STATUS OF THE MADYMO CRASH VICTIM SIMULATION PACKAGE 1985

J. Wismans, T. Hoen and L. Wittebrood
Research Institute for Road Vehicles TNO
Delft, The Netherlands

ABSTRACT

MADYMO is a compact general purpose computer program package for two- or three-dimensional crash victim simulations. The program predicts the kinematics and dynamical behaviour of the victim during the crash, based on data of the victim, the environment, the safety devices and the crash conditions. The package differs from most of the existing CVS programs by its flexibility in choice of number of linkages and number of elements in each linkage. Great flexibility in the modelling of force interactions between elements and environment is assured by the fact that user-defined submodels can readily be incorporated.

This paper summarizes the most important features of the current MADYMO 2D and 3D version and reviews a number of applications. Topics covered include side impacts, pedestrian safety, human body segment models and computer aided design. An attempt to identify areas of future developments and general trends in the field of crash victim simulations concludes this paper.

## INTRODUCTION

In the field of automotive research, simulation of crashes is of vital importance in order to evaluate and improve safety devices and occupant environment. Most of this work is done by means of experiments, using instrumented dummies, cadavers, and occasionally animals or volunteers. During the past years a strong increase could be observed in the use of computer simulations in this area due to the fast developments both in computer hardware and in simulation software. Similar trends could be observed in other engineering disciplines where mathematical modelling has been an accepted tool already for many years.

The behaviour of dynamical systems in a crash environment appears to be of a very complex nature where in general a large number of system parameters will influence the system's dynamic response. Due to this a strong emphasis should be placed on experimental verification. As soon as an adequate level of reliability is obtained for a specific application, an effective economic tool will be available for further analyses or optimization of that system.

This paper describes the most important features and reviews of various applications of the MADYMO Crash Victim Simulation program. The program is of

Paper presented at 10th International Conference on "Experimental Safety Vehicles", 1st-5th July 1985, Oxford, England

the type gross-motion simulators which describe the human body (or other structures) by means of a number of connected rigid bodies. A review of several programs of this type, including the CALSPAN CVS model and the MVMA model, is given by Robbins [1]*, King [2] and Prasad [3].

Theoretical background of the MADYMO package will not be discussed here. Readers interested in this subject are referred to [4] for a general treatment of rigid body dynamics theories and to [5] for a brief summary of the specific MADYMO equations of motion.

## CURRENT MADYMO FEATURES

### General

MADYMO is a compact general purpose computer program package for two- or three-dimensional simulations of human body gross-motions. The program, which is based on rigid body dynamics using Lagrange equations, can be used to simulate one or more linkage systems without closed loops. Such systems are also known as "tree-structures" [3]. However, MADYMO allows the behaviour of a closed loop system to be approximated by connecting the end segment of a tree to any other segment by means of a massless element. The number of elements (rigid bodies) in each linkage system can be selected freely. The connections (joints) between the elements in a linkage system are of the hinge type for the two-dimensional and of the ball and socket type for the three-dimensional simulations.

Motion of the tree-structure of joint connected elements is caused by external forces. MADYMO offers the user a set of "standard" force-interaction models e.g. for belts, joints and contacts of segments with each other or with the environment. The program is organized in such a way, that the user can modify these routines in a relatively simple way, while in addition user-defined submodels can readily be incorporated.

The standard solution technique to solve the equations of motion is a fourth order Runge-Kutta method with a fixed time step. In MADYMO 3D optional a fifth order Runge-Kutta-Merson method with variable time step is available. A restart option in MADYMO 3D allows restart of a simulation at any point of time on the basis of calculation results in a preceding simulation.

The description of MADYMO to be presented here relates to MADYMO 2D version 3.0 which has been available already for several years for external users and MADYMO 3D which will become available later this year. A number of features described for MADYMO 3D and not yet incorporated in the current MADYMO 2D version will be included in the next MADYMO 2D release. Both the 2D and 3D version have been applied extensively in various research programs in the past years as will be described later in this paper. Based on the experience in these research applications the MADYMO 3D version has gone through considerable debugging and optimizations with particular emphasis on the user convenience of the package.

---

* Numbers between brackets designate references at end of paper.

In the next section some of the current features of MADYMO 2D and 3D will be discussed in more detail. Among other things attention will be given to joint-, contact- and belt models.

Joint loads

In MADYMO 2D elements are connected by pin joints with one degree of freedom (Fig. 1a). A non-linear joint torque can be specified consisting of elastic, viscous damping and coulomb friction components. The standard features of MADYMO 2D allow in addition the simulation of a three degrees of freedom planar joint i.e. with one rotational and two translational degrees of freedom by specification of the joint segments as elements of different systems. Interaction between the two elements can be represented by for instance spring-damper models and contact models. A hypothetical example simulating the human knee-joint is illustrated in Fig. 1b.

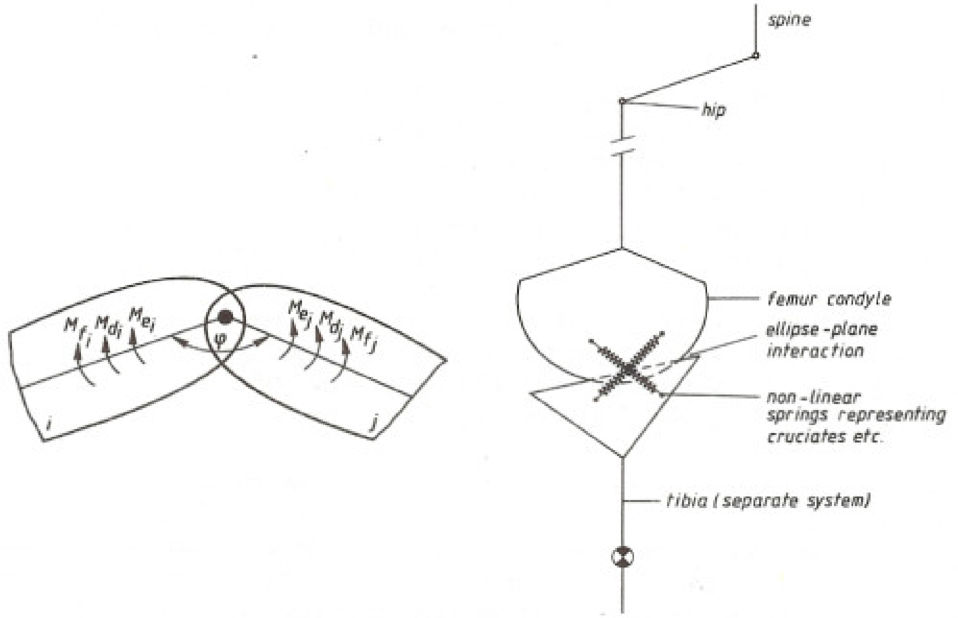


Figure 1. Methods to apply joint loads in MADYMO 2D:
a. pin joint
b. hypothetical example of a joint with three degrees of freedom

The standard joint connecting two segments in the MADYMO 3D version is of the ball and socket type with three degrees of freedom. Three methods are currently available to apply joint loads (Fig. 2):

Option I : the cardan joint model
Option II : the flexion-torsion joint model
Option III: spring-damper and/or contact models.

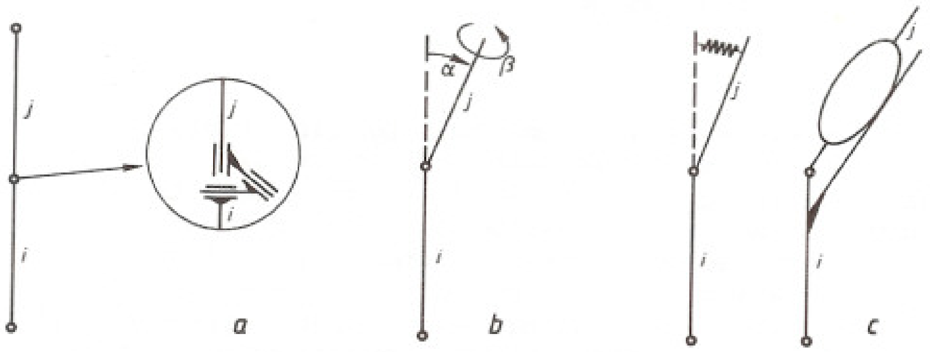


Figure 2. Methods to apply joint loads in MADYMO 3D:
a. cardan joint model
b. flexion-torsion joint model
c. spring-damper and/or contact models

In the cardan joint model (option I) the relative position between the joint segments is considered to be the result of three successive rotations. The first rotation is round an axis fixed to segment i, the second rotation round a floating axis and the third rotation round an axis fixed to segment j (Fig. 2a). The centers of rotation for the three hinge joints are assumed to coincide in one point. Joint torques can be specified for each rotation separately by means of non-linear elastic, viscous damping and friction torque components similar to the MADYMO 2D version. One or more rotations can be locked by defining relatively stiff elastic torque characteristics. This joint model is suitable to describe for instance some of the joints in the Part 572 dummy such as the shoulder-, elbow- and knee-joint.

In the flexion-torsion model (option II) the relative rotation is thought to be the result of a flexion and a torsion (Fig. 2b). Similar to the cardan joint model non-linear elastic joint torques can be specified as function of these angles. In addition a damping and friction torque can be applied as function of the relative rotational velocity between both segments. This joint model can be used for instance to approximate the behaviour of the rubber cylinders representing the spine and neck in the Part 572 dummy.

For each joint in a MADYMO 3D linkage system it is possible to define the cardan joint model or flexion-torsion joint model. Both joint models can also be defined in combination for the same joint which allows the user additional flexibility in modelling a more complicated joint type. In some situations the application of spring damper-systems or contact models (option III) might also offer realistic additional possibilities for joint modelling (Fig. 2c).

Joints with six degrees freedom can be represented in MADYMO 3D by assigning the two joint segments to separate linkage systems similar to the three degrees of freedom joint in MADYMO 2D (Fig. 1b).

Contact loads

In MADYMO 2D, contact lines and hyperellipses can be attached to any element of any system or to the laboratory reference frame. A hyperellipse is defined as follows:

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

where a and b are the semi-axes of the hyperellipse and n is the degree (Fig. 3). 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. 3. In this way edge contacts can be described quite realistically. In a similar way in MADYMO 3D contact planes and hyperellipsoids can be specified.

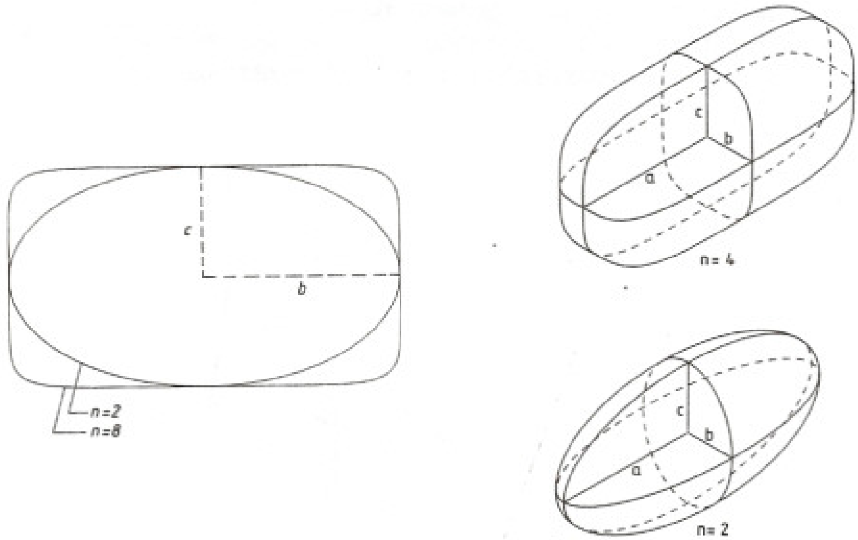


Figure 3. Hyperellipses (left) and hyperellipsoids (right)

The contact lines (planes) and hyperellipses (hyperellipsoids) allow for instance to describe the occupant interaction with vehicle interior surfaces. Two contact models are available, namely for contact lines (planes) interacting with ellipses (ellipsoids) and for hyperellipses (hyperellipsoids) interacting with each other. The reaction forces on the system segments are generated as function of the penetration between these contact contours. More details on the penetration algorithmes are provided in [6]. Non-linear elastic, damping as well as friction forces can be applied.

Additional features of these contact models are:
<u>simulation of intrusion etc.:</u> A user-defined subroutine (standard in MADYMO 3D) allows specification of the position of contact contours as function of time. In this way for instance intrusion of the car side structure into the compartment can be simulated .

initial penetration correction: The penetration used to calculate contact forces can be taken relative to the initial penetration. In this way in a relatively simple way a state of equilibrium can be obtained at the start of the simulation, provided that the effect of gravity can be neglected.

hysteresis: The effect of energy absorption in material can be simulated by defining the unloading slope of the force-deflection characteristic.

Belt loads

Two force-interaction routines are available to represent belt-restraint systems:

1. A simple massless spring-damper element which can be used for instance to simulate a lap belt or the upper or lower part of a torso strap.
2. An advanced belt system model. This model is basically the same in MADYMO 2D and 3D and describes the real spatial belt geometry (Fig. 4). The model consists of 5 segments and can account for slip between the belt segments and initial belt slack (or penetration). For the belt material energy dissipation and permanent elongation can be specified. An option called "film spool effect" is available for belt systems with a retractor.

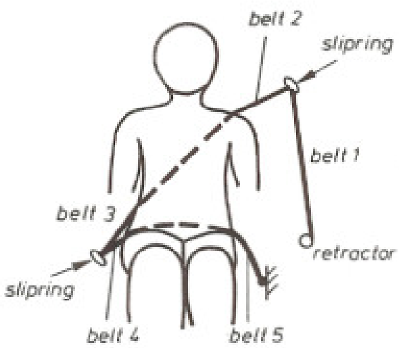


Figure 4. Advanced belt model

Point-constraint model

This routine constrains the position of one point of a segment relative to an arbitrary point fixed to another segment (or the environment). Both elastic and damping constraint loads can be specified in three mutually perpendicular directions (MADYMO 3D). Application of this model is useful for instance to constrain the motion of a separate ribcage segment [7] or to simulate a deformable steering column.

Deformable steering column

MADYMO does not have a separate force-interaction routine for a deformable steering column since the standard features of MADYMO allow to specify such a system directly in a simple way. Fig. 6 illustrates a realization of such a model as it was successfully implemented by several MADYMO users. A 2-segment linkage system is used here where one segment represents the steering column and one segment the steering wheel. The column is connected to the vehicle by means of two point-constraints describing the column deformation characteristics.

Airbag

The current MADYMO versions do not include a standard force interaction model for an airbag. An user-defined subroutine has been developed recently for the driver-airbag interaction where the airbag can be connected to a deformable steering column. This routine is expected to be available as an option in a next MADYMO 2D release.

Software characteristics

MADYMO is a compact modular program package written in FORTRAN 77. Due to the limited size of the program the MADYMO package can be implemented even on small computer systems which is illustrated by the following figures.

A simulation of an occupant in a frontal collision with MADYMO 2D requires 100 kByte memory and 3.5 minutes CPU time, whereas a complicated simulation of a cyclist impacted by a car with MADYMO 3D needs only 200 kByte memory and 12 minutes CPU time (above data relate to a VAX 11/750).

Pre- and post processing

The input for the current MADYMO versions is contained in a single formatted input file which can be changed simply by the user's editor. A special user-convenient subroutine has been developed in MADYMO 3D for specifying the initial position of the occupant and the various local coordinate systems that define inertia axes, joint rotation axes, hyperellipsoids orientations and point-constraint directions.

Special attention has been paid to user-convenient post-processing in MADYMO 3D. In the input dataset the user has to define which parameters must be calculated for output purposes, like

- kinematics
- linear displacements, velocities and accelerations of specified points
- angular velocities and accelerations of specified elements
- forces of specified force models
- torques of specified joints.

For additional output an user-defined subroutine can be incorporated in the program for instance to generate the model data in a format similar to experimental test data in order to apply user's standard experimental analysis software for further data processing.

For post-processing of the kinematics a three-dimensional graphics package is available which can be used in conjunction with both MADYMO 2D and MADYMO 3D. Features of this package include:

- isometric projections of ellipsoids and planes
- user-defined viewpoint
- intersecting ellipsoids
- contour lines on the surface of the ellipsoids
- hidden lines elimination
- self-contained; only simple plot routines are used.

Some of the features of this graphics package are illustrated in Figures 5, 6, 7, 9 and 12.

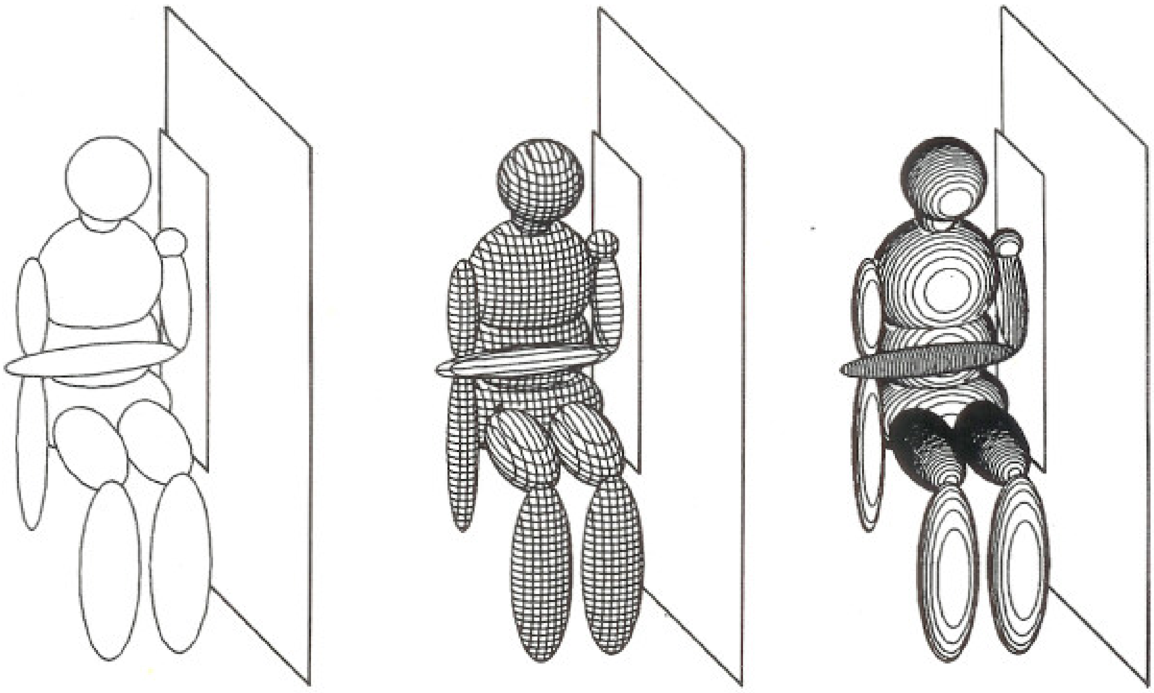

Figure 5. Examples of output from the MADYMO 3D graphics package

## APPLICATIONS

The versability of the MADYMO program package will be demonstrated here by means of a number of simulations that were conducted in the past years. For most of these examples a detailed experimental verification was performed. The applications will be divided into six categories:

- frontal collisions
- side collisions
- pedestrian and cyclist impacts
- child in a child restraint system
- human body segment models
- computer-aided design studies.

### Frontal collisions

The general model set-up of an occupant in a frontal collision most often used nowadays is illustrated in Fig. 6. The first experimental verification of the MADYMO 2D model was for a sled test with the simple 5-segment TNO adult test dummy. This verification was followed by several studies with the (much more complicated) Part 572 dummy under various test conditions.

In a research program started in 1979 in cooperation with the Organisme National de Securitė Routiere (ONSER) an attempt was made to simulate a real accident [8,9]. This accident had been reconstructed before experimentally with dummies and human cadavers which allowed a detailed validation of the MADYMO model for this specific accident situation. For both the dummy and cadaver tests quite realistic results were obtained from the mathematical simulations. Based on these results a mathematical reconstruction could be made for the real accident by simulating the real occupant anthropometry.

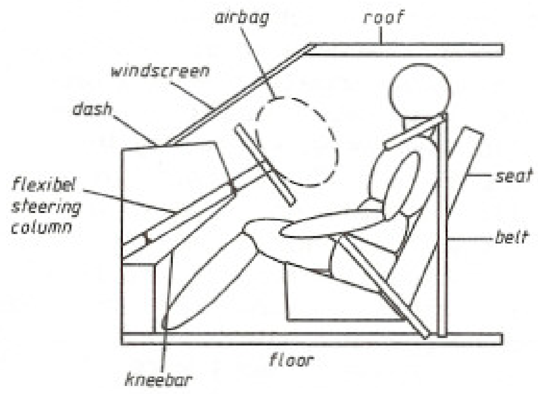


Figure 6. General model set-up for an occupant in a frontal collision

Side collisions

The first side-impact simulations conducted in our laboratory were rigid wall sled tests and drop tests with the Part 572 and APROD 80 dummy [10]. The 3D option of MADYMO was used for this purpose. Model predictions like contact loads and dummy accelerations were found to agree quite well with experimental results.

Side-impact accident reconstruction. The model of the Part 572 dummy was also used in a simulation of a more complicated impact: a real collision between a Peugeot 504 (stationary) impacted on the side (impact angle $70^o$) by another Peugeot 504 having a velocity of approximately 75 km/h [11]. For this accident several experimental reconstructions were conducted by the Lab. of Phys. and Biom. Peugeot S.A./Renault. The mathematical simulation was limited to the interaction between the occupant in the struck vehicle (a Part 572 dummy) and the inside structure of the vehicle. The displacement of the struck door was used as model input. The stiffness characteristics of door padding and of the arm-rest were determined with a hydraulic tester. The predicted dummy kinematics in this accident are illustrated in Fig. 7.

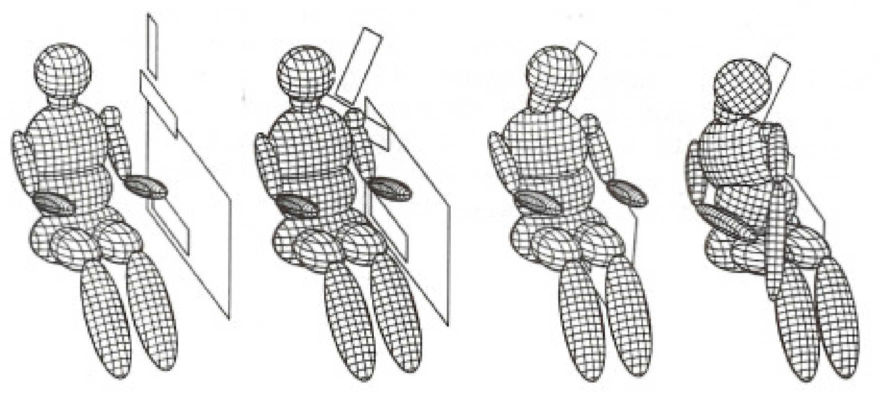

Figure 7. Mathematical simulation of a Part 572 dummy in a Peugeot 504 during a lateral collision 75 km/h)

Dummy thorax models. Another side impact application of MADYMO that will be presented here is the analysis of the dynamical behaviour of the thorax section in four different side impact dummies: the DOT/SID, MIRA, APROD 82 and ONSER-dummy. The basic design characteristics of the four thorax sections are completely different. Several models with varying complexity were formulated during this project. In these models the complete dummy was simulated in a rigid pendulum impact as illustrated in Fig. 8. Dependent on the complexity of the thorax design the ribcage was simulated by 0-, 1- or 2-segments in case of two-dimensional simulations and 7 segments in the three-dimensional model set-up. The mathematical simulations offered a very good insight into the dynamical behaviour of the four thorax designs. In the ONSER as well as the MIRA-dummy the thorax behaviour appeared to be mainly determined by the elasticity of the ribcage structure. In the DOT-dummy elasticity as well as damping (due to the viscous damper in this design) and inertia effects were found to play a significant role. These effects were of such a complex nature that a detailed three-dimensional representation had to be used for adequate simulation. A decisive judgement of the reliability of the APROD mathematical simulation could not be given due to inadequate functioning (jamming) of this thorax design. More details of this study are presented in [7] and [12].

Pedestrian and cyclist impacts

In the past years the Research Institute for Road Vehicles TNO has been involved intensively in research in the field of pedestrian and cyclist safety. As part of this research program four pedestrian models with varying complexity were formulated with MADYMO: three two-dimensional models with 2-, 5- and 7-segments, respectively and one three-dimensional model with 15-segments (Fig. 9). Model results were compared with experimental results of a Part 572 dummy impacted laterally by an Audi 100 vehicle at two velocities (30 and 40 km/h). In general all models appeared to provide values for the body segment accelerations within or close to the experimental range of responses. A slight improvement of the model results could be observed in the more complex models. For instance, due to the lower head impact velocity in the three-dimensional model a lower and much more realistic peak head acceleration during the hood impact could be observed. More details of this study are presented in [6] and [13].

More recently research in this area in our laboratory has focussed primarily on the integration of pedestrian and cyclist safety [14]. As part of this study a model of a cyclist has been formulated where the bicycle is represented by a separate one segment system (Fig. 9). The cyclist is simulated by a 9-segment system without arms in order to avoid the complex interaction of the arms with the hood in this type of impacts. Experimental verification for several test conditions with a simulated vehicle front is incorporated in a separate contribution to this conference [15].

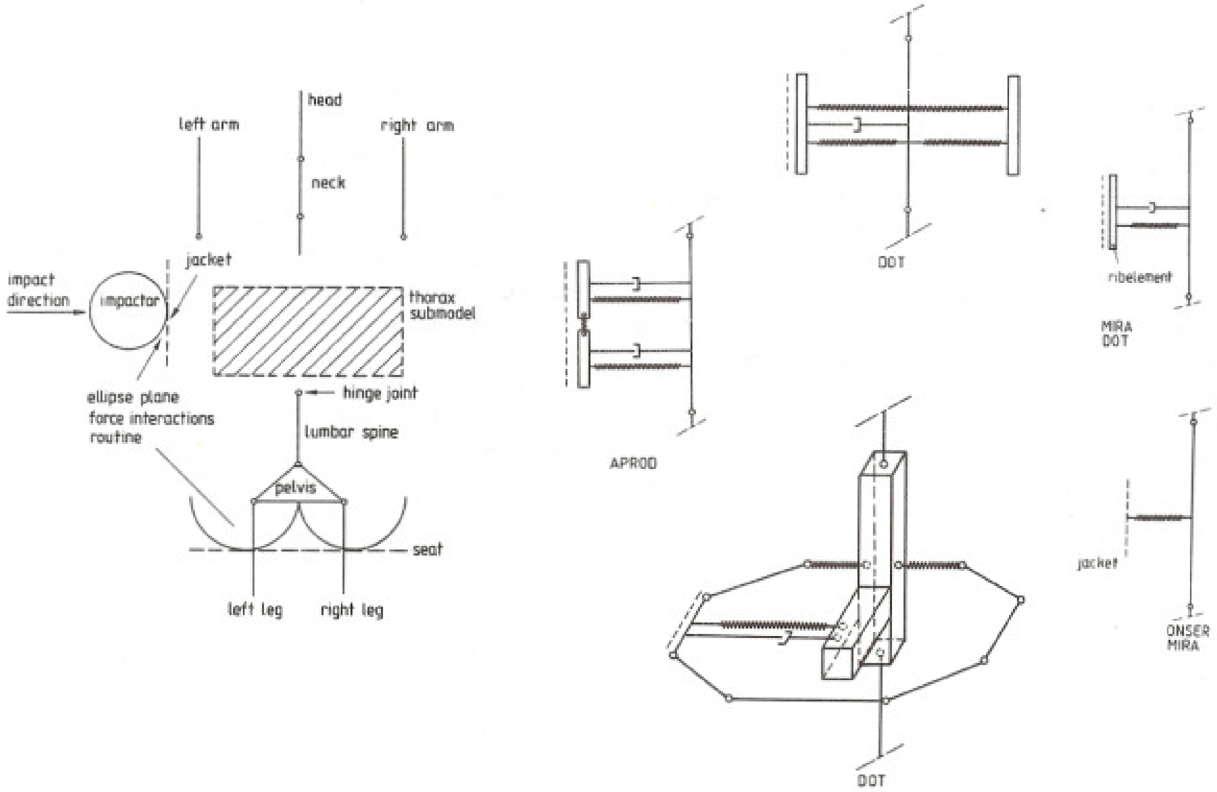


Figure 8. Simulation of thorax pendulum impact tests with four different side-impact dummies

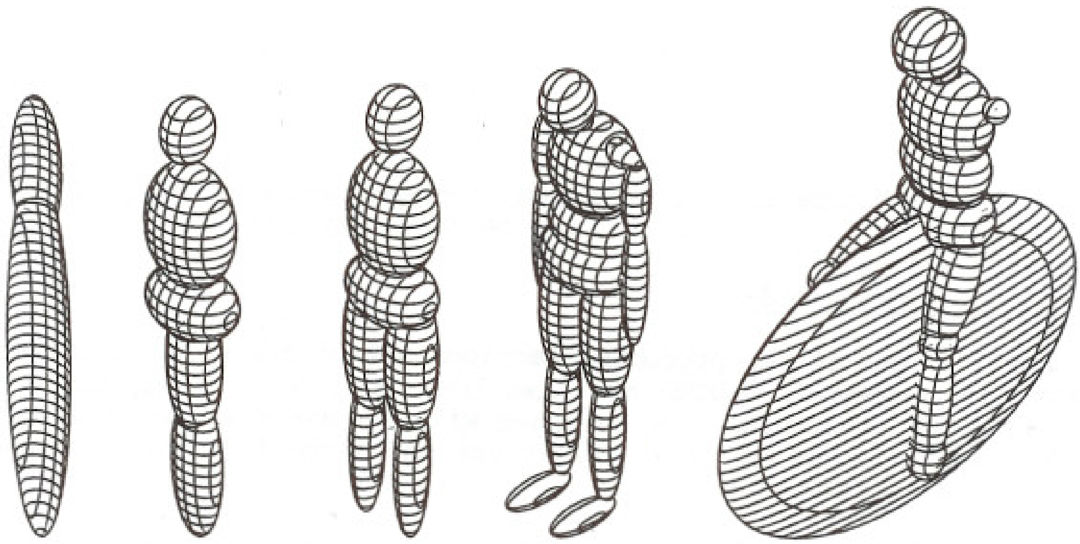

Figure 9. Geometry and contact ellipses of 2-, 5- and 7-segment 2D pedestrian, a 15-segment 3D pedestrian and a 3D 9-segment cyclist model, respectively

Child in a child restraint system

The next example is the simulation of an impact sled test with a child in a harness type child restraint system (Fig. 10). Details of this study were presented at the 23th Stapp Conference [16]. The child restraint system is represented by a separate 1-segment system connected to the sled by a lap belt and a back strap. Because of the 2D nature of the motions the 2D option of MADYMO was used for this analysis. Model results were compared with two sled tests conducted at the Highway Safety Research Institute in Michigan: one sled test with a 3-year old Part 572 dummy and the other with a child cadaver. In general a satisfactory agreement could be obtained between model and experimental results. Model predictions of the dummy behaviour were, however, found to be more realistic than for the cadaver, which may mainly be due to the great number of estimations that had to be made for the mass distribution and joint properties of the child cadaver.

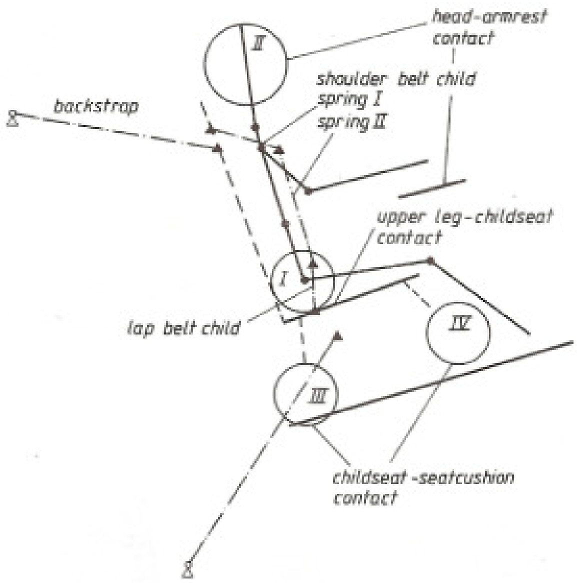


Figure 10. Mathematical representation of a child in a child restraint system

Human body segment models.

Applications in the preceding sections all relate to the simulation of the whole body response. MADYMO has also been applied to study the behaviour of specific body structures. Two examples will be presented here: a model for the head-neck kinematics of human volunteers and a model for the thorax behaviour in human cadavers.

Head-neck model. The model describing the head-neck kinematics was formulated with MADYMO 3D and consists of 3 segments: a torso link, a neck link and a head link which are connected by means of a pivot in the head near the occipital condyles and a pivot close to the T1 vertebral body in the torso (Fig. 11). A detailed description of this model and the experimental verification by means of lateral, oblique and frontal human volunteer tests is given in [17-20]. Fig. 12 illustrates model predictions in case of a lateral human volunteer test.

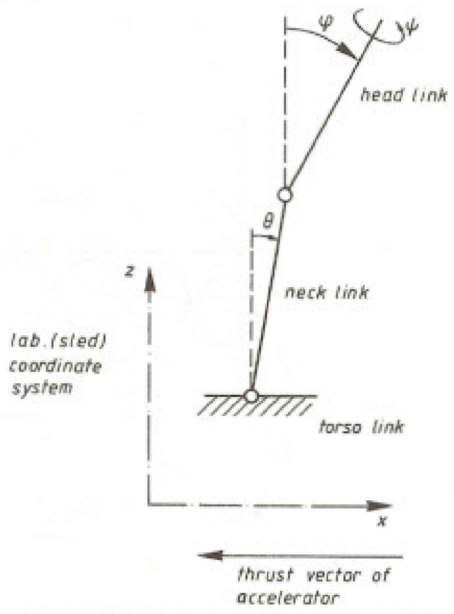


Figure 11. Mathematical model for head-neck motion of human volunteers in frontal, lateral and oblique impacts

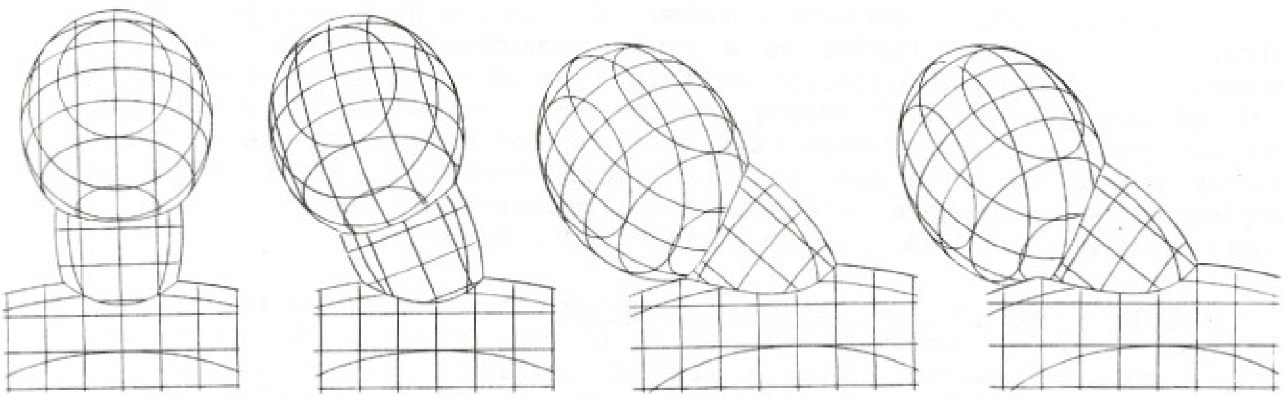

Figure 12. Prediction of the head-neck kinematics of a volunteer in lateral flexion

Thorax model. The thorax model was developed at the Ohio State University using the MADYMO 2D program [21]. The model which represents the ribcage including sternum consists of a series of 17 elements (Fig. 13). A special user-defined subroutine was developed which accounts for pressure changes within the chest cavity during simulation. The model was used to study some of the thorax impact tests with human cadavers conducted during the mid 1970's at the Highway Safety Research Institute. Thoracic accelerations in these tests were collected using a 12-accelerometer array [22]. The general shape of the acceleration time histories and force-deflection characteristics predicted by the model showed good agreement with the tests. Predictions for the thorax pressure, however, showed significant deviations.

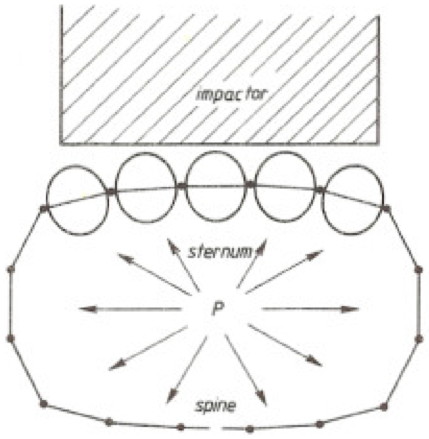


Figure 13. Thorax mathematical model

## Computer aided design studies

In the preceding sections a number of examples have been presented illustrating the use of MADYMO as a basic biomechanical crash research tool. Another interesting application of this type of programs is the development and optimization of crash safety devices such as seat belts, child seats and vehicle paddings. One example will be presented here which illustrates this, namely the design of a dynamic acting child restraint system. Two other examples to be given here relate to the computer-aided design of dummy components, namely of a dummy abdomen section and a dummy neck.

A dynamic acting child restraint system. This new child restraint system features a moving impact shield, which is horizontal during normal use. The shield rotates upwards during a frontal collision to restrict the forward motion of the child's head and thorax. The 2D option of MADYMO was firstly used to design and optimize the actuating mechanism for the shield and secondly to optimize the performance of the whole system in a standard ECE 44 50 km/h sled test with a 3-year old child dummy (Fig. 14). The shield actuating mechanism consists of a lever arm on the pivoting shield to which a rod with a mass is connected. During the car crash the shield moves into an upright position due to deceleration forces acting on the mass. The downward motion of the shield caused by loadings from head and chest is prevented by a locking device. Several calculations together with only a limited number of sled tests, finally led to an optimized child restraint system, which is commercially available today. Details of this study are provided in [23].

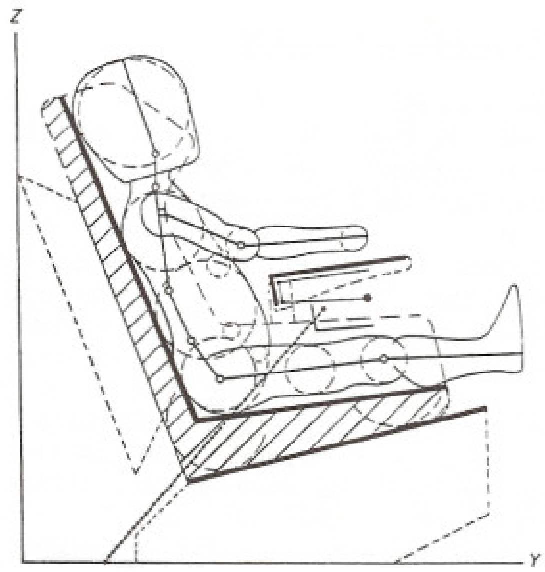


Figure 14. Mathematical model of child restraint system with dynamic acting impact shield

A dummy abdomen section for side impacts

The principle of this design is a rigid drum placed at the critical penetration tolerance level around the lumbar spine, with pressure-threshold contact switches on its surface. This drum is covered by a composite material which should have a dynamic stiffness identical to the human abdomen. The outside layer of the abdomen is made of a relatively heavy but flexible material. To avoid preparing and testing of a large number of specimens necessary to obtain the correct response empirically, it was decided to use computer simulations to find the design parameters. MADYMO was utilized to formulate a dynamical non-linear finite segment model of the cross section through a half abdomen (Fig. 15). This model was exercised with a wide variety of mass distributions and for different impact velocities. A few specimens of the most promising combinations were made and tested and were used for validation of the model. A prototype abdomen section has been built based on the optimal parameters found with the simulation model and will be incorporated in the future Eurosid side impact dummy. More details of this study are provided in [24].

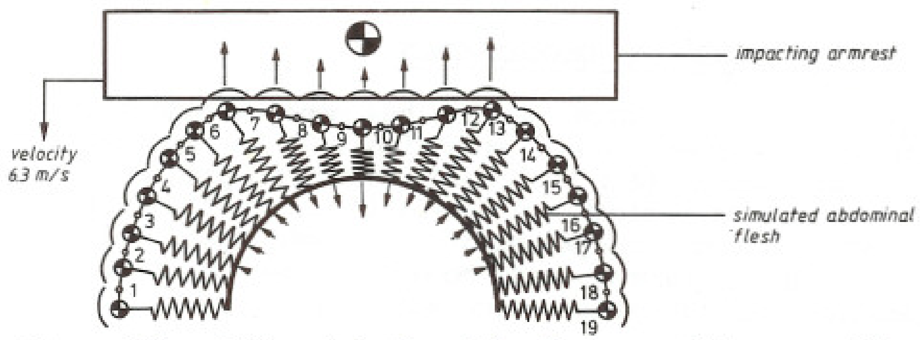


Figure 15. Mathematical model of dummy abdomen section

A dummy neck with improved biofidelity

Experimental evaluation of the Part 572 neck system with respect to the volunteer behaviour showed that this neck is much too stiff [20]. Mathematical simulations have been conducted in order to optimize the design of this neck [18]. A model of the Part 572 head-neck assembly was used for this purpose where the neck is represented by a 7-segment linkage system. Experimental verification of this model was conducted for a calibration pendulum test and a more severe sled test. The first results of the computer-aided design efforts that include simulation of longer and softer necks were quite promising. The best results were obtained by a design that consists of a soft neck reinforced by a relatively stiff structure in the front and back section (Fig. 16). A possible realisation of such a design principle is a soft rubber cylinder imbedded in strong fibers or provided with one or more separate stiff rubber segments. Based on these findings several prototypes have been built which are currently tested at the Vehicle Research and Test Center in East Liberty under test conditions representative for the human volunteer tests.

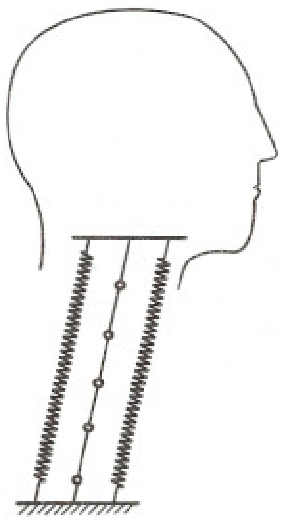

Figure 16. Mathematical model of a dummy neck with improved frontal biofidelity

DISCUSSION: FUTURE TRENDS AND DEVELOPMENTS

In the past years the MADYMO package has gone through a continuous process of optimizations, refinements and extensions. It is expected that such developments will proceed. In fact the rapid growth and progress in computer technology will open new directions and perspectives, particularly in the field of database management and post-processing. Another trend will be that further progress in vehicle structural crash models can lead to an integrated computer analysis approach for the vehicle-occupant interaction in a crash situation.

One of the most critical areas in current crash victim simulation programs is the description of contact between occupant and environment. Present algorithms applied for instance for contact interaction of occupant with vehicle interior or between pedestrian and vehicle cannot account in a realistic way for the effect of strain rate and shape of the contact geometries. As a consequence a large number of impactor tests is often required with varying impactor velocities and impactor shapes in order to obtain realistic model input data. The need for such elaborate input data experiments can be reduced considerably, if more realistic contact models become available. Beside improvements in contact-interaction models further developments can also be expected in the area of restraint system modelling, for instance with respect to the description of the belt-occupant interaction or the development of advanced three-dimensional airbag models capable of simulating the complex occupant interaction with passenger and driver airbag systems.

Human body databases used nowadays in crash victim simulation programs mostly relate to a representation of crash test dummies. A comparison of the databases for the description of the standard Part 572 test dummy by various researchers showed differences particularly with respect to the joint characteristics. Therefore a strong emphasis should be placed on future standardization of this type of databases.

Experimental validation of the whole body response predicted by mathematical models is related mostly to dummy experiments. Studies reporting model verification for human volunteer or human cadaver tests appear to be limited. In most cases they are related to the behaviour of certain body segments such as the thorax or neck as was illustrated in the application section in this paper. Development of well-validated human body databases describing different sized real vehicle occupants and pedestrians is considered to be a challenge in the near future for the biomechanical community. Only if the status of mathematical models becomes such that they offer a more realistic representation for the human body than current crash test dummies, a major step forward in the field of automotive safety modelling has been made. Further program extensions for instance with respect to flexible elements might be necessary to achieve an adequate level of validation.

Further acceptance of this type of models can also improve by an increasing user convenience. A MADYMO 2D version is expected to become available in 1986 as a special purpose program for the simulation of frontal collisions. This program will be installed on a micro computer system and could be used for instance as local computer-aided design workstation in design departments. Although detailed specifications are not available at the present time, features expected to be included are menu-driven modules to generate databases, interactive graphical supported positioning of the occupant and extensive output display capabilities with animation facilities.

A final trend which will be briefly mentioned here is found in the area of computer graphics. The MADYMO 3D graphics package used to visualize the complex occupant kinematics, appears to be of invaluable importance for the analysis of three-dimensional motions. An even more realistic representation, however, can be obtained with a colour graphics package developed in the field of solid modelling. Fig. 17 illustrates the use of such a program for the visualization of the MADYMO Part 572 dummy model. This graphics program was developed at the the Department of Industrial Design Engineering of the University of Technology in Delft and is still in an experimental stage. A relatively large CPU time is required for this type of visualizations which at the moment prevents applications on a large scale.

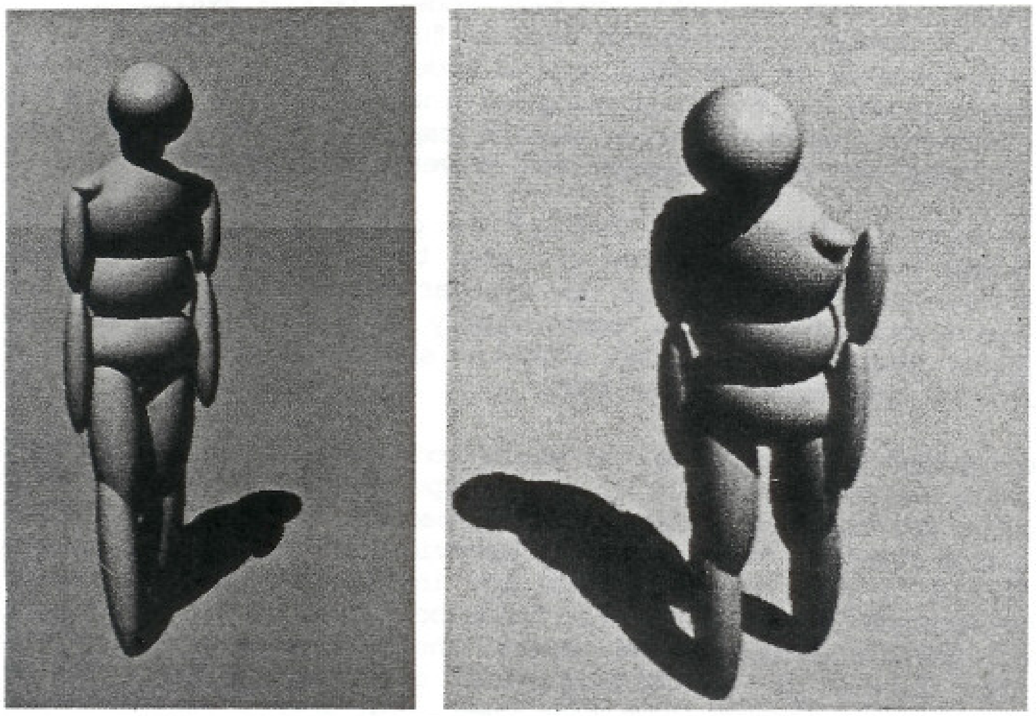

Figure 17. Part 572 dummy represented by the new generation 3D graphics package

ACKNOWLEDGEMENT

MADYMO has been developed at the Research Institute for Road Vehicles TNO in cooperation with The Netherlands Institute for Road Safety Research SWOV. Development has been supported by the Dutch Government and the European Communities.

REFERENCES

1. Robbins, D.H.: "Simulation of human body response to crash loads". Shock and vibration computer programs. Monograph No. SVM-10, Shock and Vibration Computer Center, U.S. Dept. of Defense, 1975.

2. King, A.I. and Chou, C.C.: "Mathematical modelling, simulation and experimental testing of biomechanical system crash response".J. Biomechanics, Vol. 9 pp 301-317, 1976.

3. Prasad, P.: "An Overview of Major Occupant Simulation Models". SAE 840055, Warrendale, Pensylvania, 1984.

4. Wittenburg, J.: "Dynamics of systems of rigid bodies", B.G. Teubner, Stuttgart, 1977.

5. Maltha, J. and Wismans J.: "MADYMO-Crash Victim Simulations, A Computerized research and design tool". Proceedings of the 5th IRCOBI Conference on the Biomechanics of Impacts, Birmingham, 1980.

6. Wismans, J. and Wijk, J.J. van: "Mathematical Models for the Assessment of Pedestrian Protection Provided by a Car Contour". Proceedings of the 9th International Technical Conference on Experimental Safety Vehicles, Kyoto, 1982.

7. Wismans, J. and Wittebrood, L.J.J.: "The MADYMO Crash Victim Simulation Package and its application in analysing thoraxes of side impact dummies". EEC seminar: Biomechanics of impacts in road accidents, Brussel, 1983.

8. Cesari, D. and Ramet, M.: "Comparison between in-the-field accidents and reconstructed accidents with dummies and cadavers". Proceedings of the 19th Stapp Car Crash Conference, Inc. Warrendale, Pensylvania, 1975.

9. Wismans, J., Cesari, D., Maltha, J. and Ramet, M.: "Evaluation of the experimental reconstruction of a real frontal collision with a mathematical model". Proceedings of the 5th IRCOBI Conference on the Biomechanics of Impacts, Birmingham, 1980.

10. Wismans, J. and Maltha, J.: "Application of a three-dimensional mathematical model for the evaluation of side impacts". Proceedings of the 6th IRCOBI Conference on the Biomechanics of Impacts, Salon de Provence, 1981.

11. Wismans, J., Maltha, J.J., Wijk, J. van and Janssen, E.G.: "MADYMO - A Crash Victim Simulation Computer Program for Biomechanical Research and Optimization of Designs for Impact Injury Prevention". AGARD-meeting, Cologne, Germany, 1982.

12. Wismans, J. and Wittebrood, L.: "Lateral dummy comparison: theoretical analyses". Final report phase 4 EEC Biomechanics Programme, Contract NL8, IW-TNO, 1982.

13. Wijk, J. van, Wismans, J., Maltha, J. and Wittebrood, L.: "MADYMO Pedestrian Simulations". SAE P-121 Pedestrian Impact Injury & Assessment, Detroit, 1983.

14. Janssen, E.G. and Huijskens, C.G.: "Cyclists impacted by simulated vehicle fronts". Proceedings of the 10th IRCOBI Conference on the Biomechanics of Impacts, Delft, 1984.

15. Janssen, E.G. and Wismans, J.: "Experimental and mathematical simulation of pedestrian-vehicle and cyclist-vehicle accidents". Proceedings of the 10th International Technical Conference on Experimental Safety Vehicles, Oxford, 1985.

16 Wismans, J., Maltha, J., Melvin, J.W. and Stalnaker, R.L.: "Child Restraint Evaluation by Experimental and Mathematical Simulation". Proceedings of the 23rd Stapp Car Crash Conference, San Diego, 1979.

17. "Preliminary Development Head-Neck Simulator". Vol. 1: Analysis volunteer tests, Final report, Phase I, Project SRL-59, Vehicle Research and Test Center, Ohio, East Liberty, 1985.

18. "Preliminary Development Head-Neck Simulator". Vol. 2: Mathematical Simulations. Final report, Phase I, Project SRL-59, Vehicle Research and Test Center, Ohio, East Liberty, 1985.

19. Wismans, J. and Spenny, C.H.: "Performance requirements for mechanical necks in lateral flexion". Proceedings of the 27th Stapp Car Crash Conference, SAE 831613, 1985.

20. Wismans, J. and Spenny, C.H.: "Head neck response in frontal flexion". Proceedings of the 28th Stapp Car Crash Conference, 1984.

21. Wiechel, J.F.: "The Development of a bidirectional multi-speed impact model of the adult human thorax". Dissertation, Ohio State University, 1983.

22. Robbins, D.H., Lehman, R.J. and Augustijn, K.: "Prediction of thoracic injuries as a function of occupant kinematics". Proceedings of the 7th International Technical Conference on Experimental Safety Vehicles, Paris, 1979.

23. Stalnaker, R.L. and Maltha, J.: "MADYMO used for computer aided design of a dynamic acting child restraint seat". Proceedings of the 5th IRCOBI Conference on the Biomechanics of Impacts, Birmingham, 1980.

24. Maltha, J. and Stalnaker, R.L.: "Development of a dummy abdomen capable of injury detection in side impacts". Proceedings of the 25th Stapp Car Crash Conference, San Francisco, 1981.