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Validation of Human Pedestrian Models Using Laboratory Data as well as Accident Reconstruction

Abstract

Human pedestrian models have been developed and improved continually. This paper shows the latest stage in development and validation of the multibody pedestrian model released with MADYMO. The biofidelity of the multibody pedestrian model has been verified using a range of full pedestrian-vehicle impact tests with a large range in body sizes (16 male, 2 female, standing height 160-192cm, weight 53.5-90kg). The simulation results were objectively correlated to experimental data. Overall, the model predicted the measured response well. In particular the head impact locations were accurately predicted, indicated by global correlation scores over 90%. The correlation score for the bumper forces and accelerations of various body parts was lower (47-64%), which was largely attributed to the limited information available on the vehicle contact characteristics (stiffness, damping, deformation). Also, the effects of the large range in published leg fracture tolerances on the predicted risk to leg fracture by the pedestrian model were evaluated and compared with experimental results. The validated mid-size male model was scaled to a range of body sizes, including children and a female.

Typical applications for the pedestrian models are trend studies to evaluate vehicle front ends and accident reconstructions. Results obtained in several studies show that the pedestrian models match pedestrian throw distances and impact locations observed in real accidents. Larger sets of well documented cases can be used to further validate the models especially for specific populations as for instance children. In addition, these cases will be needed to evaluate the injury predictive capability of human models.

Ongoing developments include a so-called facet pedestrian model with a more accurate geometry description and a more humanlike spine and neck and a full FE model allowing more detailed injury analysis.

Introduction

Statistics show that pedestrian accidents are a major source of fatalities and injuries. In the European Union alone, about 6,250 pedestrians are killed every year in road accidents, while over 100,000 are severely injured (OTTE, 2001; EEVC, 1998). When the total amount of world-wide traffic fatalities estimated by MACKAY (2000) at 950,000 are combined with the World Bank (2003) statement that 65% of all traffic fatalities involve pedestrians, a yearly world-wide pedestrian traffic fatality number of 615,000 is estimated.

As the vehicle front is considered the cause for a significant amount of all pedestrian injuries, a considerable amount of effort has been put in recent years into designing strategies to reduce the aggressiveness of the vehicle exterior. In particular, changes in the design of the vehicle front and bonnet are considered to be effective, where both shape and stiffness of the vehicle are important parameters. Optimizing the vehicle front for pedestrian protection while maintaining the vehicle crashworthiness is a complicated and timely process. Mathematical simulations using biofidelic pedestrian models can help to efficiently assess the pedestrian protection in the early stages of the design process. In addition, mathematical modelling is a valuable tool to reconstruct pedestrian vehicle accidents as the models can provide insight into relevant crash parameters and into the kinematics of the pedestrian involved.

This paper describes the development and validation of the MADYMO human pedestrian models. In addition, typical applications and future developments are discussed using information from earlier studies done with the human pedestrian models. Special attention is paid to accident reconstruction to show the capabilities of the current models and to indicate how accident cases could improve the models validation.

Model Development and Validation

The pedestrian model (shown in Figure 1) presented in this paper has been created using multibody techniques available in the software package MADYMO. A first version of this model has been developed in a cooperation with Chalmers University as reported by de LANGE, HAPPEE, YANG and LIU (2001). A major update of the MADYMO pedestrian model has been published by HOOF et al. (2003) and the model is released with MADYMO 6.2.2. The outer surface of the model is represented by 64 ellipsoids and is based on the anthropometry data of an average Western European male obtained from the RAMSIS software (SEIDL, 1994).

The human-body pedestrian biomechanical data for the joints and segment parts were implemented from a variety of publications, together with detailed validation for the whole body as well as components. The majority of this data is concerned with the 50th percentile adult male model.

The contact characteristics for the various body regions were based on data found in literature and optimized in simulations of a large range of PMHS impactor tests on various body parts. The different impactor test configurations simulated are shown in Figure 2.

The validation results obtained with the pedestrian model are published by van HOOF et al. (2003). In general, the model approximates the measured PMHS response well, especially when the large range in test conditions and impacted body parts is considered.

A flexible leg model was implemented. Three spherical joints are specified in the upper leg dividing the upper leg (femur) into four equal parts. For the lower leg, also three joints are specified. For the required bending stiffness, a rotational force model was implemented. Angular stiffness functions were derived from simulations of quasi static bending tests done by YAMADA (1970).

In car-pedestrian collisions often fracture of the leg occurs. Therefore leg fracture is implemented in the human pedestrian model. Fracture joints were sited at the middle femur joint and at each of the tibia bending joints. The 50th percentile fracture levels were derived from literature.

Model validation has been made on both the body segments and on whole body simulations. For the verification of the lower extremity, the lower extremity model was separated from the full body pedestrian model. Impact tests with real human lower extremity specimens (KAJZER et al. 1990 and 1993) were simulated. In addition, three different sets of PMHS pedestrian-vehicle impact tests have been simulated to verify the biofidelity of the pedestrian model. Since PMHS subjects of different anthropometries were used in the tests, the pedestrian model was scaled to the specific body dimensions of each PMHS subject prior to simulating the corresponding test. In total 18 subjects (16 male, 2 female) were used in these tests, ranging in height from 160-192cm and in weight from 53-90kg. The results of the simulations were objectively compared with available experimental data. An extended description of the validation simulations and results can be found in van HOOF et al. (2003). From the extended validation of the pedestrian models it can be concluded that:

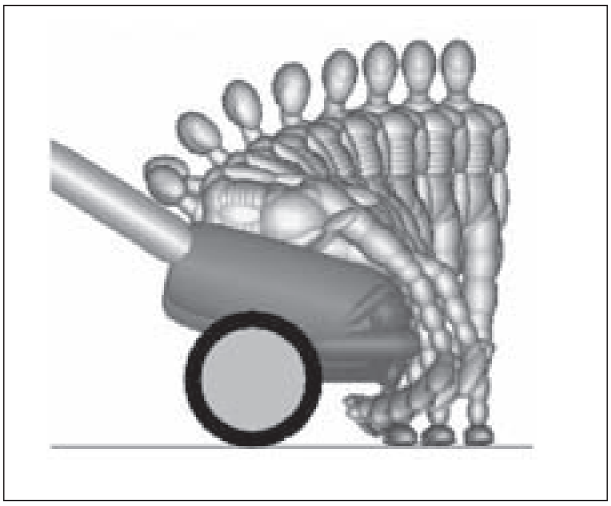

Figure 1: The MADYMO mid-size male pedestrian model

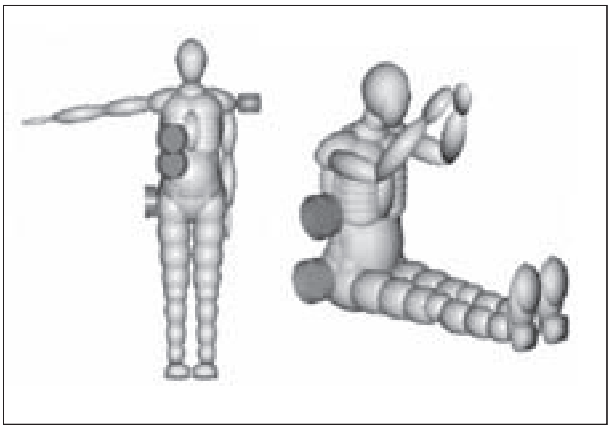

Figure 2: Range of impactor test configurations used for model validation

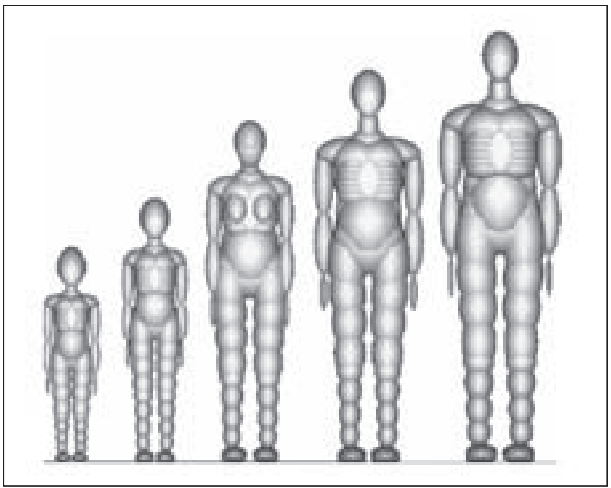

Figure 3: From left to right: models of 3 and a 6 year old child, small female, mid-size male and large male

	3 yr. old child	6 yr. old child	Small female	Mid-size male	Large male
Standing height [m]	0.95	1.17	1.53	1.74	1.91
Seated height [m]	0.55	0.64	0.81	0.92	1.00
Shoulder width [m]	0.25	0.28	0.40	0.47	0.52
Knee height [m]	0.28	0.35	0.47	0.54	0.59
Weight [kg]	14.5	23.0	49.8	75.7	101.1

Table 1: Anthropometry parameters of different body sizes

- the models accurately predict the global kinematics;
- the models accurately predict the impact points on the vehicle, especially for the head;
- the models can reasonably predict the occurrence of fractures in the upper and lower legs during the impact between the pedestrian and the vehicle;
- the models can predict the signal shape and trends of the head, chest and pelvis accelerations and the bumper forces.

The validated average male model was scaled towards a 3 year old child, 6 year old child, small female, and large male model (see Figure 3). The anthropometries of the small female and large male pedestrian models were also based on the RAMSIS database. The anthropometries of the 3 and 6 year old child were based on the specification of the Q child dummies. The global anthropometry specifications are given in Table 1.

The scaling of the pedestrian models was performed using the MADYMO/Scaler module (HAPPEE et al., 1998). Different scaling factors were specified for x-, y-, and z-dimensions and for different body parts to adapt the model geometry to the desired anthropometry. In addition to the geometry other model parameters were scaled.

As the pedestrian models are based on rigid body techniques the main advantages of this kind of models are the low computational costs, robustness and accurate predictions of kinematics. Therefore the model can be applied in studies involving a large number of runs, like stochastic simulations, for instance to determine ranges of impact conditions (e.g. head impact speed, head impact angle) for subsystem tests.

Typical Model Applications

A typical application is the evaluation of the pedestrian protection of the car front as for instance was done by HAPPEE and WISMANS (1999). HAPPEE and WISMANS first modelled and evaluated a production vehicle in MADYMO. Modifications were introduced such that all injury values were below 80% of the applicable tolerance values according to the EEVC test procedures (EEVC, 1998). Based on this optimised vehicle model, various vehicle models with markedly differing shapes were developed. As a next step, the 50th percentile male, a 5th percentile female and 3 and 6 year old child pedestrian models were applied to simulate lateral impact with the different vehicle models. From the simulations trends in injury reduction over the different vehicle models and over the various body sizes were identified.

As the pedestrian model can be scaled towards any desired body size, accident reconstruction is another typical application. Already a number of studies exist where the MADYMO pedestrian models are used in accident reconstruction simulations. COLEY et al. (2001) used an earlier version of the pedestrian model to reconstruct a real-world accident with a scaled version of the 5th percentile female pedestrian model. The performance of the pedestrian model was evaluated and afterwards the model was applied to reconstruct a fatal accident using a detailed vehicle model. Firstly the impact points between the pedestrian and the vehicle were matched and secondly the injury pattern was assessed by relating the injury value to an AIS level. In addition, further impact scenarios were explored to assess the ‘injury variation’ based on vehicle stiffness, initial pedestrian posture and position.

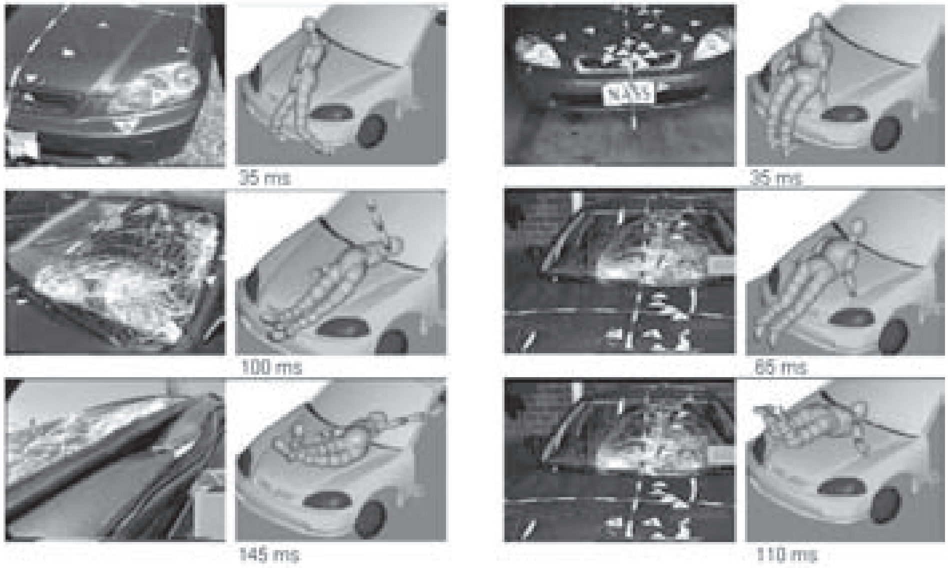

Figure 4: Comparison of the marks on the case vehicles with the contact locations in the MADYMO simulations (source: van ROOIJ et al., 2003)

In GLATIN et al. (2002) the focus was more on the throw distance of the pedestrian. In his study, GLATIN found an accurate match of throw distances between the simulations and the real-world data.

In 2004 STRZELETZ et al. compared the accident reconstruction simulations with the pedestrian models in MADYMO with several other numerical and experimental methods to further analyse pedestrian accidents. In his study STRZELETZ concluded that the accident reconstruction simulations in MADYMO do provide valuable information on the pedestrian model kinematics and the impact locations on the vehicle. As most parameters relevant in the accident are defined explicitly, the simulations were well suited to study the influence of differences in the initial conditions and the importance of different input parameters.

Van ROOIJ et al. (2003) developed and validated a vehicle model of a small family car using subsystems. He applied the developed vehicle model together with pedestrian models to reconstruct two pedestrian accident cases from the PCDS database (CHIDESTER et al., 2001). Case 1 was a non-fatal accident where a male (standing height: 1.75m; body weight: 79kg) was impacted with about 69km/h. Case 2 was a fatal accident where a female (standing height: 1.65m; body weight: 105kg) was impacted with 55km/h. A braking of 0.7G was applied to the vehicle model based on tire marks. The pedestrian models were scaled towards the required anthropometry using the MADYMO/Scaler module. A variation study was performed with a number of parameters like vehicle velocity, initial position and posture of the pedestrian model. Contact points between the pedestrian and the vehicle were compared with the marks on the accident vehicle. Based on this comparison (see Figure 4), the most likely accident scenario was derived.

For the two most likely scenarios, the injury outcome from the accidents was compared with the injury predictors in the models. In case 1, the leg injury results matched the observed severe leg injury and for case 2, the neck loads (N_{ij}) matched the fatal atlanto-occipital fracture observed in the accident.

Currently the MADYMO pedestrian models are used in the EC project APROSYS, to reconstruct pedestrian-vehicle and cyclist-vehicle accidents. The main aim of these reconstructions is to determine the impacted areas of the vehicle and to determine the nature of the loading conditions on the body of the pedestrian and pedal cyclists, including the head.

Ongoing Model Developments

The pedestrian models presented in this paper are based on the rigid body techniques available in MADYMO. As mentioned, the main advantages of this kind of models are the low computational costs,

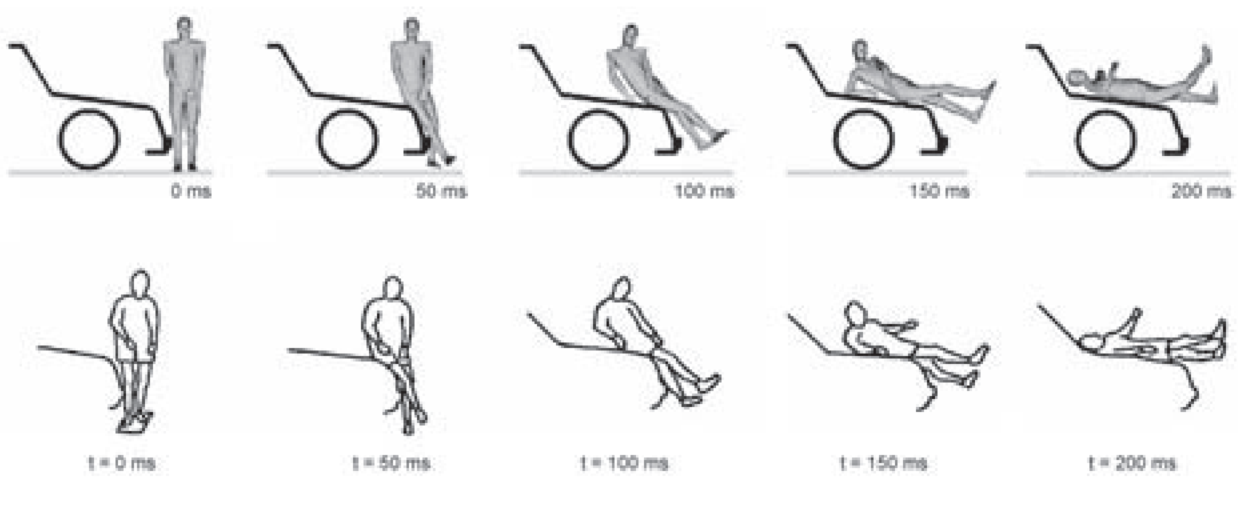

Figure 5: The kinematics of the facet pedestrian model in a 25 km/h impact and the corresponding test result as published by ISHIKAWA (1993)

robustness and accurate predictions of kinematics. Since ellipsoids were used to represent the geometry of human and vehicle, the prediction of the contact interaction is largely simplified.

A more advanced modelling technique is used for the MADYMO facet human model which can be seen in Figure 5. In this model the articulations are modelled with rigid body techniques and the skin with an so-called arbitrary surface. The model contains a more realistic spine and neck and a more detailed geometrical representation of the human body, but has limited capabilities to predict deformations. The model has been developed and validated for occupant impact simulations (LANGE et al., 2005). Due to its biofidelic set-up and the more accurate geometry description compared to the ellipsoid pedestrian models, this model is currently evaluated for its suitability for pedestrian impact simulation. As a first validation, several pedestrian tests published by ISHIKAWA et al. (1993) have been simulated. Figure 5 shows the kinematics of the average male pedestrian model in a 25km/h impact and the corresponding test result. As can be seen, the pedestrian kinematics correspond well with the pedestrian kinematics obtained in the test and also the impact locations between the pedestrian and the vehicle correspond well.

Additionally, the finite element (FE) technique enables prediction of detailed contact interactions and resulting deformations in structures with complex geometries. Recently, the FE human model developed in the EC project HUMOS 2 was adapted to a standing model and evaluated for lateral pedestrian impact (VEZIN and VERRIEST, 2005). Such a FE model enables more detailed analyses of the injury biomechanics associated with pedestrian impacts, such as bending and fracture of the bones and rupture of the ligaments. However, the main disadvantage of the FE approach is the much higher computational cost compared to rigid body. Furthermore critical stability issues are observed in soft tissue compression, which as yet prohibit routinely usage of such full FE human models.

One way to circumvent these limitations is to combine rigid body and FE techniques in one model. In this way an optimal combination of computational speed and accuracy can be obtained. A valuable combination could for instance be a rigid body pedestrian model combined with a FE model of the impacted leg. Such a model could provide a detailed insight in the leg injuries obtained, and as the remainder of the body is modelled with rigid body techniques, the computation time is still acceptable.

Discussion

As shown in this paper, the developed pedestrian models are used in a number of studies to reconstruct pedestrian-vehicle accidents. From these accident reconstruction studies it was concluded that throw distances of the pedestrian and, similar to the results of the validation, impact locations on the vehicle match fairly accurate with the experimental results and reconstructed accidents. This indicates a correct kinematic response of the pedestrian models. As such, accident reconstruction simulations help to obtain more details on specific accident cases and to provide an increased understanding of the sequence of events in the car-pedestrian impact. From the validation study it was concluded that the pedestrian models can reasonably predict the occurrence of fractures in the legs during the impact and that the models can predict trends in other injury parameters. This is supported by the findings of van ROOIJ et al. (2003), but more accident reconstructions of well documented cases are needed to further evaluate the predictive injury capability of human models, such as in LONGHITANO et al. (2005).

If a large number of accidents is reconstructed using similar methods as described above, such studies could lead to an improved validation of the human pedestrian models. This is thought to be valuable especially for specific populations as children and elderly pedestrians, where body tissue and bone fracture properties vary significantly from the 50th percentile due to the age effects. For children, where neither body properties nor tolerance values are known, scaled human-body models can be used as a start and further modified based on the known differences between children, mid-aged adults and elderly people. As a first step in this method, LIU developed child pedestrian models and used the models to reconstruct two real world accidents using the accident data from in-dept accident investigations (LIU and YANG, 2002). In this study, it was concluded that the overall trajectories of the child models and vehicles and the head impact locations did correspond well with the accident data and the results indicated an acceptable correlation with the real-world injuries.

Besides the availability of a large number of accidents cases, such accident reconstruction studies for validation can only be performed if the cases are well documented and the reconstruction simulations are performed with a vehicle model that accurately matches the detailed geometry and the stiffness. Both parameters will have a significant influence on the model's response. Also the anthropometry of the pedestrian involved in the crash has a significant influence on the pedestrian kinematics in a pedestrian-vehicle impact. Therefore, the anthropometry has to be matched accurately by the pedestrian model which can be obtained using the MADYMO/Scaler module.

Conclusion

The MADYMO human pedestrian models have been verified using a range of full pedestrian-vehicle impact tests with a large range in body sizes. The models are available in number of body sizes ranging from a 3 year old child to a large male. In addition a scalable version has been developed.

The models are suitable as a tool for the reconstruction of pedestrian-vehicle accidents. The accident reconstruction studies described in this paper have shown that the simulations with the pedestrian models provide an improved understanding of the reconstructed accidents. Pedestrian kinematics, impact locations and pedestrian throw distances resulting from the simulations can be matched accurately with the accident observations. Provided that a large number of well documented pedestrian accidents could be reconstructed, this can even lead to an improved validation of the pedestrian models. This is thought to be especially valuable for specific population groups like children were currently sufficient data for validation is lacking.

Ongoing developments include a so-called facet pedestrian model with a more accurate geometry description and a more humanlike spine and neck and a full FE model allowing more detailed injury analysis.

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