APPLICATION OF A THREE-DIMENSIONAL MATHEMATICAL OCCUPANT MODEL FOR THE EVALUATION OF SIDE IMPACTS

J. Wismans and J. Maltha

Research Institute for Road Vehicles-TNO,
Delft, The Netherlands

ABSTRACT

A three-dimensional mathematical model for simulation of the human body crash dynamics was formulated, for which the general MADYMO CVS program package was used. This model is employed for the analysis of the side impact behaviour of two different dummies: the Part 572 50 percentile male dummy and the APROD 80 dummy.

Model predictions for both dummies are compared with the results of lateral drop tests and rigid wall sled tests.

It is concluded that the mathematical model gives a realistic prediction of kinematics, impact forces and accelerations. The influence of the arm-shoulder assembly in loading the vehicle paddings and dummy ribcage is analysed.

INTRODUCTION

Side impacts produce a significant portion of the present fatality and injury totals (1). In the past five years injury protection for this type of accidents has become an important research objective. A large part of the present research in this complex field is directed toward obtaining insight in the injury mechanisms, establishment of injury protection criteria and toward the development of lateral impact crash dummies enabling injury detection of the most endangered areas of the human body (2,3,4,5,6,7,8,9,10).

With a view to dummy development, subjects of ongoing research are, for instance, the importance of incorporation of arms in side impact dummy designs, and to what extent thorax rigidity and mass distribution influence the resistance of paddings, and the injury prediction capability of the various dummy instrumentation readings. Another interesting problem in this respect is the effect of differences in anthropomorphic characteristics of cadaver subjects on proposed injury tresholds.

This paper presents a mathematical model which simulates the occupant in side impacts in interaction with its environment. Such a model, if well - validated, can contribute to the insight in the above research problems. Other applications of such a model are the interpretation and enhancement of biomechanical data obtained from experiments and the improvement and optimization of car interior paddings (Computer Aided Design).

Robbins (11) gives a review of several computer programs now available for simulation of human body gross motion. In literature a few model studies were described related to the study of occupant response in a side collision. A study with the MVMA two-dimensional CVS program, a model which is normally used to investigate frontal collisions, was carried out by Bowman et al. (12). A primary goal in this study was the analysis of the head-neck motions. The near-side arm, i.e. the arm between occupant and struck vehicle side, was included in the model. The simulations were limited to motions in a lateral plane. Padgaonkar and Prasad (13) applied the Calspan 3D model in their side impact study. Both the striking and the struck car were included in this simulation. The occupant part of this model was, however, limited to three body segments: head, torso and pelvis, so the influence of the arm- shoulder assembly could not be analysed in detail.

In the model presented in this paper the three-dimensional version of the MADYMO CVS program package (14) is used for the simulation of two different dummies under various test conditions. Earlier applications of MADYMO were limited to two-dimensional studies of adult and child car occupants in frontal collisions (15,16,17) or to simple three-dimensional systems with a known analytical solution.

MODEL DESCRIPTION

A 15-segment linkage system was selected to simulate the human body while the MADYMO-3D package was used (Fig. 1). The head, neck, the upper and lower arms (including hands), the upper and lower legs (including feet) are each simulated by one rigid element. For the torso, three elements are introduced, while, moreover, each shoulder is represented by one element. This model can be easily expanded to simulate more details, like the rib mass, because in MADYMO the number of elements is not limited. In next sections the model for the Part 572 50 percentile male dummy and the APROD 80 dummy will be discussed separately.

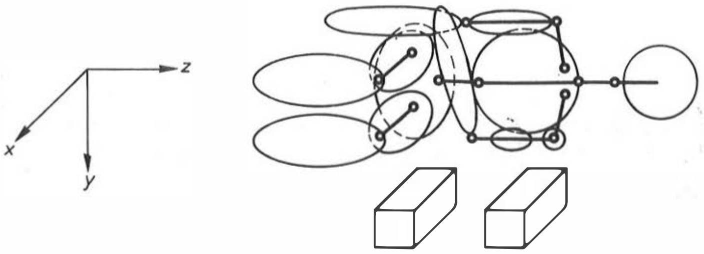


Fig. 1 Overall view of the 3D human body model and orientation of the laboratory coordinate system (x,y,z).

Model of the Part 572 dummy - Elbow, knee and hip joints of this model are corresponding to the real position in the dummy. The neck and the spine joints are located corresponding to the attachements of the rubber cylinders representing neck and spine. The upper arm - shoulder joint is located in the centre of the pinned connection of arm with shoulder while the shoulder - thorax joint is located in the centre of both links that simulate the clavicle - spine articulation. Since in literature no detailed data on the 3D-mass distribution of the Part 572 dummy were available, an extensive program of measurements was carried out to determine these characteristics. A detailed description of the mass distribution of this dummy model is given in reference (18).

The relative orientation of two adjacent body segments is defined in MADYMO by three successive and independent rotations, the relative Bryant angles (19). In the present version of the program it is assumed that the resistive joint torque can be expressed as a function of these relative angles in such a way that for each angle a resistive joint torque function can be defined. This torque can be the sum of contributions from elastic, viscous damping and coulomb friction actions. In various dummy joints by means of a joint-torque measuring device, static joint torque characteristics (including range of motions and joint-stops) were determined for flexion-extension, abduction-adduction and torsion motions. On the basis of these characteristics, input data sets were defined for the elastic joint torque and for the constant friction torque. In addition, a velocity dependent resistive torque (viscous damping) is defined in some of the joints; the magnitude of the viscous damping coefficients is estimated to be below calculated values for critical damping. In reference (18) a detailed description is given of the data characterizing the joint properties in the dummy model.

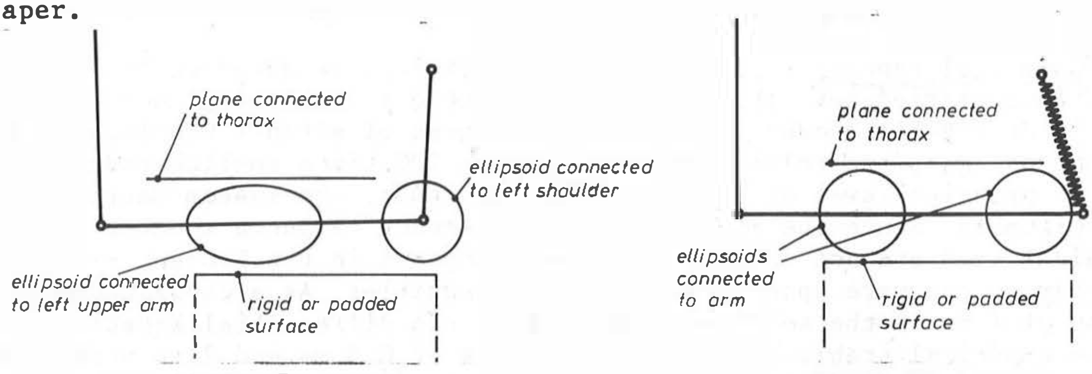
Ellipsoids or planes are connected to the surfaces most likely to be contacted in a side impact. Whenever a positive penetration between an ellipsoid and a plane is detected, an elastic force which is a function of the penetration depth is calculated by the model.

Fig. 2 illustrates the simulation of the contact between arm and thorax and between arm and environment. The influence of a direct contact between thorax and environment is not taken into account in the simulations dealt with in this paper.

Static force-deflection characteristics for the most significant dummy regions in a side impact, i.e. the arm (including shoulder), the thorax and the pelvis were determined by means of a hydraulic tester. Some of the test configurations and the corresponding force-deflection characterictics are shown in Fig. 3. In these tests, rigid contacting bodies were used; for the thorax this body approximated the outside geometry of the dummy arm, whereas in the other tests a flat body was used.

With this model, impacts between dummy and rigid and padded surfaces were simulated. In case of a contact with padded surfaces the shock absorbing material consists of two rectangular polyurethane blocks (2). Static and dynamic force deflection characteristics were determined with different types of rigid contacting bodies. Results achieved from the static test for the body with a shape similar to that of the dummy arm are included in Fig. 3.

The data set characterizing the elastic properties of the ellipsoid-plane contacts are formulated on the basis of these measurements. For the other less important contacts estimations are made. In addition hysteresis and a small permanent deformation were assumed. MADYMO offers the possibility to define viscous damping and friction forces in the contacts. With the exception of the APROD 80 ribcage these forces are taken zero in the simulation dealt with in this paper.



Part 572 dummy

APROD 80 dummy

Fig.2 Simulation of arm-shoulder assembly.

Model of the APROD 80 dummy - The APROD 80 dummy, developed by the Laboratory of Physiology and Biomechanics Peugeot-Renault Association, is a modification of the Part 572 dummy (50 percentile male) with the aim of obtaining a more realistic behaviour in lateral impacts (5,7). Differences between the Part 572 dummy and the APROD 80 dummy (version specified in reference (5)) are in the shoulder, the arm and the thoracic cage designs.

The mathematical model of the APROD 80 dummy was obtained by some modifications in the model of the Part 572 dummy. The flexible shoulder is simulated by omitting the rigid shoulder element and introduction of a non-linear spring (Fig. 2). APROD 80 thorax and arm are simulated by adaptation of the characteristics of the various ellipsoid-plane interactions.

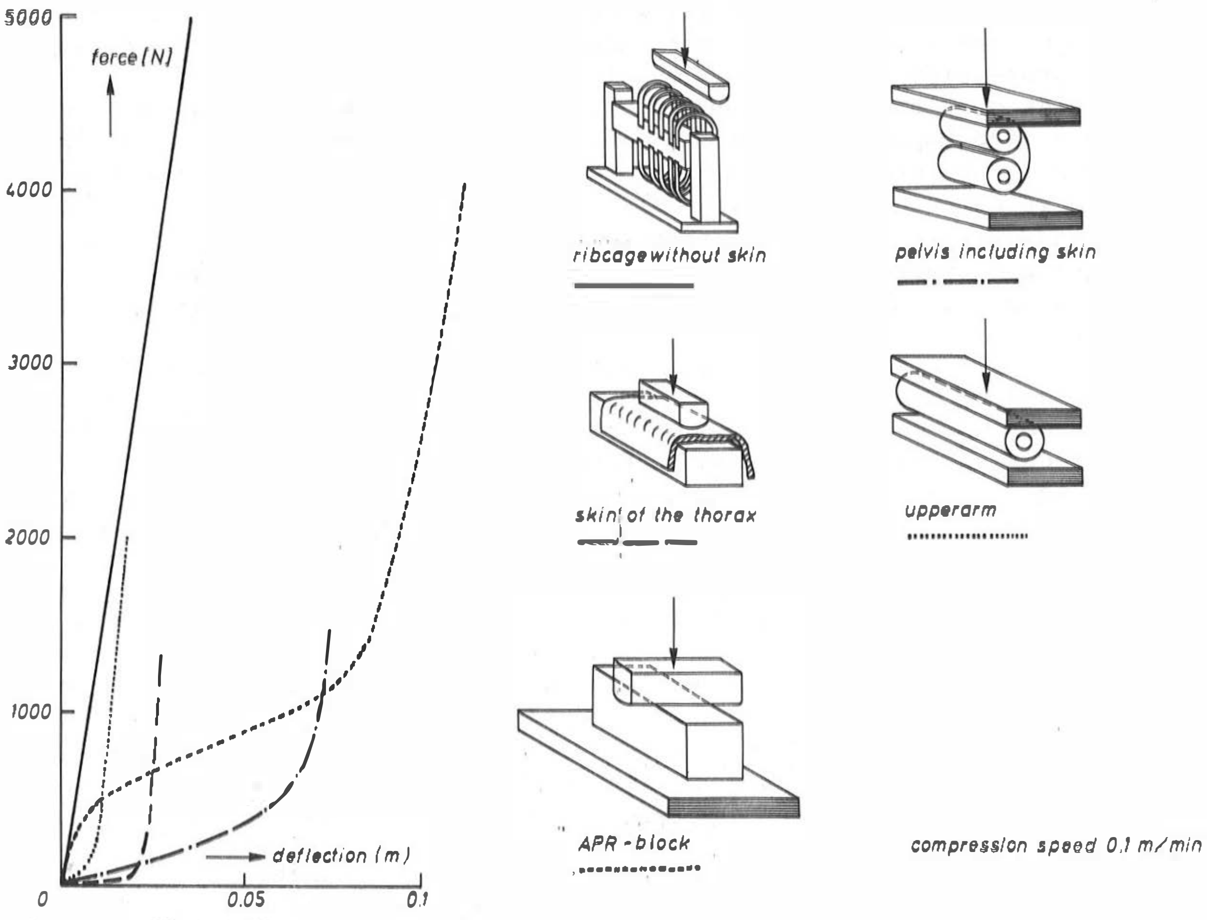


Fig.3 Static force-deflection characteristics of various contact surfaces.

Numerical aspects - Numerical instabilities were observed in the first simulations carried out. The main cause of these instabilities was that the moments of inertia around the longitudinal axes of slender elements, like the arms and legs, are relatively small (10 to 100 times smaller than for both other principal axes of inertia). Owing to this, the system matrix is ill - conditioned. Since the rotations of the slender elements about their longitudinal axes are not considered to be important in the present simulations, higher values were specified for these quantities. As a consequence, a time step of 1 ms in the solution procedure of the differential equations resulted in a numerical stable solution. Time steps of 0.5 ms and 2 ms were found not to influence the model results.

RESULTS OF MATHEMATICAL SIMULATIONS AND COMPARISON WITH EXPERIMENTAL RESULTS

With both models of the Part 572 dummy and the APROD 80 dummy calculations are carried out concerned with the simulation of lateral drop tests and rigid wall sled tests. The results of the Part 572 dummy in 3 rigid wall sled tests and of the APROD 80 dummy in one drop test on padding blocks will be presented here with special emphasis on the comparison with experimental results.

Simulations of the Part 572 dummy in rigid wall sled tests - Melvin et al. (3) conducted a series of rigid wall sled tests with the Part 572 dummy. Three impact velocities, 25 km/h (6.94 m/s), 33 km/h (9.16 m/s) and 43 km/h (11.94 m/s) were used in these tests. The model formulated for the Part 572 dummy was used to reproduce these tests. Gravitational forces and frictional forces between dummy and seat are neglected in these simulations.

The predicted occupant kinematics (projections on the (y,z)- and (x,y)-plane) for the 25 km/h impact are shown in Fig. 4 and the resultant linear head, chest and hip accelerations in Fig. 5. Fig. 6 shows a comparison of the load between arm and thorax with that between arm-shoulder assembly and the rigid wall. It can be seen that owing to the low compliance of the shoulder only a small part of the rigid wall load is transmitted to the thorax. The major part of this load is transmitted by the shoulder element; this causes the head almost directly to rotate toward the rigid blocks. In general, the predicted kinematics are in agreement with the observations of Melvin (3).

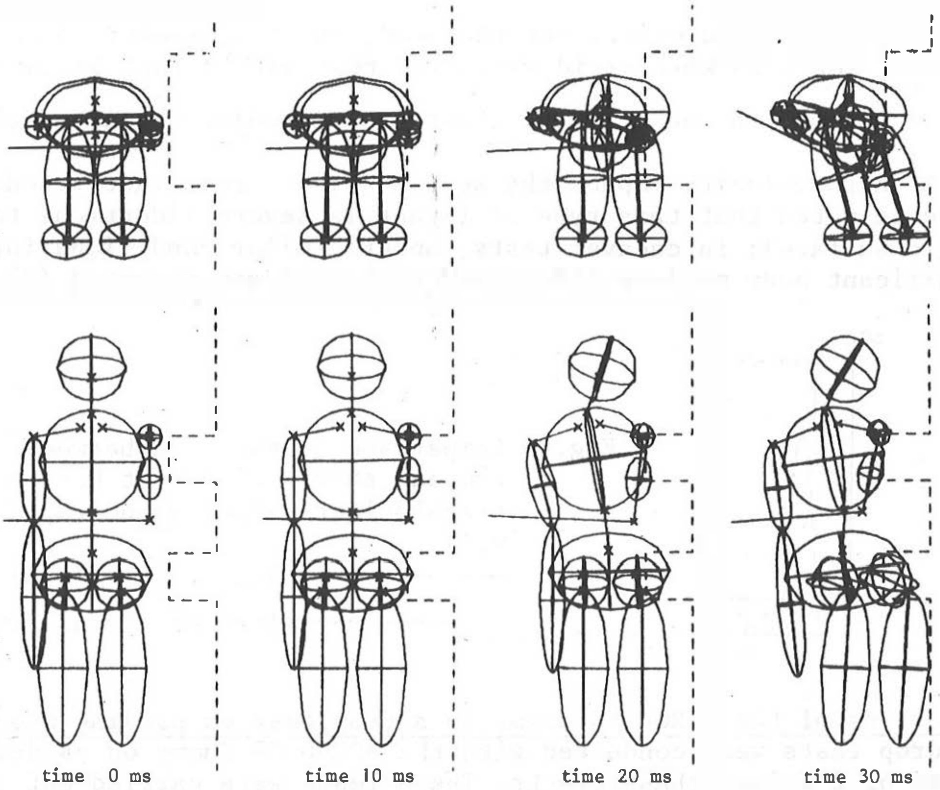


Fig.4 Model predictions of the kinematics for a 25 km/h rigid wall sled test with a Part 572 dummy.

Table 1 Maximum resultant linear head and chest accelerations resulting from rigid wall sled test (3) and model predictions

Impact velocity	Maximum linear accelerations			
	Head (g)		Chest (g)	
m/s	Model	Exp.	Model	Exp.
6.94 (low)	79	81	94	65
9.16 (medium)	109	97-117	150	144-150
11.94 (high)	140	177	157	187

Table 1 summarizes the resultant peak head and chest accelerations of model and experiments for three impact velocities. It can be seen that for both low

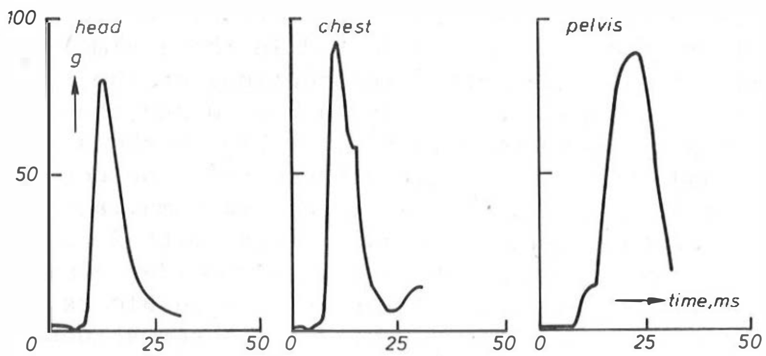


Fig. 5 Model predictions for the head, chest and pelvis accelerations for a 25 km/h rigid wall sled test with a Part 572 dummy.

and medium velocities the head and chest model predictions are rather realistic.

For the high velocity impact the accelerations are slightly under-estimated. It should be noted that this type of impact is severe (identical to a 7 m drop on a rigid surface); in cadaver tests, under similar conditions for most of the significant body regions AIS values of 5 or 6 are reported (3).

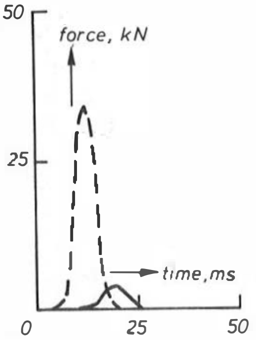


Fig. 6 Comparison of the load between arm and thorax with that between arm-shoulder assembly and rigid wall.

— — — — — = load on rigid wall

———————— = load on thorax ribcage.

Simulations of the APROD 80 dummy in a drop test on padding blocks - Four lateral drop tests were conducted with the APROD 80 dummy on padded surfaces consisting of 2 polyurethane blocks. These tests were carried out in our laboratory in 1980. Acceleration-time histories for the head, chest and pelvis were recorded and also the impact force-time history on the padding block near the thorax. Deflections of the dummy-ribcage were obtained from high speed movies. Fig. 7 shows the corridors indicating the spread in test results for the most important measurements in these experiments.

The APROD 80 thorax used in these tests was provided with pistons having a stroke of 40 mm. Static lateral force-deflection characteristics of the thorax assembly were measured and used as input in the mathematical model of this dummy. The first model calculation showed that maximum piston stroke was reached in about 20 ms in contrast to the experiments, where maximum stroke did not occur at all. This difference between model and experiment is most likely explained by a combined effect of jamming of the piston rods (20), of friction and damping forces between pistons and cylinders and of inertial forces of pistons and ribs. These phenomena were partly taken into account by the introduction of viscous damping forces for the arm - thorax contact. A viscous damping coefficient of 1000 Ns/m was found to give realistic model results.

The resulting linear head, chest and pelvis accelerations and the load on the padding block near the thorax are presented in Fig. 7 together with the experimental corridors. It can be seen that the model results are located in or close to the experimental corridors. The kinematics predicted by the mathematical model are shown in Fig. 8. This figure shows that, as compared with the Part 572 dummy model (see Fig. 4), larger shoulder deflections and smaller head rotations are predicted for the APROD 80 dummy, which is in agreement with experimental findings.

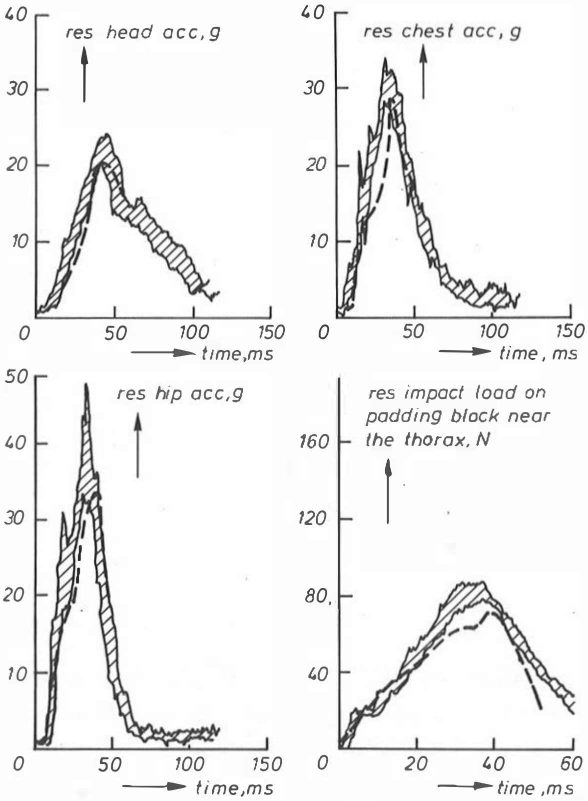


Fig. 7 Model predictions and experimental corridors for a 2 m drop test of the APROD 80 dummy on padding blocks.

SENSITIVITY ANALYSIS

There are various reasons to conduct a sensitivity analysis with a mathematical model. One objective is the evaluation of the influence of model parameters for which estimates have to be made. Another objective is to analyse the influence of variations in experimental conditions. Owing to the complete reproducibility of a mathematical model, the effect of such changes can be predicted accurately. This feature will be illustrated in the following example:

The effect of the initial dummy orientation - A dummy may develop a small rotation during the free-fall part of a drop test. Accurate evaluation of the effect of these rotations by means of experiments is not possible since in such an experiment all the other test parameters will also be slightly different.

With the mathematical model of the Part 572 dummy two variations were carried out. In the first calculation the dummy is initially rotated by 10° about the A-P axis and in the second one by 10° about the S-I axis (see Fig. 9). The referential simulation is a 2 m drop test with the dummy in the horizontal position on two padding blocks.

The resulting model predictions are summarized in Table 2, which clearly shows the sensitivity of this initial orientation.

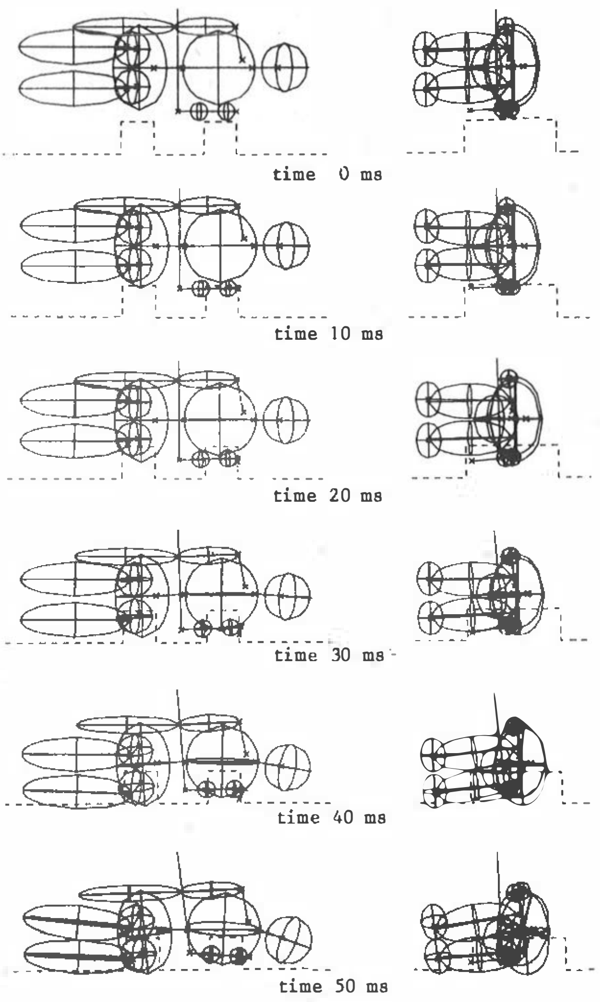


Fig. 8 Model predictions of the kinematics for a 2 m drop test on padding blocks with the APROD 80 dummy.

Table 2 Effect of initial orientation in a lateral drop test [1)]

Description	Change max. res. lin.			Change in max. padding load	
	head (%)	chest (%)	pelvis (%)	thorax (%)	pelvis (%)
Variation 1 (see Fig. 9)	- 7	+25	+ 5	- 7	+ 9
Variation 2 (see Fig. 9)	+17	+28	+23	+11	- 9

1) Reference: Part 572 dummy in padded impact.

ANALYSIS OF THE ROLE OF THE ARM-SHOULDER ASSEMBLY IN SIDE IMPACTS

The behaviour of the Part 572 dummy and the APROD 80 dummy will be analysed here in more detail to obtain a better insight in the role of the arm-shoulder assembly. This analysis is based on four mathematical simulations of lateral drop tests from 2 m height:

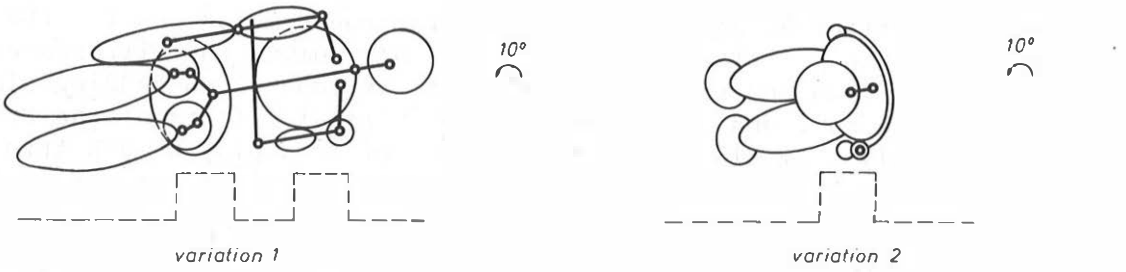
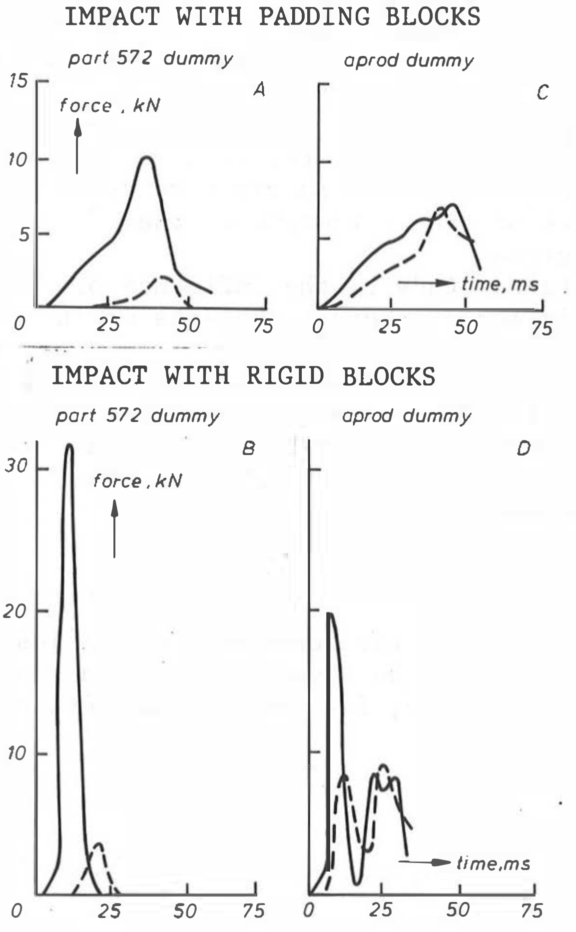


Fig. 9 Variations of the initial orientation of the dummy in a lateral drop test.

- impact of Part 572 with rigid blocks (this simulation is almost identical to a rigid wall sled test (v = 6.94 m/s) presented before)
- impact of Part 572 with the padding blocks
- impact of APROD 80 with rigid blocks
- impact of APROD 80 with the padding blocks (this simulation is presented before).

Fig. 10 shows for both dummies the impact load on the thorax ribcage and on the padding or rigid blocks.

In the case of the Part 572 dummy, when impacting the padding blocks, the peak load on the padding is almost 5 times higher than the load transmitted to the thorax (Fig. 10 A). A much larger deviation is predicted for the rigid impact (Fig. 10 B). This behaviour can mainly be explained by the low compliance of the shoulder structure, but also inertial effects of the arm will contribute to this.


IMPACT WITH PADDING BLOCKS

IMPACT WITH RIGID BLOCKS

Fig. 10 Comparison between forces on ribcage and padding or rigid blocks (simulation of 2 m drop tests with mathematical model).
——— = force on rigid or padding blocks
------ = force on ribcage

A complete different behaviour results from the simulations for the APROD 80 dummy. Owing to the flexible shoulder in this dummy, the differences between padding load and thorax ribcage load for impacts on padding blocks are found to be small and are mainly due to inertial effects of the arm-shoulder assembly (Fig. 10 C). These inertial effects play a much stronger role in case of a rigid impact: the peak load on the rigid surface is found to be more than 2 times the load on the thorax ribcage (Fig. 10 D).

DISCUSSIONS AND CONCLUSIONS

In the preceeding sections a selection was presented of simulations conducted with the MADYMO 3D version. This selection varied from high velocity rigid wall sled tests to drop tests on padded surfaces. These simulations were carried out for two dummy types (the Part 572 dummy and the APROD 80 dummy). From the comparison with results of various experiments it was concluded that the model predictions for this type of test conditions are reliable. It should be noted in this respect, however, that the results for the simulations of the APROD 80 dummy could only be achieved after prescribing a rather high damping force for the thorax ribcage assembly.

The mathematical analyses showed the important role of the shoulder-arm assembly. Owing to the great flexibility of the APROD 80 shoulder in comparison with the Part 572 dummy a smaller loading on the padding is found, which is corresponding to experimental findings. It is also shown that for rigid impacts on the APROD 80 dummy, with the arm located between ribcage and impacting surface, the externally applied load is completely different from that on the ribcage. This feature is mainly due to inertial effects of the arm and could also be expected for cadaver tests. Since in the latter type of test the externally applied load is usually recorded, it is recommended that thorax load injury criteria are corrected for these inertial effects particularly in case of rigid impacts.

Possible further applications of the model presented here, are:

- Detailed analyses of the influence of small variations in experimental conditions. An example of such an application (the influence of the initial orientation in a drop test) was given.
- Analysis of biomechanical tests; for instance study to the influence of differences in anthropomorphic characteristics of cadaver subjects on injury thresholds.
- Contribution to the improvement of dummy design and vehicle paddings (Computer Aided Design). One of the features of MADYMO is that extra elements simply can be added to the model. As a consequence relevant parts of a system can be simulated in more detail. In this way, for instance, the ribs can be represented as separate elements.

ACKNOWLEDGEMENTS

This study was conducted under contract NL4 with the European Communities. Grateful acknowledgement is made to the Laboratoire de Physiologie et de Biomécanique Association Peugeot S.A. - Renault, France, for their contribution to this study.

REFERENCES

1. Eppinger, R.H. (1979): "Considerations in side impact dummy development". 7th ESV Conference, Paris.

2. Fayon, A., Tarrière, C., Walfisch, G., Got, C. and Patel, A. (1977): "Contribution to defining the human tolerance to perpendicular side impact". Ircobi Conference.
3. Melvin, J.W., Robbins, D.H. and Stalnaker, R.L. (1976): "Side impact response and injury". 6th ESV-Conference.
4. Walfisch, G., Fayon, A., Tarrière, C., Got, C., Patel, A. (1979): "Travaux effectués pour disposer d'un mannequin et de critères convenables pour améliorer la protection en choc latéral". Proceedings of "Ingénieurs de l'Automobile" (S.I.A.), A.T.P. Sécurité de Véhicule - No 3 - Mars 1979.
5. Fayon, A., et al. (1979): "Presentation of a frontal impact and side impact dummy, defined from human data and realized from a "Part 572" basis". 7th ESV-Conference, Paris.
6. Walfisch, G., Fayon, A., Tarrière, C., Rosey, J.P., Guillon, F., Got, C., Patel, A., Stalnaker, R.L. (1980): "Designing of a dummy's abdomen for detecting injuries in side impact collisions". Ircobi 1980.
7. Stalnaker, R.L., Tarrière, C., Fayon, A., Walfisch, G., Balthazard, M., Masset, J., Got, C. and Patel, A. (1979): "Modifications of Part 572 dummy for lateral impact according to biomechanical data". 23rd Stapp Conference.
8. Robbins, D.H., Lehman, R.J. (1979): "Prediction of thoracic injuries as a function of occupant kinematics". 7th ESV-Conference, Paris.
9. Melvin, J.W., Robbins, D.H., Benson, J.B. (1979): Experimental application of advanced thoracic instrumentation techniques to anthropomorphic test devices". 7th ESV-Conference, Paris.
10. Tarrière, C., Walfisch, G., Fayon, A., Rosey, J.P., Got, C., Patel, A., Delmas, A. (1979): "Synthesis of human tolerances obtained from lateral impact simulations". 7th ESV-Conference, Paris.
11. Robbins, D.H. (1975): "Simulation of human body response to crash loads". In "Shock and Vibration Computer Programs". Monographs No. SVM-10, Shock and Vibration computer center, U.S. Dept. of Defense.
12. Bowman, B.M., Schneider, L.W., Foust, D.R. (1975): "Simulated occupant response to side-impact collisions". 19th Stapp-Conference, San Diego.
13. Padgaonkar, A.J., Prasad, P. (1979): "Simulation of side impact using the CAL 3D Occupant Simulation Model". 23rd Stapp-Conference, San Diego.
14. Maltha, J. and Wismans, J. (1980): "MADYMO-Crash Victim Simulations. A computerized research and design tool". Ircobi Conference, Birmingham.
15. Wismans, J., Maltha, J., Melvin, J.W. and Stalnaker, R.L. (1979): "Child restraint evaluation by experimental and mathematical simulation". 23rd Stapp Car Crash Conference, Society of Automotive Engineers. Inc. Warrendale, Pa.
16. Stalnaker, R.L. and Maltha, J. (1980): "MADYMO used for computer aided design of a dynamic acting child restraint seat". Ircobi Conference, Birmingham.
17. Wismans, J., Cesari, D., Maltha, J. and Ramet, M. (1980): "Evaluations of the experimental reconstructions of a real frontal collision with a mathematical model". Ircobi Conference, Birmingham.
18. Maltha, J., et al. (1980): "MADYMO manuals". Vol. 1-4, IW-TNO Delft, The Netherlands.
19. Wittenburg, J. (1977): "Dynamics of systems of rigid bodies". Teubner, Stuttgart.
20. Mellander, H. and Bohlin, N. (1980):"A comparison between different dummies in car to car side impacts". 8th ESV-Conference, Wolfsburg.