MADYMO PEDESTRIAN SIMULATIONS

J. v. Wijk, J. Wismans, J. Maltha
and L. Wittebrood

Research Institute for Road Vehicles TNO,
Delft, the Netherlands

ABSTRACT

In this paper four pedestrian models will be presented: three 2-dimensional models with 2, 5 and 7-segments respectively and one 3-dimensional model with 15 segments. All these models were formulated with the general Crash Victim Simulation package MADYMO. Model results will be compared with the experimental results of a Part 572 dummy impacted lateral at two velocities (30 and 40 km/h). The reliability of the models with respect to their complexity will be discussed. Special attention will be given to the mathematical representation of the contact between the pedestrian and sharp vehicle edges and the visualization of the complex 3-dimensional pedestrian motions with a recently developed 3D-Graphics Package.

PEDESTRIANS ARE AMONG the most vulnerable traffic participants. A pedestrian runs more than twice as high a risk of being fatally injured in a road accident as a car occupant. In recent years traffic safety research has concentrated more and more on this problem of pedestrian accidents. One of the methods to analyse the impact between a pedestrian and a vehicle is mathematical modeling. Advantages of mathematical models are the exact reproducibility of a simulation, the absence of measuring problems and the possibility to conduct sensitivity-analyses in a simple, rapid and inexpensive way.

This study was conducted with the MADYMO program package, developed at the Research Institute for Road Vehicles TNO. A description of this package, along with several examples of applications can be found in (1)*. The main features of this package can be summarized as follows:

- a compact FORTRAN source which can be implemented on small computer systems;
- a 2D and a 3D option;
- a variable number of linkage systems;
- a set of standard force interaction routines;
- easy incorporation of user defined subroutines for specific force interactions and user defined output.

Based on a literature review of existing pedestrian models presented at the 9th ESV Conference (2) and results of several recent accident analyses, a number of requirements were formulated for mathematical simulations of pedestrian-vehicle impacts. The models described in literature varied strongly in complexity: 2-dimensional models with the number of segments for the pedestrian varying between 1 and 11 as well as 3-dimensional models having up to 15 segments were reported. This literature study did not show a clear relationship between the complexity of the different models (i.e. number of elements, 2D versus 3D) at the one side and their reliability at the other side. One of the aims of our study therefore was to get a better insight in this problem. Several models with varying complexity were developed. Three of the models were 2-dimensional and presented in (2). In this paper results of a 3-dimensional model will be shown in addition to

* Numbers in parentheses designate references at end of paper.

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2-dimensional simulations. The predictions of these models are for a Part 572 dummy impacted by an Audi 100 at two velocities, namely 30 and 40 km/h.
The literature review showed that contact models are very important for a reliable description of the pedestrian-vehicle impact. The contact model must be able to cope with the problem of edge contacts. In this paper a new contact model will be described that successfully was applied in the presented simulations.

MODELING OF EDGE CONTACTS

One of the most important aspects concerning the simulation of pedestrian accidents is the representation of the contact between vehicle and pedestrian. For 2D-simulations a special contact model has been developed in which the external geometries of pedestrian and vehicle are simulated by hyperellipses, i.e.:

$$\left(\frac{|x|}{a}\right)^n + \left(\frac{|y|}{b}\right)^n = 1 \qquad (1)$$

where a and b are the semi-axes of the hyperellipse and n the degree (see Fig. 1). If $n = 2$, this equation describes a standard ellipse; if n increases the hyperellipse approximates more and more a rectangle as is illustrated in Fig. 1 for $n = 8$.

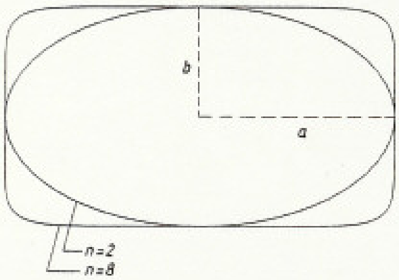

Fig. 1 Hyperellipses with identical semi-axes, n = 2 and n = 8.

Fig. 2 shows two penetrating hyperellipses he_1 and he_2. Let l_1 be an arbitrary tangent line to hyperellipse he_1. A tangent line to the hyperellipse he_2 and parallel to l_1 is denoted by l_2. The distance between l_1 and l_2 is denoted by λ. The penetration between the both hyperellipses is defined by the minimum value of λ. In other words, the penetration is calculated by rotating the tangent lines until the distance between them reaches a minimal value. The starting position of the tangent lines in this calculation is perpendicular to the line connecting the centers of both hyperellipses. In this contact model an elastic contact force can be defined which is a function of the penetration. In addition hysteresis, friction and damping can be defined. The direction of the elastic and damping forces is taken perpendicular to the tangent lines while the point of application of these forces is selected in the intersection of the tangent line to the hyperellipse with the highest stiffness.

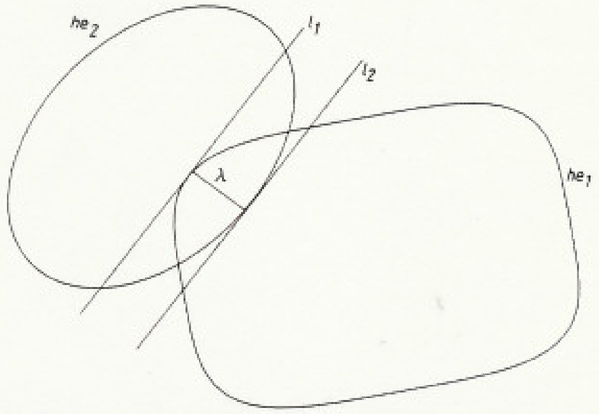

Fig. 2 Penetration of two hyperellipses.

In case of 3-dimensional simulations a similar approach is chosen. Here the external geometry of the pedestrian elements is represented by ellipsoids of the form.

$$\left(\frac{x}{a}\right)^2 + \left(\frac{y}{b}\right)^2 + \left(\frac{z}{c}\right)^2 = 1 \qquad (2)$$

where a, b and c are the semi-axes of the ellipsoid. The car structure (i.e. the bumper and the hood) is approximated by hyperellipsoids with one of the semi-axes having an infinite length:

$$\left(\frac{|x|}{a}\right)^n + \left(\frac{|y|}{b}\right)^n + \left(\frac{|z|}{c}\right)^n = 1 \qquad (3)$$

where $a \to \infty$

n = 2

n = 4

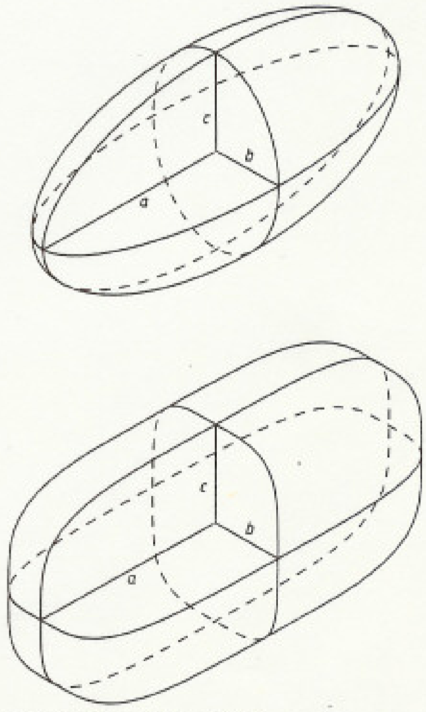

Fig. 3 Hyperellipsoids with a degree of 2 and 4 respectively and identical semi-axes.

In other words this hyperellipsoid represents a cylindrical body with a hyperelliptical cross-section in the yz plane.
A first step for generalisation of this contact model to hyperellipsoid interactions was made. In some cases, however, numerical problems could be observed which are not yet completely solved.
An illustration of two hyperellipsoids with identical semi-axes and degrees of respectively 2 and 4 is shown in Fig. 3.

DESCRIPTION OF THE PEDESTRIAN MODELS

The simulations are limited to the primary impact (pedestrian-car contact) and are concerned with lateral impacts, since this is the type of impact most frequently observed in pedestrian accidents (3). Three 2-dimensional models with 2, 5 and 7 segments respectively have been formulated as is shown in Fig. 4.

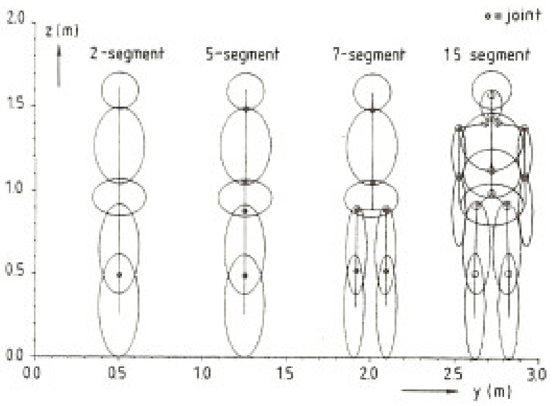

Fig. 4 Geometry and contact ellipses of respectively 2-, 5- and 7-segment 2D-model and the 15-segment 3D-model.

The same contact ellipses are attached to the 2 and 5 segment models. In the models the arms are not incorporated as separate segments: a part of the mass of the arms is added to the mass of the thorax segments. In addition a 15 segment model was defined with the 3-dimensional option of MADYMO. This model has 15 segments representing the head, the neck, the upper torso, the spine, the lower torso, the shoulders, the upper and lower legs (Fig. 4). A recently developed 3-dimensional MADYMO Graphics Package was used to present the initial position of the pedestrians (Fig. 5) which was estimated from high speed films.
Features of this graphics package include; hidden lines elimination, plotting of intersection lines between ellipsoids, arbitrary viewpoint selection and a variable number of surface visualization lines.
The input data set describing the pedestrian (e.g. the geometry, mass distribution and joint characteristics) is derived from a standard data set of a Part 572 50th percentile male dummy.
The four models were applied to simulate a Part 572 dummy impacted by a vehicle of the type Audi 100. Vehicle dimensions were determined from scale drawings and measurements. Fig. 6 illustrates the representation of the vehicle in the models.

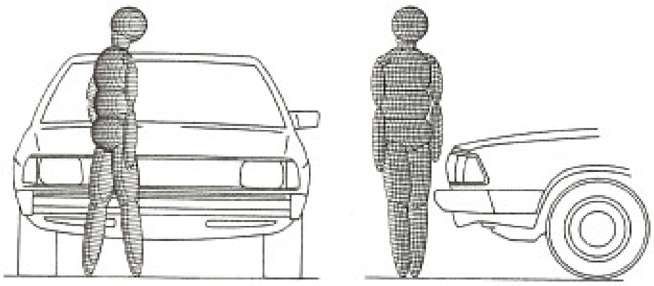

Fig. 5 Initial position of the pedestrian in the 3D simulations.

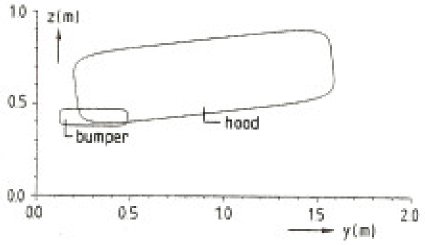

Fig. 6 Representation of Audi 100 in the models.

Dynamic force-deflection characteristics of the bumper, hood and hood-edge of the Audi 100 vehicle were determined experimentally by the BASt (Bundesanstalt für Strassenwesen). Pendulum tests were used for the bumper and the hood-edge. The rigid wooden pendulum was equipped with an accelerometer, while the vehicle deflection was measured with a lineair transducer, mounted in the car. The pendulum mass was 10 kg for the bumper impact and 15 kg for the hood-edge while the impact velocity was 25 km/h in these tests. For the hood a drop-test was used. The impacting body was a rigid wooden sphere with a mass of 5.25 kg and an impact velocity of 30 km/h. Based on these measurements and additional information on the stiffness of various dummy body parts the force-deflection characteristics of the pedestrian-vehicle contact interactions were estimated. Identical data were used in all four models. The mathematical models are compared with a number of dummy tests, which were conducted by the BASt. The dummy in these tests, a Part 572 50th percentile male, was equipped with triaxial accelerometers in the head, chest and pelvis and uniaxial accelerometers in the knees and feet. Test velocities were taken 30 and 40 km/h and the car deceleration 6 m/s^2. Three tests were conducted at each impact velocity.
The dummy position before impact is shown in Fig. 7. This position was selected after

several pretests. In these pretests it could be observed that in case of a pure lateral impact no direct head-hood contact occurs due to the stiff neck and shoulder assembly of the Part 572 dummy. Since head-impact was desired in these tests, the dummy torso was slightly rotated (25°) causing the dummy to rotate around its vertical axis during impact and resulting in a direct head impact. Experimental results of these tests will be presented in the next section together with mathematical model results.

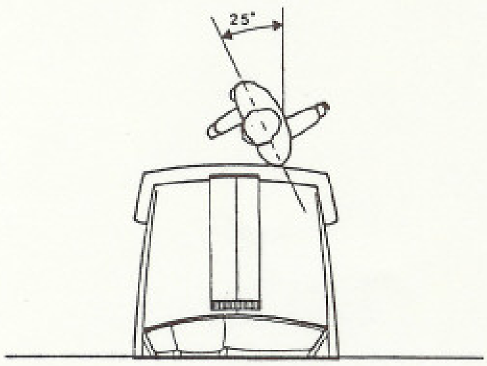

Fig. 7 Dummy position at impact.

RESULTS

Fig. 8 shows model predictions for the kinematics in a 40 km/h impact resulting from the 2D 7-segment model and Fig. 9 the kinematics from the 15-segment 3D-model. A comparison of predicted trajectories of the head, chest, pelvis and foot relative to the vehicle and resulting from the 2D-models is presented in Fig. 10. Fig. 11 compares the trajectories from the 7-segment 2D-model and the 15-segment 3D-model. These figures show that the trajectories of the 2-segment and 5-segment model are almost identical. Representation of the legs by separate elements which was done in the 7-segment model results in an increase of the distance between head impact point and hood-edge.
From the 15-segment model a similar increase in the distance between head impact point and hood-edge can be observed. Table 1 summarizes the location of the head impact point on the hood resulting from the model calculations for the 30 km/h as well as the 40 km/h impact together with experimental results.
All model predictions are within or close to the experimental range. Table 1 also includes calculated and measured head impact

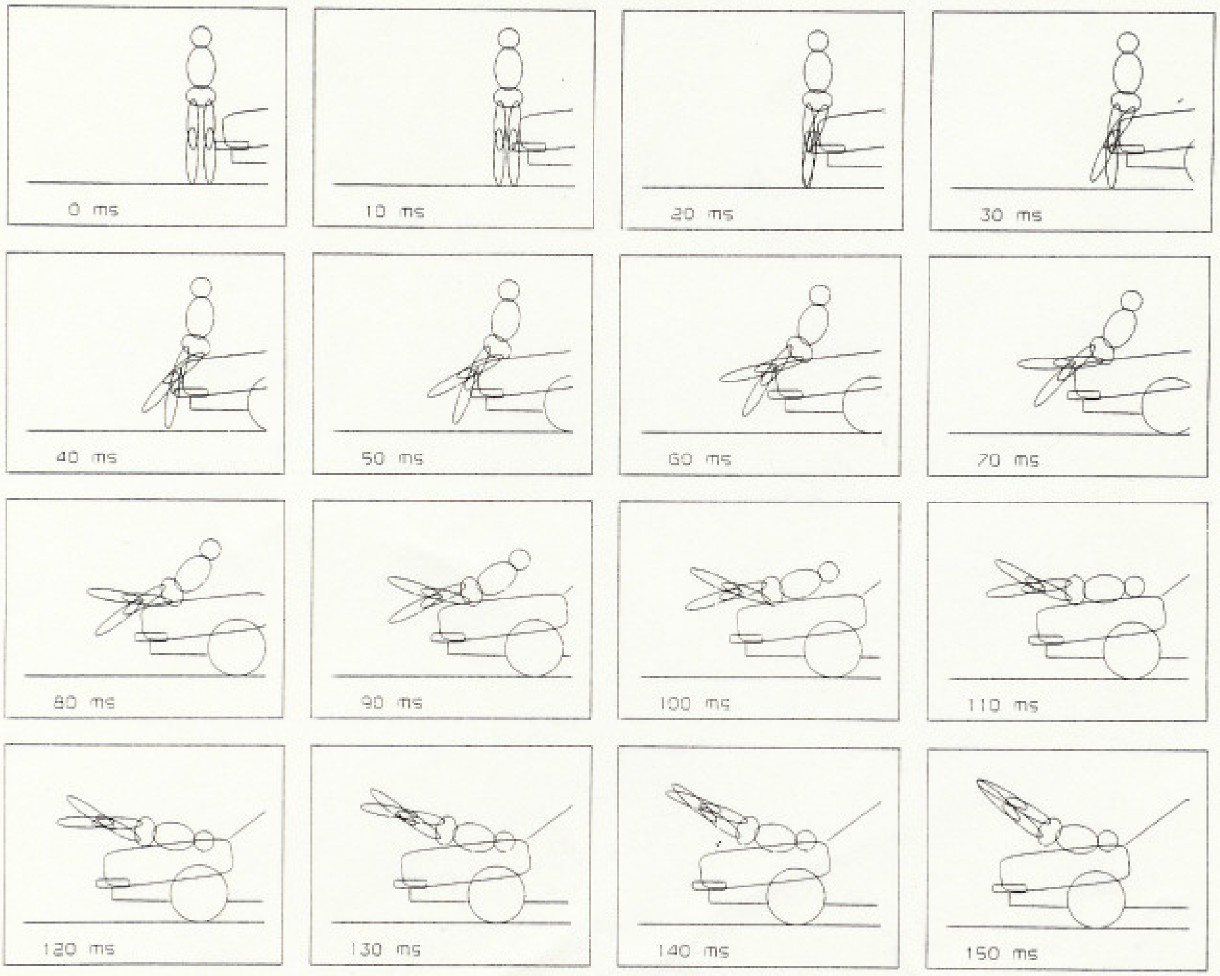

Fig. 8 Kinematics of 7-segment model, v = 40 km/h.

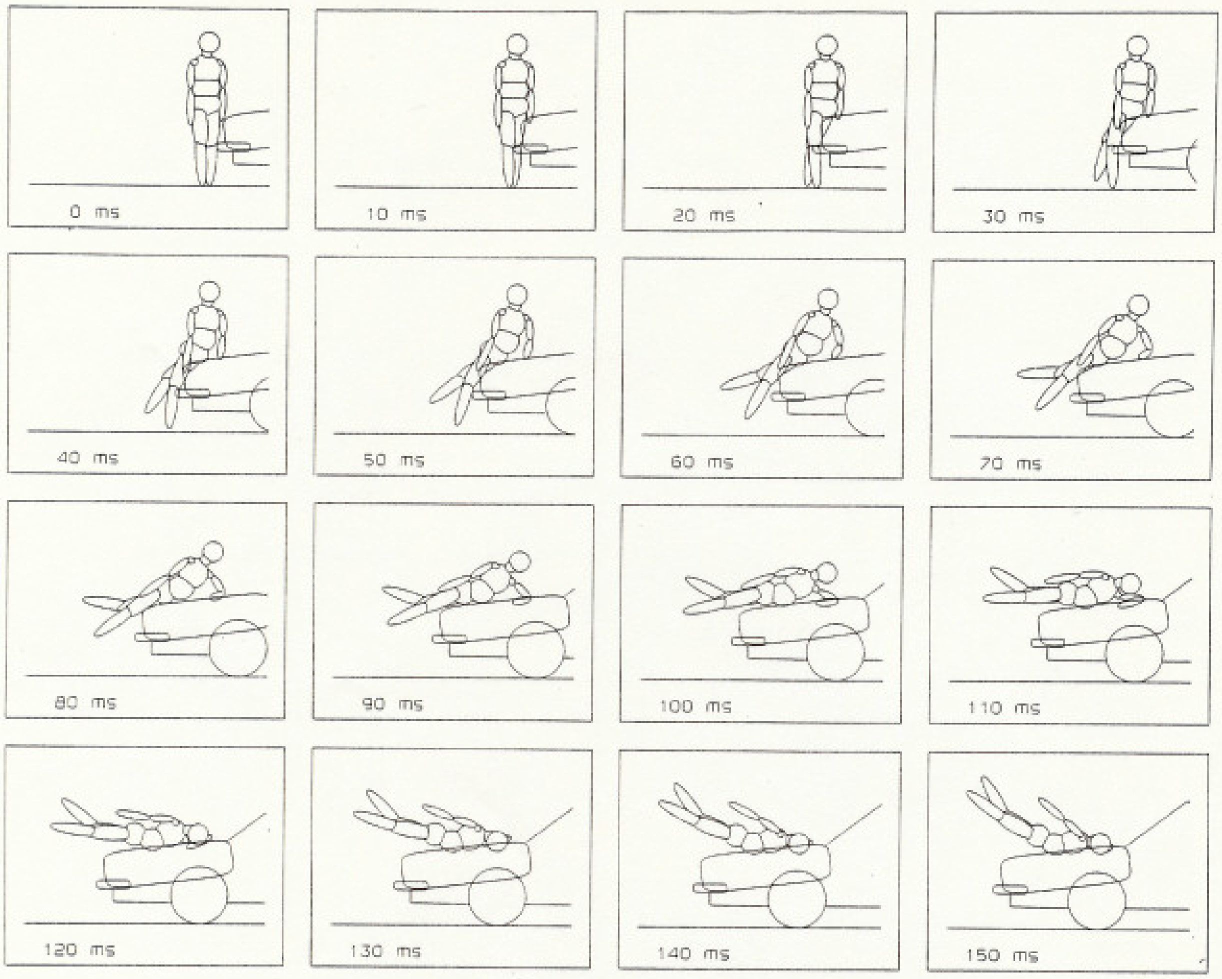

Fig. 9 Kinematics of 15-segment 3D-model, v = 40 km/h.

velocities on the hood. Both the 5 and 7 segment 2-dimensional model appear to predict too high values for this quantity in comparison to the experimental observations. The head impact velocity resulting from the 3-dimensional model however is much smaller and below the experimental range.

The 3-dimensional model predicts a large rotation around the vertical body axis. A similar rotation was observed in the experiments.

Figure 12 presents model results together with experimental data for the knee, pelvis, chest and head accelerations in a 40 km/h impact. For the pelvis, chest and head, resultant linear accelerations are presented and for the knee joint the linear acceleration in lateral direction. The simple 2-segment model gives quite reasonable results for the acceleration-time histories (i.e. these accelerations appear to be in or close to the experimental corridors). Application of the 5-segment model does not result in better predictons for the knee and pelvis acceleration. A small improvement of the head and chest acceleration-time histories, however, can be observed particularly for t < 20 ms, where head and chest acceleration become smaller and more corresponding to the experimental observations. The peak head acceleration, however, is too high in this simulation.

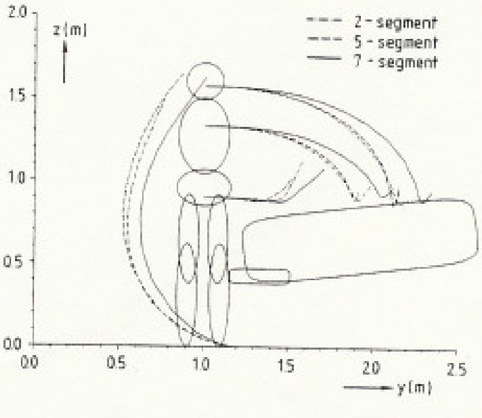

Fig. 10 Comparison of the trajectories of the 2, 5 and 7-segment 2D-model, v = 40 km/h.

Table 1 HEAD IMPACT VELOCITY AND HEAD IMPACT POINT FOR FOUR MODELS, ALONG WITH EXPERIMENTAL RESULTS.

	2-segment	2D-model 5-segment	7-segment	3D-model	Experimental test-range
v = 30 km/h resultant head-impact velocity (m/s)	9.1	12.3	11.4	6.1	6.7 - 9.2
distance head-impact point/hood-edge (m)	0.91	0.90	1.02	0.96	0.82 - 1.00
v = 40 km/h resultant head-impact velocity (m/s)	12.7	16.6	15.6	9.9	11.2 - 12.5
distance head-impact point/hood-edge (m)	0.96	0.95	1.08	1.03	1.00 - 1.07

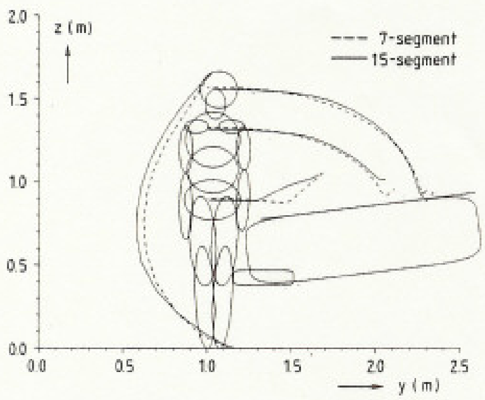

Fig. 11 Trajectories of the 7-segment 2D-model compared with the 15 segment 3D-model.

Extension of the 5-segment model with 2 segments in order to represent the left and right leg separately, results in a slight improvement with respect to the knee accelerations. Also, the alignment between model and experimental head and chest accelerations appears to become more realistically now.
A further improvement of the model predictions can be observed if the 3-D model is used, particularly with respect to the pelvis acceleration time histories and the peak head acceleration. Model results for the left and right foot acceleration and the right knee acceleration are shown in Fig. 13 together with experimental corridors (not available for the left foot. Also these model results appear to be in or close to the experimental corridors.
Accelerations predicted by the models in a 30 km/h impact showed in general the same characteristics as in the 40 km/h impact. The agreement between model and experiment in this impact was found to be less, however, than in the more severe 40 km/h impact.

A limited sensitivity study was conducted to analyse the response of the 2, 5 and 7-segment models to variations in some of the model input parameters. Results of the some of these variations were presented in (2). From variations conducted with the 3D-model it could be observed that the model results are quite sensitive to the initial position of the arm at the impact side. Some of the arm positions were found to result in numerical instabilities in the model (high frequent oscillations of outputparameters). The reason for these instabilities is not yet completely clear and is objective of future research.

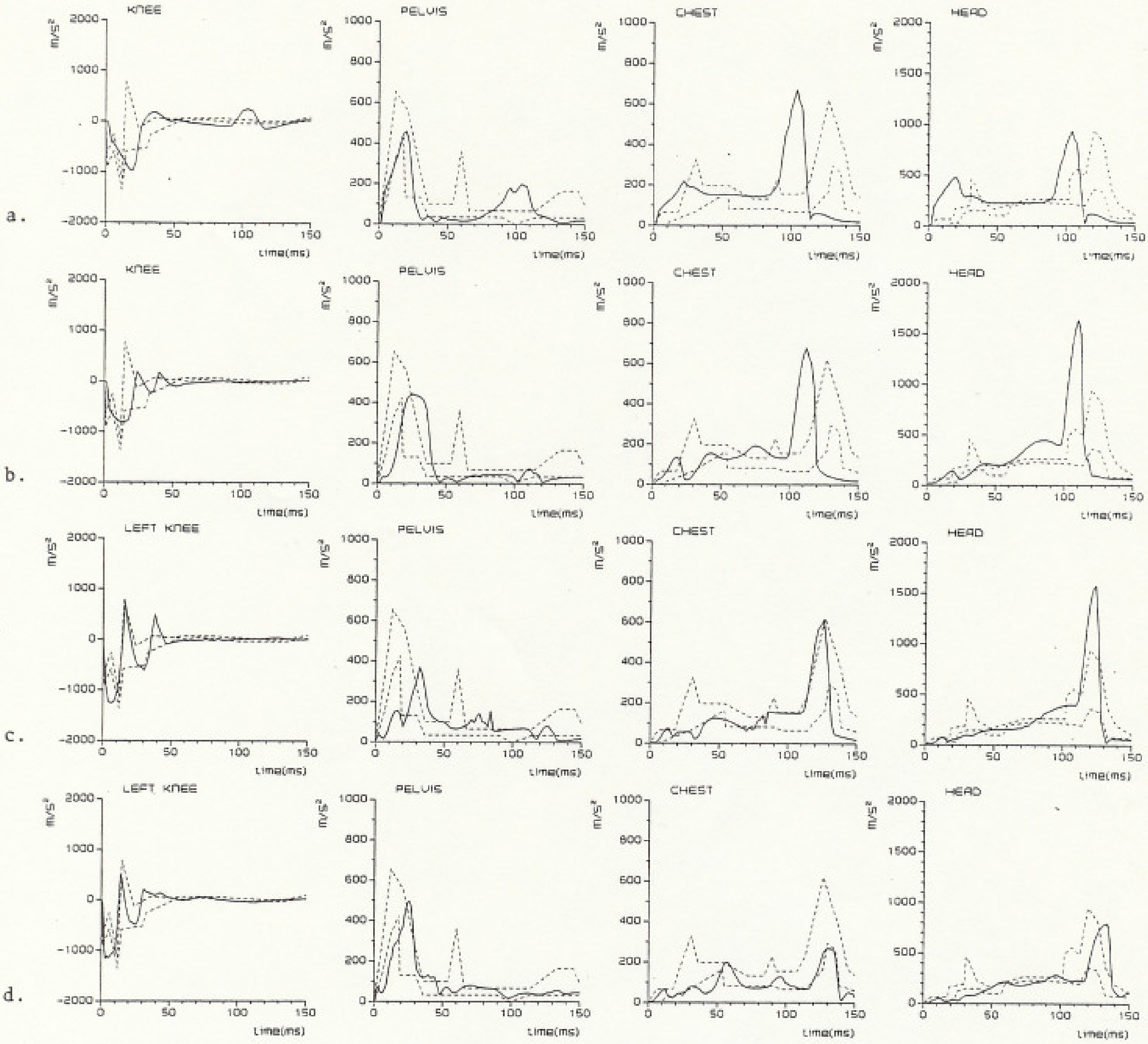

Fig. 12 Accelerations of knee, pelvis, chest and head for a) 2-segment, b) 5-segment c) 7-segment model and d) 15-segment 3D-model.
(—— = model, -- = experimental corridor) in a 40 km/h impact.

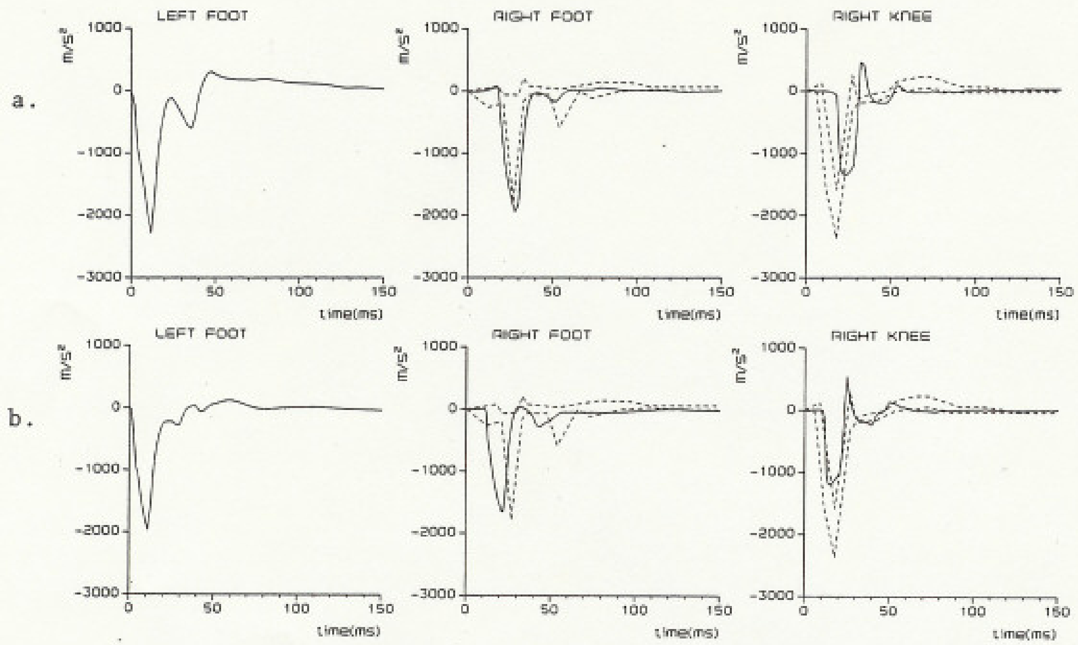

Fig. 13 Accelerations of left foot, right foot and right knee for a) 7-segment model 2D-model and b) 15-segment 3D-model (—— = model, --- = experimental corridor) in a 40 km/h impact.

DISCUSSION AND CONCLUSIONS

Mathematical simulation of the highly complicated gross motion of the human body impacted by a vehicle has gained increasing importance in the past years. In this paper a series of three 2-dimensional pedestrian models with 2, 5 and 7 segments and one 3-dimensional model with 15 segments are presented. These models are formulated with the General Crash Victim simulation program package MADYMO.

A literature study presented in an earlier paper (2) showed that adequate description of the contact between pedestrian and vehicle is of crucial importance for a successful simulation. Particularly the contact with sharp vehicle edges like bumper and hood appeared to cause sometimes problems in the existing type of contact models. Therefore a more advanced contact model was developed in which the vehicle in case of 2-dimensional simulations is represented by a number of so-called hyperellipses. In case of 3-dimensional simulations the vehicle contour is represented by a number of hyperelliptical cylinders. These new MADYMO contact models were found to perform very well for this type of applications.

For the 3-dimensional simulations the new MADYMO 3D Graphics Package was used to visualize the complex occupant kinematics. This post-processing computer program appeared to be of invaluable importance for the interpretation of the model results.

The four models presented here were used to simulate a Part 572 dummy impacted at two different impact velocities (30 and 40 km/h) by an Audi 100 vehicle. All models including the simple 2-segment model were found to predict the head impact location on the hood within or close to the experimental range of results. Predictions for the head impact velocity on the hood were too high (± 35%) in the 5 as well as the 7-segment model. The 3-dimensional model however predicted much lower and more realistic values for this quantity. The most important reason for this might be that in the experiment considerable rotations around the vertical body axis could be observed. These rotations are quite well predicted by the 3-dimensional model. In other words a part of the impact energy is transformed into rotations of the pedestrian resulting in a decrease of the lineair head velocity. In addition the arm-hood impact might contribute to the lesser head impact velocity in the 3-dimensional model compared to the armless 2-dimensional models.

In general all models appeared to provide values for the body segment accelerations within or close to the experimental range of results. A slight improvement of the model results can be observed in the more complex models. For instance due to the lower head impact velocity in the 3-dimensional model a lower and much more realistic peak head acceleration during the hood impact can be observed.

The observed differences between the most realistic model, i.e. the 15-segment 3D model, and the experiments mainly may be due to the following reasons:

- High speed films were used to determine the head velocity before impact with the hood. Due to 3-dimensional head motions and absences of adequate calibration procedures, this measurement might be rather inaccurate.
- Dynamic force-deflection characteristics were determined for the bumper, hood and hood edge. However, due to possible differences in impact velocities, shape of contact bodies, and location of the impact, the force deflection characteristics in the actual dummy-vehicle impact may vary. Development of a contact model that accounts for geometric and velocity effects could contribute considerably to the improvement of the models reliability.

The influence of the complexity of the models can be summarized as follows:

- the reliability of the model for lateral dummy impacts slightly improves if a greater number of segments is defined and if the 3-dimensional version is used
- absence of an initial peak in head (and chest) accelerations if the number of segments for the upper part of the body increases
- more realistic lower leg accelerations (and consequently bumper loads) if the legs are separately represented in the models
- more realistic head impact velocities (and peak head accelerations) if the 3-dimensional model is used.

Disadvantages of the application of the 15-segment 3D-model are:

- increase of computer time (3x compared to the 7-segment 2D-model)
- increase of input parameters
- a relative large sensitivity of the initial arm position at the impact side
- a larger possibility of model instabilities.

Based on this in many cases use of the 7-segment 2-dimensional model (or an extended model with arms) is advisable.

The model results presented here, are only valid for lateral (or oblique) Part 572 dummy impacts. A disadvantage of the Part 572 dummy in this respect is the stiff thorax and shoulder structure. Another restriction is that these results are based on only one single car type. Future studies will include different car types, child dummy impacts and the simulation of cadaver experiments. If the mathematical models then show reliable results for such different conditions, successful model application for the evaluation and improvement of pedestrian protection provided by different car contours might be expected.

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