONCLUSIONS

The SAE PDTG has developed a performance standard for specification of minimum anthropometric, kinematic, and response requirements of a pedestrian dummy. Existing hardware has been shown to be capable of achieving the majority of requirements at both a global (i.e., whole body kinematics) and component level (i.e., specific body region biofidelity). The goal of the SAE PDTG is to have the standard completed by

June 2005. Therefore, while the intent of the PDTG in specifying performance targets will remain unchanged, many of the precise tolerances on these requirements should be considered preliminary.

DEFINITIONS

PMHS – post-mortem human subject
PDTG – Pedestrian Dummy Task Group
SAE – Society of Automotive Engineers
NHTSA – National Highway Traffic Safety Administration
VRTC – Vehicle Research and Test Center
UVA – University of Virginia
PSA – Citroen Peugeot

ACKNOWLEDGEMENTS

We would like to thank the organizations who have been actively involved in the PDTG actives for their generous contributions. In particular we thank DaimlerChrysler, PSA-Citroen Peugeot, Nissan, Autoliv, and the University of Virginia for their test and evaluation programs. We also thank GESAC, DTS, and FTSS-Europe for their technical support and TRW and TNO for simulation support. Finally we thank Honda R&D for making the Polar-II available for industry wide evaluation.

REFERENCES

Akiyama, A., Okamoto, M., Rangarajan, N., Development and Application of the New Pedestrian Dummy, Paper 463, 17th ESV, Amsterdam, Netherlands, 2001.

Bhalla, K.; Bose, D.; Madeley, J.; Kerrigan, J.; Crandall, J.; Longhitano, D.; Takahashi, Y.; "Evaluation of the Response of the Mechanical Pedestrian Knee Joint Impactors in Bending and Shear Loading,", Paper Number 429, 18th International Technical Conference on the Enhanced Safety of Vehicles, Nagoya, Japan, May, 2003.

Bose, D., Bhalla, K., Rooij, L., Millington, S., and Crandall, J., 2004, "Response of the knee joint to the pedestrian impact loading environment," Society of Automotive Engineers, 2004-01-1608, Warrendale, PA, March, 2004.

Dempster, W. T., Space requirements of the seated operator. Technical Report USAF,WADC TR-55-159 (AD 87 892), Wright Air Development Center, Wright-Patterson Air Force Base, Ohio,1955.

European Enhanced Vehicle-Safety Committee, "EEVC Working Group 17 Report – Improved Test Methods to Evaluate Pedestrian Protection Afforded by Passenger Cars" www.eevc.org, 2002.

Frederiksson, R., Haland, Y., Yang, Evaluation of a New Pedestrian Head Injury Protection System with a Sensor in the Bumper and Lifting of the Bonnet's Rear Part, Paper 131, 17th ESV, Amsterdam, Netherlands, 2001.

Harris, J. A study of test methods to evaluate pedestrian protection for cars. European Experimental Vehicles Committee. The 12th International Technical Conference on Experimental Safety Vehicles, 1989.

Harrison C. and Robinette, K. "CAESAR: Summary Statistics for the Adult Population (Ages 18-65) of the United States of America," AFRL-HE-WP-TR-2002-0170; United States Air Force Research Laboratory, Wright-Patterson AFB, Ohio, 2002.

Hattori, K., Hayashi, S., Sakuma, S., Study for evaluation method of pedestrian injury on simulated pedestrian accidents, Paper 20005406, JSAE, Yokohama, Japan, 2000.

Hodgson, V. R. and Thomas, L. M.,"Breaking Strength of the Human Skull versus Impact Surface Curvature," NHTSA Report No. DOT-HS-800-583, June 1971; partial results published as "Comparison of Head Acceleration Injury Indices in Cadaver Skull Fractures," Paper 710854, Proceeding of Fifteenth Stapp Car Crash Conference, P-39, New York; Society of Automotive Engineers, Inc., 1971.

Hodgson, V. R. and Thomas, L. M., 1975, "Head Impact Response," Vehicle Research Institute Report-VRI 7.2, Society of Automotive Engineers, 1975.

Huang, T. J., McDonald, J., Artis, M., Rangarajan, N., Shams, White, R., Beach, D., Campbell, R., Akiyama, A., Yoshida, S., Ishikawa, H., Konosu, A., Development of a Biofidelic Dummy for Car-pedestrian Accident Studies, IRCOBI, Sitges, Spain, 1999.

ISO/TC22/SC12 Road vehicles – Anthropomorphic side impact dummy – Lateral impact response requirements to assess the biofidelity of the dummy. Reference number ISO/TR 9790:1999.

ISO TC 22/SC 22/WG 22. "Motorcycles — Test and analysis procedures for research evaluation of rider crash protective devices fitted to motorcycles — Part 4: Variables to be measured, instrumentation, and measurement procedures". ISO/DIS 13232-4, August 31, 2004, Copyright ISO, 2004.

ISO TC 22/SC 22/WG 22. "Motorcycles — Test and analysis procedures for research evaluation of rider crash protective devices fitted to motorcycles — Part 5: Injury indices and risk/benefit analysis". ISO/DIS 13232-4, September 7, 2004, Copyright ISO, 2004.

Ivarsson, J., Lessley, D., Bhalla, K., Kerrigan, J., Crandall, J., and Kent, R., "Dynamic response corridors and injury thresholds for the pedestrian lower extremities," 2004 IRCOBI Conference on the Biomechanics of Impacts, Graz, Austria.

Kam C, Kerrigan J, Meissner M, Drinkwater C, Murphy D, Bolton J, Arregui C, Kendall R, Ivarsson J, Crandall J, Deng B, Wang JT, Kerkeling C, Hahn W. (2005) Design of a full-scale impact system for analysis of vehicle pedestrian collisions. Paper 2005-01-1875, Society of Automotive Engineers, Warrendale, PA.

Kerrigan, J., Bhalla, K., Funk, J., Madeley, N., Crandall, J., "Experiments for Establishing Pedestrian-Impact Lower Limb Injury Criteria ", SAE Paper 2003-01-0895, Warrendale, PA, 2003.

Kerrigan J, Drinkwater DC, Kam CY, Murphy D, Ivarsson BJ, Crandall J, Patrie J. "Tolerance of the human leg and thigh in dynamic latero-medial bending." International Journal of Crashworthiness, 9(6): 607 – 623, 2004.

Kerrigan, J. R.; Drinkwater, C.; Kam, C.; Murphy, D.; Crandall, J. R.; "Kinematic Corridors comparing the Polar II with Cadavers in Pedestrian Impact Tests," Paper 05-0394, ESV 2005, Washington, D.C., June 2005

Kroell, C., Schneider, D., Nahum, A., (1971) "Impact Tolerance and Response of the Human Thorax." Proceedings of the 15th Stapp Car Crash Conference, SAE Paper 710851.

Kroell, C., Schneider, D., Nahum, A., (1974) "Impact Tolerance and Response of the Human Thorax II." Proceedings of the 18th Stapp Car Crash Conference, SAE Paper 741187.

Kroell, C (1976) "Thoracic Response to Blunt Frontal Loading." Society of Automotive Engineers, Warrendale, PA.

Lessely, D. R., Crandall, J. R., Shaw, C. G., Kent, R. W., Funk, J. R., "A Normalization Technique for Developing Corridors for Individual Subject Force-Deflection Responses," Society of Automotive Engineers, 2004-01-0288, Warrendale, PA, March, 2004.

ManneQuinPRO V8.0 Software Program as used and displayed by Natick US Army Database. (1988) Anthropometric database for creating mannequins and the Highway Safety Research Institute database for creating child mannequins.

Meissner, M., Van Rooij, L., Bhalla, K., Crandall, J. R., Longhitano, D. C., Takahashi, Y., Dokko, Y., "A Multi-body Computational Study of the Kinematic and Injury Response of a Pedestrian with Variable Stance upon Impact with a Vehicle," Society of Automotive Engineers, 2004-01-1607, Warrendale, PA, March, 2004.

NHTSA (2004) "Anthropomorphic Test Devices" 49 CFR Ch. V Pt. 572; Code of Federal Regulations, National Archive and Records Administration, Washington.

Snedeker, J., Muser, M., Walz, F., Assessment of Pelvis and Upper Leg Injury Risk in Car-Pedestrian Collisions: Comparison of Accident Statistics, Impactor Tests and Human Body Finite Element Model, 47th Stapp, San Diego, CA, USA, October 2003.

Takahashi, Y.; Kikuchi, Y.; Okamoto, M.; Akiyama, A.; Ivarsson, J.; Bose, D.; Subit, D.; Shin, J. H.; Crandall, J.; "Biofidelity Evaluation for the Knee and Leg of the Polar Pedestrian Dummy," Paper Number 05-0280, ESV 2005, Washington, D.C., June 2005.

Teresinski, G. and Madro, M., A Comparison of Mechanisms of Ankle, Knee, Pelvis and Neck Injuries in Pedestrians and in Cyclists According to the Direction of Impact and Type of Vehicle, IRCOBI, Lisbon, Portugal, 2003.