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Advances in MADYMO Crash Simulations

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Side Impact Occupant Protection Technologies

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ABSTRACT

MADYMO is a well accepted multibody program for crash analyses. The main emphasis of the program is the prediction of the kinematics and dynamic behaviour of crash victims during a crash. A brief description of the MADYMO history and theory is presented as well as recently developed couplings with explicit finite element programs for non-linear structural analyses. The development of dummy databases is described with special emphasis on the development of the EUROSID dummy database using a new multibody module. This module is based on a recursive algorithm and allows modelling of other kinematic joints in addition to the currently available ball and socket joints. The use of MADYMO in impact biomechanics is illustrated with examples from the area of vehicle safety and sports biomechanics. The use of MADYMO for structural modelling is illustrated by a side-impact simulation using MADYMO to model both car and occupant.

THE SIMULATION OF CRASHES is of vital importance in order to evaluate and improve safety devices and human body surroundings. Most of this work is done experimentally using instrumented dummies. With the advent of computers, numerical simulations became feasible. Due to rapid developments in computer hardware there has been a marked increase in the use of computer simulations in the last two decades. They can contribute significantly to the understanding of the impact behaviour of complex biodynamic systems, particularly if models are used in conjunction with experimental work. Computer simulations to determine the crash behaviour of car structures are becoming more customary due to the rapid development of the explicit finite element codes in recent years.

In 1963 McHenry proposed a 2D numerical model to describe the motion of a vehicle occupant in a collision event (1)*. In 1970 a 3D model with three mass-segments was published by Robbins (2). These initial developments were followed by a number of more general occupant simulation tools. The best known are MVMA2D, CAL3D and MADYMO 2D/3D. The development of MADYMO (MAthematical DYnamical MOdels) started in 1973 as a joint effort of TNO and the Delft University of Technology. An important step forward was made as a result of the combined efforts of the TNO Road-Vehicles Research Institute (TNO-IW) and the Netherlands Institute for Road Safety Research (SWOV) in a mutual project that was started in 1976 and completed in 1982. In 1983 the first version for external use, version 3, was released. Versions 1 and 2 were only meant for in-house use. In 1987 version 4.1 was released. Between version 3 and version 4.1 a major improvement in user convenience was realized with the introduction of keywords. In 1988 version 4.2 was completed, in which an optional 2D airbag module was introduced. The latest version of MADYMO (i.e. version 4.3) was released in 1990. Version 5.0 will be available in 1992.

This paper will begin by giving a general description of MADYMO, followed by a brief description of a recently developed multibody module and the standard force models available in MADYMO. The development of crash dummy databases, with emphasis on the EUROSID database, and human body models will be presented. An outline of some typical applications concludes this paper.

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* Numbers in parentheses designate references at end of paper

GENERAL DESCRIPTION

MADYMO predicts the dynamic behaviour and kinematics of crash victims and other structures which can be modelled by rigid bodies connected by joints. The multibody theory on which MADYMO is based consists of two similar formalisms for generating the equations of motion for two- and three-dimensional systems of interconnected rigid bodies. The rigid bodies represent the inertia effects and can be visualized by attaching planes or ellipsoids. As a result of this approach MADYMO is more versatile than most of the other occupant simulation programs due to the fact that it gives the user a great deal of freedom in his choice of the number of elements.

In MADYMO each system must have a tree structure. For systems with closed loops, the equations of motion are generally combined differential and algebraic equations, whereas the equations of motion for tree structures are ordinary differential equations. A system with a closed loop can be transformed into a system with a tree structure by replacing one joint by a sufficiently stiff spring-damper element.

Besides the prescribed motions and contact interactions the motion of the system of rigid bodies is influenced by force interactions due to springs, dampers and restraint systems. MADYMO offers a set of standard force-interaction models such as Kelvin and Maxwell elements, belts and airbags. These models will be discussed in more detail later on.

In addition to the standard output quantities, like accelerations, displacements and contact forces, MADYMO is also able to present the results of injury parameter calculations. At present six injury parameter calculations are available:

- Head Injury Criterion (HIC)
- Gadd Severity Index (GSI)
- 3 ms Criterion (3MS)
- Thoracic Trauma Index (TTI)
- Viscous Injury Response (V*C)
- Axial loads

The axial load calculation can be used to approximate e.g. femur load or tibia load.

A new advanced menu driven pre- and postprocessor MAPP, MAdymo Pre- and Postprocessor, is currently being developed. The target machines for the postprocessor are Unix workstations, as opposed to the current postprocessor which is designed for a mainframe environment. The postprocessor is able to create graphs and animations. The graphs include data versus time and data versus data presentation. Multiple signals can be presented in one graph. The presentation of the kinematics include wireframe and solid animations. Two animations can be shown simultaneously in order to compare results.

MULTIBODY MODULE

The current (i.e. version 4.3) multibody module can be used to analyze mechanical systems that can be modelled as rigid bodies interconnected with ball and socket joints (3D) or pin joints (2D). A so-called absolute description of the kinematics is used: the motion of the bodies are described in relation to a global reference system (inertial space). However the positions of all bodies, except the position of the tree structure origin, are immediately eliminated using the recursive relation (fig. 1):

$$\underline{R}_j = \underline{R}_i + Q_i \cdot \underline{R}_{ij}$$

Q_i is an orthogonal tensor depicting the vector $\underline{R}_{ij}$, rigidly connected to body i, from the reference orientation to the current orientation. For the matrix representation of the tensor Q_i the user can select several different generalized coordinates q_j. Thus only the position of the tree structure origin $\underline{R}_1$ and the orientation of the bodies in inertial space determine the kinematics of the system. This results in a close resemblance to a relative description, i.e. the motion of a body is described in terms of the motion of a contiguous body and the degrees of freedom of the joint which connects it to the contiguous body.

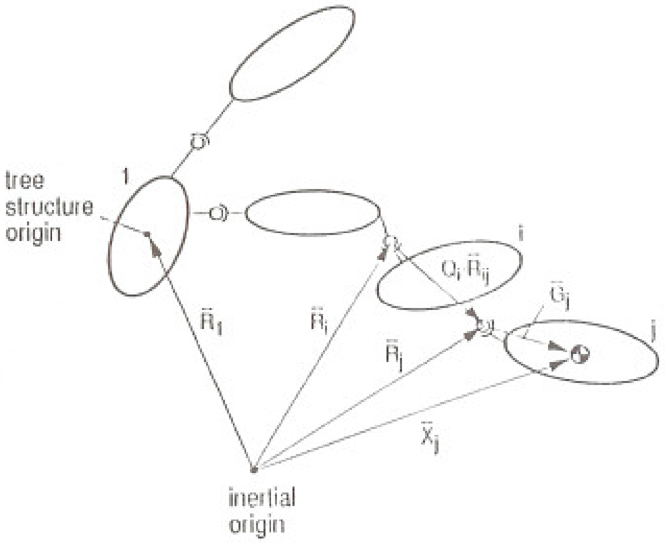


Fig. 1 MADYMO tree structure.

The position of the centre of mass of body j in inertial space, $\underline{X}_j$, can be expressed in independent variables: the position of the tree origin and the Bryant angles.

$$\underline{X}_j = \underline{B}_1 + \Sigma Q_k \cdot \underline{B}_{kl} + Q_j \cdot \underline{G}_j$$

The summation over k is related to the path from body 1 to j where each joint has one unique combination of k and l. For each joint stiffness, damping and friction can be specified resulting in joint torques. These torques are therefore a function of the relative orientation and the relative angular velocity of the two rigid bodies connected by the joint. The non-linear elastic torque is a function of the relative orientation and can be combined with hysteresis. The damping torque is computed as the product of a viscous damping coefficient and the relative angular velocity. Friction can be specified by a constant dry friction (Coulomb friction) torque.

The generation of the equations of motion is based on Lagrange's equations. The advantage of these equations over the classical Newton-Euler equations is that a minimum set of equations of motion is obtained directly and that this set consists only of ordinary differential equations. The non-linear equations of motion for a tree structure can be expressed in the following form:

$$S(q) \cdot \ddot{q} = r(\dot{q},q,t) \quad \text{where} \quad q^T = (\underline{B}_1, q_1, q_2, \ldots, q_n)$$

q is a column matrix representing the set of independent coordinates describing the position of the tree structure in inertial space. For each tree structure a similar set of equations is generated. The solution of these coupled non-linear differential equations is obtained by solving these equations with a Choleski decomposition of S followed by a numerical integration using a fourth order Runge-Kutta method with a fixed time step or a fifth order Runge-Kutta Merson method with a variable time step.

A new multibody module has been developed and will be available for MADYMO users in the next release. This module will allow the modelling of kinematic joints such as translational joints, revolute joints and user-defined joints in addition to the currently available ball and socket joints. It will be possible to prescribe the relative motion of contiguous bodies next to the motion of the tree structure origin. A relative description of the kinematics of systems of bodies is used. The generation of the equations of motion is based on the principle of virtual work in combination with a recursive algorithm for the motion of the bodies. The used algorithm is known for its efficiency and is well suited for implementation on parallel computers:

$$Q_j = Q_{ij} \cdot Q_i$$

$$\underline{B}_j = \underline{B}_i + Q_i \cdot \{\underline{B}_{ij} + \underline{d}_{ij}\}$$

Q_{ij} is an orthogonal tensor describing the rotation of body j relative to the contiguous body i, $\underline{d}_{ij}$ is the translation of the articulation point on body j relative to the articulation point on body i. Both Q_{ij} and $\underline{d}_{ij}$ depend on the degrees of freedom, q_{ij}, of the joint between bodies i and j. In case the relative motion of contiguous bodies is prescribed as a function of time both Q_{ij} and $\underline{d}_{ij}$ depend also on the time. For tree-structured systems, the motion of any body can thus be written in explicit form in terms of the degrees of freedom of the joint. The expressions for Q_{ij} and $\underline{d}_{ij}$ vary according to the type of joint. The user can define his own joints by specifying Q_{ij} and $\underline{d}_{ij}$.

By successively introducing recursive expressions for the virtual motion of bodies, starting with the bodies at the ends of the trees, recursive expressions are directly obtained for the second time derivatives of the degrees of freedom of the joint without the need to solve systems of linear equations as is required for the current version of MADYMO:

$$\ddot{q}_{ij} = C_{ij} \cdot \dot{Y}_i + c_{ij}$$

C_{ij} is a coefficient matrix depending on the masses of the bodies and instantaneous geometry of the system. c_{ij} is a column matrix depending on the external forces and instantaneous geometry. Y_i is a column matrix with the linear and angular velocities of body i. This approach leads to a reduction of computation time for large systems of bodies because the time required to solve a system of n linear equations is proportional to n^3 whereas the algorithm used for the new version requires a computation time which is proportional to the number of bodies. The methods for the numerical integration of the current MADYMO version are used. The implementation of other integration methods is anticipated. The user can also easily implement his own integration method. Due to this new multibody module the new version of MADYMO will be more user-friendly, versatile and efficient.

FORCE-INTERACTION MODELS

The motion of the tree structure of joint-connected rigid elements is caused by external forces. MADYMO offers a set of standard force-interaction models which will be briefly discussed in this paragraph.

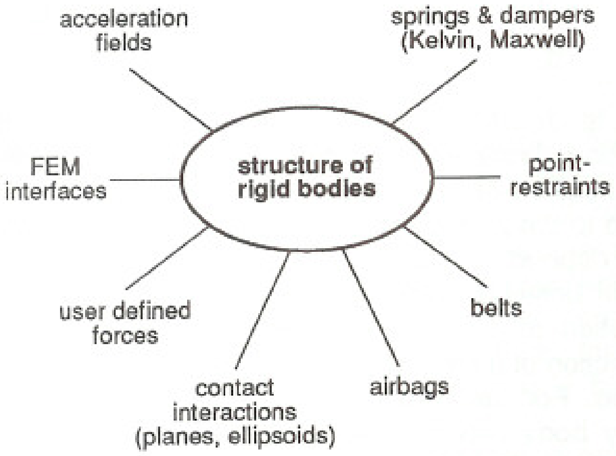


Fig. 2 MADYMO force-interaction models.

The acceleration field model calculates the forces at the centre of gravity of elements in a homogeneous acceleration field. This model is particularly useful for the simulation of the acceleration forces acting on a vehicle occupant during an impact. It is not necessary for the acceleration field to work on all elements.

Planes and ellipsoids are used to model contact with other bodies or the surroundings. The contact surfaces are of major importance for describing the interaction of the occupant with the vehicle interior surfaces. The elastic contact forces, including hysteresis, are a function of the penetration between the contact contours. In addition to elastic contact forces, damping and friction can be specified. The damping coefficient can be specified as a function of the penetration velocity. The friction coefficient can be specified as a function of the normal force.

Three different types of massless spring-damper models can be applied. The Kelvin element is a uniaxial element which simulates a spring parallel with a damper. The Maxwell element is a uniaxial element which simulates a spring and damper in series. Non-linear spring characteristics as well as velocity dependent damping can be defined. The third type is the point-restraint model. This model can be considered as a combination of three different spring-damper elements, each parallel to one of the axes of an orthogonal coordinate system. All spring-damper models can be attached to arbitrary points of any two elements.

Simple belt systems can be modelled fairly well by means of the spring-damper models. For more complicated belt systems the belt model is available. The belt model accounts for initial belt slack or pre-tension and rupture of belt segments. Elastic characteristics can be specified separately for each belt segment and slip of belt material from one segment to another is accounted for. Sliprings and retractors can be applied. The retractor reel is either of the vehicle sensitive type or of the webbing sensitive type. A vehicle sensitive reel can lock at a specified time or when a specific component of the calculated linear acceleration at the retractor location exceeds a prescribed level over a certain time interval. A webbing sensitive reel locks if the belt feed rate exceeds a specified limit.

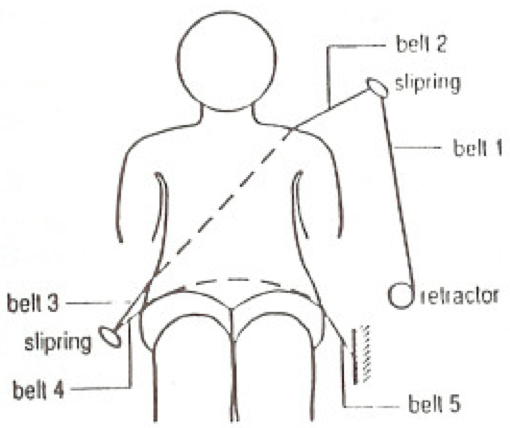


Fig. 3 A 3-point belt with retractor.

In 1988 a 2D airbag module became available for MADYMO users. In the first version the geometry of the airbag was represented by a non-deformable ellipsoid or elliptical cylinder. In the next version an arbitrary shape in the plane of simulation could also be defined. The force-interaction model generates contact forces between the airbag and penetrating objects. Due to the two-dimensional character of the model, the penetration will be evaluated only in the mid-plane of the bag shapes. The properties of the gas inside the airbag are determined by using a lumped parameter approach. Gas can flow out of the airbag through vent holes or porous bag material. Inflow of gas is specified by a constant gas temperature and tabular input of the mass flow for up to five different inflators. The inflators will be triggered when a component of the calculated linear acceleration at the sensor location of one or more sensors exceeds a prescribed level over a given time interval.

Although the current MADYMO 2D empirical airbag model has proved to be a valuable tool in the design process of airbag systems (12, 25), it has its limitations. The results obtained for more complex simulations like oblique and out-of-position impacts have limited value. Moreover, only average deformations of the airbag material can be taken into account. To overcome these limitations a finite element model, FEM, is implemented in MADYMO. This FEM airbag model will be an integral part of the MADYMO 3D program and will be optimized for airbag simulations in a CVS environment (20).

The airbag material is modelled using triangular membrane elements of constant thickness with a linear elastic orthotropic material behaviour which allows for the special properties of the woven bag material. Tension-only elements, following a smeared wrinkling approach, are used to allow wrinkling at the airbag circumference with a relatively course mesh. Similar thermodynamics to those in the 2D airbag model are used for the calculation of the gas properties in the airbag. The gas flowing out of the inflators and the triggering of the inflators can, however, be modelled in more detail. The gas temperature can be specified as a function of time and the gas inflow can be specified as a mixture of gases with predefined heat capacities. Combinations of sensors can be specified to trigger each inflator independently.

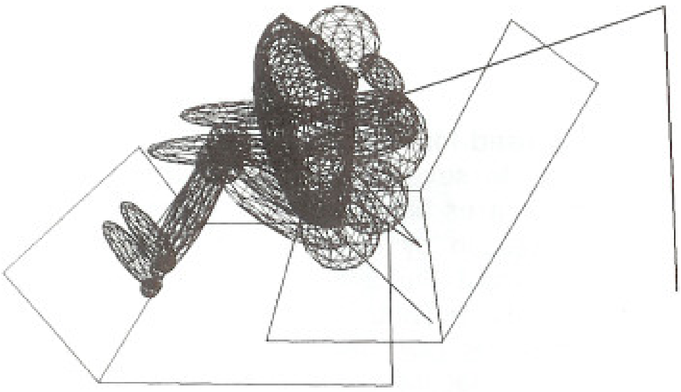


Fig. 4 Simulation of a frontal crash with the MADYMO finite element airbag and multibody dummy.

The user can make and link his own routines to the MADYMO package. Dummy routines for user-defined input, output, forces and common blocks for data transfer are available. This option is particularly useful to prescribe a time dependent force acting on selected elements. Also couplings with explicit finite element programs have been realized by specifying the FEM program as a subroutine.

In 1989 the coupling between MADYMO and the finite element/finite difference (FEM/FD) code PISCES 3D ELK was realized. Besides that this was the first coupling realized and applied to airbag simulations, the PISCES program also allows for an eulerian description of the gases inside the airbag (16, 20). More recently interfaces between MADYMO and the explicit FEM codes PAM-CRASH and DYNA3D have been realized. Normally, MADYMO and the finite element program use different steps for time integration. Depending on stiffness and finite element size the time step of the FEM program is 10 to 1000 times smaller than a typical MADYMO time step. For the coupled calculations the FEM time step is also used for the MADYMO time integration. Extensive evaluation of these interfaces is anticipated (24).

CRASH DUMMY DATABASES

An important requirement for the effective use of computer models in the field of crash victim simulations is that reliable, well validated, databases are available, particularly for the simulation of test dummies (mechanical models of human beings) in a crash environment (13, 19, 26, 27). Two and three-dimensional databases of dummies are supplied with the MADYMO program. The databases currently available are for the P3/4 and P3 child dummies, the 50th percentile Hybrid II and Hybrid III dummies and most recently for the EUROSID dummy (first production prototype).

The first step in developing a dummy database is dividing the dummy into functional components. Dummy parts which do not show any relative motion are considered to be part of one segment. These segments are used to make a multibody model of the dummy. The second step is the determination of the geometrical parameters. Very important is the determination of the joint locations within the individual segments and the surface description. The third step is the specification of the inertial properties. The mass, location of the centre of gravity, the principal moments of inertia and the orientation of the principal axes must be determined for each dummy segment. The fourth step is the specification of the joint properties. The stiffness of the connection between the different segments is one of the parameters having a major effect on the movement and position of the dummy segments in a crash environment. The fifth and last step is the specification of the surface compliance. Static as well as dynamic measurements with several penetrating surfaces must be performed. With this information an initial database is designed which is used to simulate the dummy in a sled or drop test environment. The first validation of the database is based on a comparison of the numerical and experimental results of these tests.

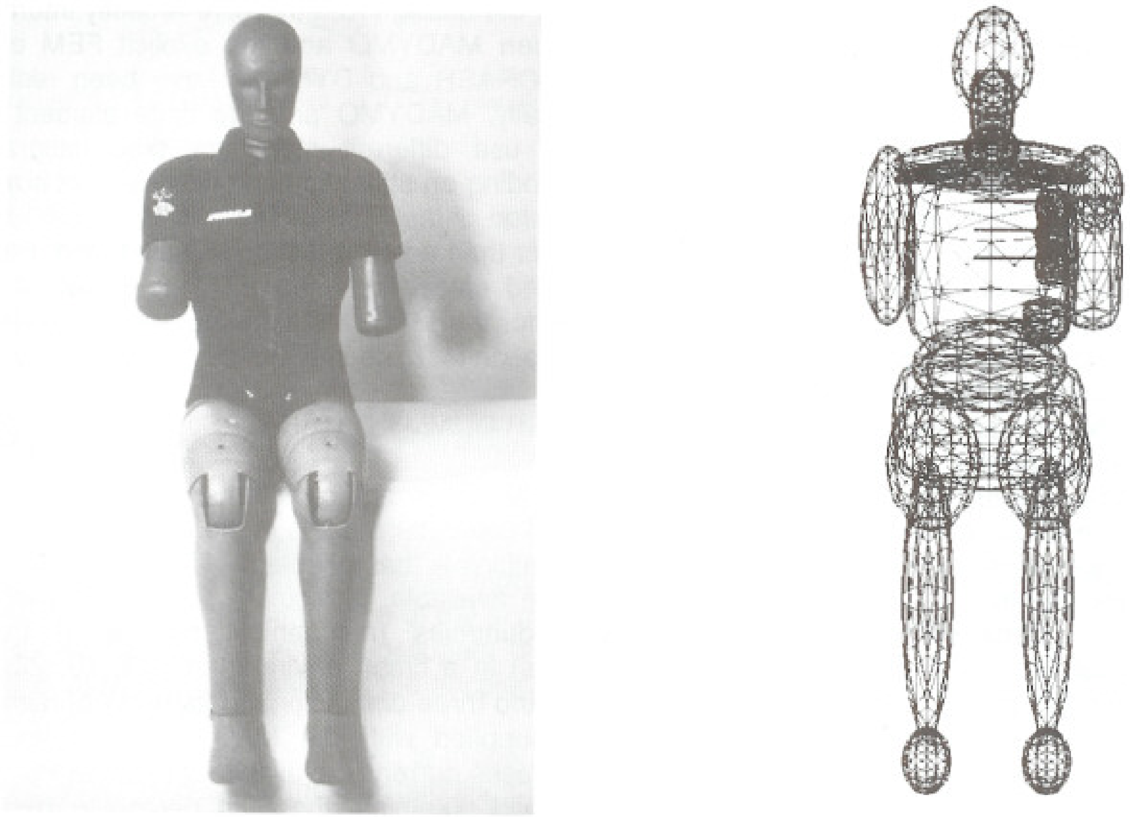


Fig. 5 EUROSID: dummy and model.

An initial database for the EUROSID dummy has been developed. The EUROSID dummy (10) has been designed, constructed and improved by a group of European research laboratories. Since 1987 production prototypes of this dummy have been evaluated in Europe, the United States, Canada and Japan. Following this evaluation improvements were proposed and incorporated in the dummy. The EUROSID dummy database consists of 13 elements representing the dummy body, with additional elements for the three ribs and the abdomen. The joints in the EUROSID model were defined on locations identical to the locations of the hinges in the dummy, figure 5. Contact ellipsoids have been defined according to the various dummy segments whose dimensions and locations are derived from technical drawings of EUROSID. The hip and knee joint characteristics in the EUROSID originate from the MADYMO HYBRID II dataset. The clavicle/spine joint only allows for rotation in forward direction. Free range of motion and joint stops have been defined for the shoulder joints.

With the current MADYMO 3D multibody module (version 4.3) two types of joint models are allowed. The cardan joint model is used in shoulders, arms and legs. The flexion-torsion joint model is used for representation of lumbar spine and neck. In several joints only rotations about one or two axes are relevant. The other rotations are suppressed by defining a high stiffness for rotations about the appropriate axes. Pin joints and translational joints can be modelled more efficiently with the new multibody module in MADYMO 3D. A second model has therefore been designed using the new multibody module with pin joints for the knees, the joint between the upper upper left arm and lower upper left arm, and the joints between the left and right clavicles and spine. The point-restraints between the ribs and the spine, and between the abdominal insert and the spine have been replaced by translational joints.

Impactor and drop tests were used to validate the shoulder, thorax, abdomen and pelvis models separately (17). Figure 6 shows the simulated kinematics for a thorax impactor test. The free dummy drop tests were performed based on ISO requirements. The EUROSID dummy was suspended horizontally 1 meter above a flat, rigid impact surface or 2 meters above a padded impact surface. A pendulum test was used to test the performance of the head/neck combination. The response of the complete dummy database, including the interaction between the various body segments, was validated with rigid and padded wall sled tests.

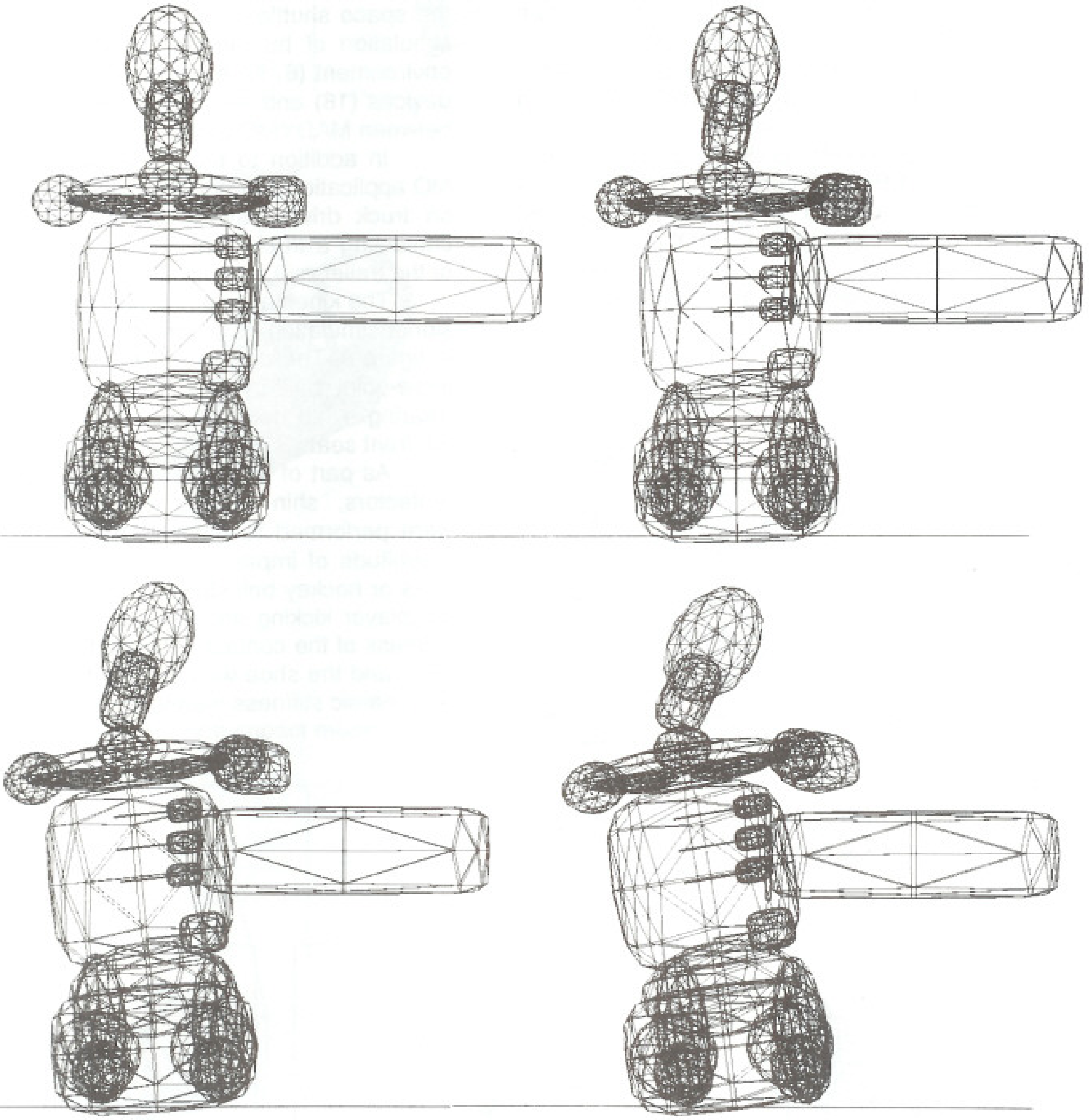


Fig. 6 Thorax impactor test.

Both multibody modules give approximately the same results. With the current multibody module high stiffnesses are required to prohibit certain motions in connections. These high stiffnesses tend to reduce the necessary time step and therefore increase the computing time. Since unwanted motions are lacking in the joint models of the new multibody model, much less CPU time is required for the simulations considered. Both model predictions appear to correlate quite well with the experimental results (19).

HUMAN BODY MODELS

Realistic models of real human bodies are much more difficult to develop than dummy databases, particularly due to the lack of reliable joint properties and body compliance data. A first step has been made by a recently developed interface with the program GEBOD (GEnerator of BOdy Data). This public domain computer program produces geometric and inertial properties of human beings (5). GEBOD generates a body built up of 15 segments: head, neck, upper and lower arms, thorax, abdomen, pelvis, upper and lower legs and feet, figure 7. It obtains the geometric and inertial properties of these segments from regression equations based on human measurements. These data are available for children (aged between 2 and 20 years) and adult males and females. After providing the program with data specifying a particular body (e.g. sex, mass, stature, etc.) GEBOD generates for that body the corresponding locations of the joints, masses, moments of inertia, locations of the centres of mass and ellipsoids, but not joint properties and compliance characteristics, for representation of the body segments.

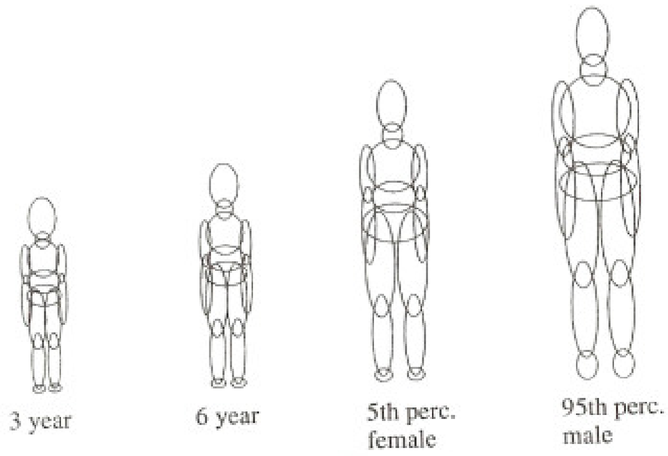


Fig. 7 Human body geometries created with GEBOD.

APPLICATIONS

Among the MADYMO applications and validation studies published in the past are simulations of occupants in frontal (13, 22, 25) and side impacts (19, 23), pedestrians and cyclists hit by a passenger car front (7, 8, 11), wheelchair occupants during transport (14), a child in a child restraint system (3, 4), an astronaut escaping from the space shuttle in an emergency situation (15), simulation of human body segments in a crash environment (6, 9), evaluation of sports protection devices (18) and simulations utilizing an interface between MADYMO and a FEM code (16, 21, 24).

In addition to the above mentioned MADYMO applications, in-house studies were carried out on truck driver safety, pedestrians and cyclists contacting a truck front or various side structures of the trailer and motorcycle simulations.

The kinematics obtained from a three-dimensional simulation of a frontal car crash are shown in figure 8. The driver is restrained by means of a three-point belt system. The front passenger is wearing a lap belt and the child standing behind the front seats is not restrained at all.

As part of an effectiveness evaluation of leg protectors, shin guards, MADYMO simulations were performed to gain insight into the order of magnitude of impact forces resulting from soccer kicks or hockey ball strikes. Figure 9 shows a soccer player kicking another player on the leg. The stiffness of the contact between the protected shin bone and the shoe was obtained from experimental dynamic stiffness measurements.

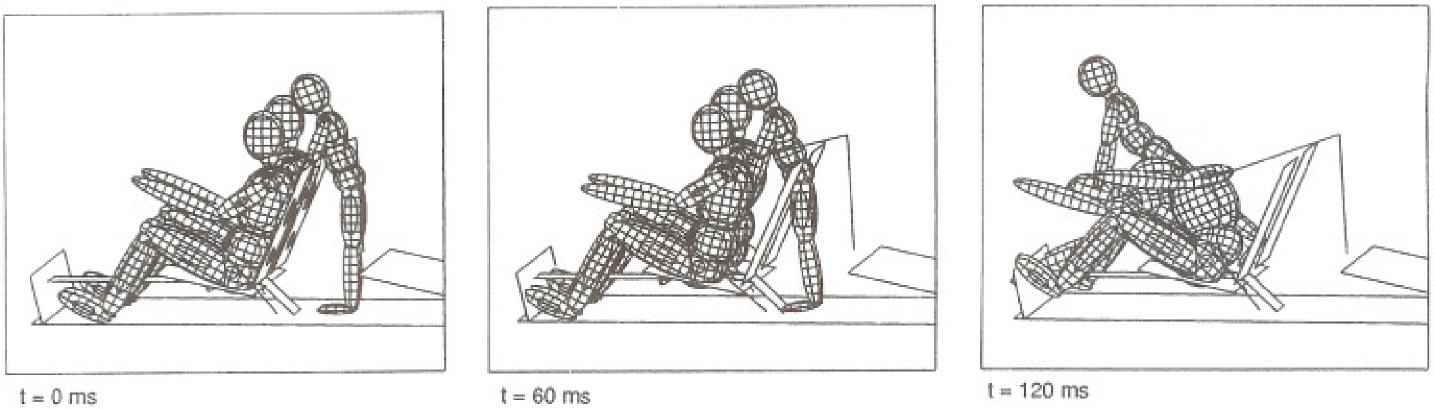
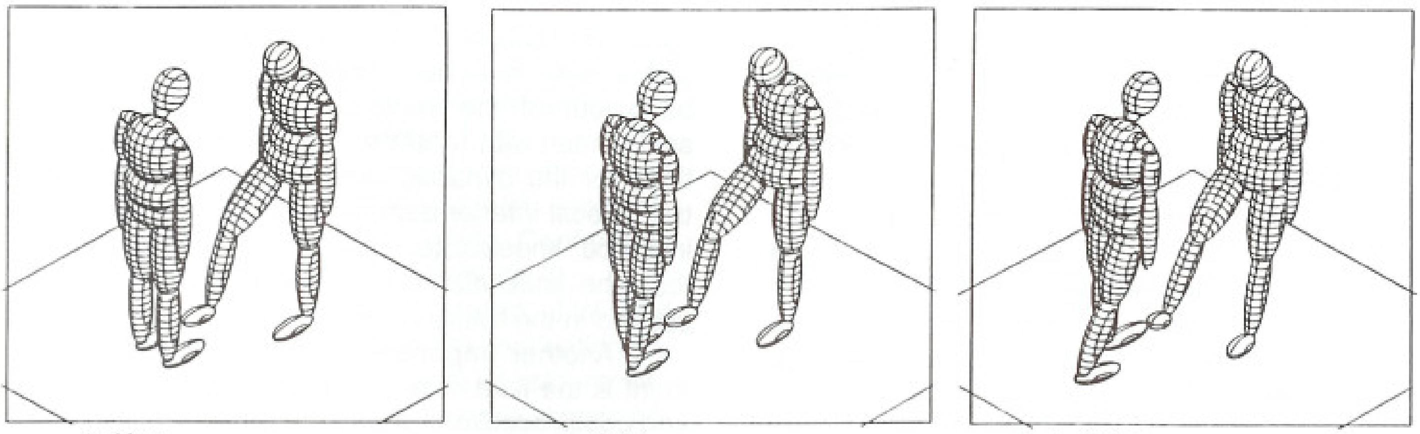


Fig. 8 Frontal car crash with multiple occupants.



t = 30 ms
t = 60 ms
t = 120 ms

Fig. 9 Kicking soccer player.

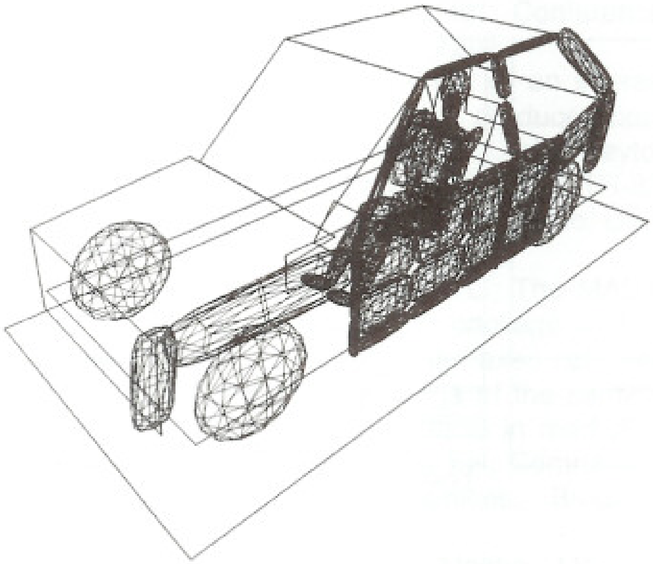
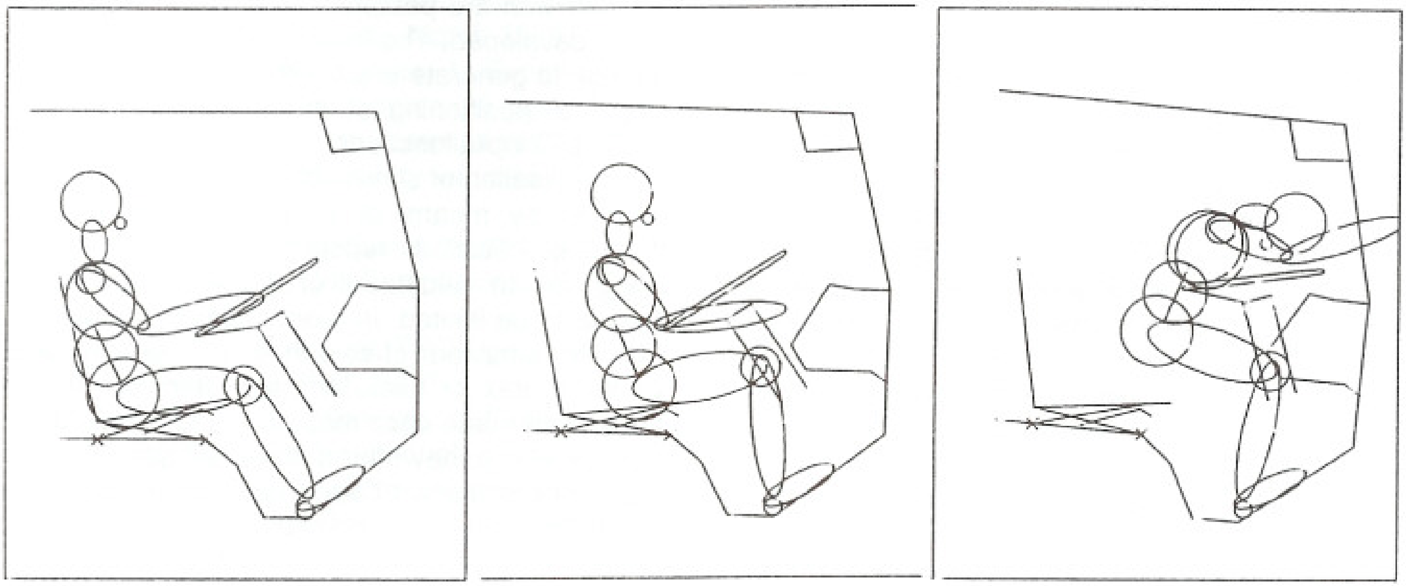


Fig. 10 Multibody side-impact model.

The interaction between occupant and inner door structure during side impact could be modelled by using a multibody model for the dummy and a finite element model for the deformable structure. As an alternative to this rather costly approach, the structure can be modelled with MADYMO tools. Figure 10 illustrates a side impact test where both dummy and car structure are modelled with MADYMO. Several linkage systems, interconnected by spring-dampers, are used for the side structure. This structure is mounted with point-restraints upon a single large mass, representing the main inertia of the car. The occupant is represented by the EUROSID database. Since the main aim of this application was to consider the capability of MADYMO for simulating structural behaviour, the dummy results were not considered. The motion of the car as a whole compared very well with the test results. A reasonable agreement of local deformation could be observed as well.



Time 0.00
Time 80.00
Time 160.00

Fig. 11 Unrestrained truck driver.

Figure 11 shows the simulated kinematics of a truck driver during a frontal crash. The unrestrained driver, represented by a 50th percentile Hybrid III dummy, experiences severe contact with the steering wheel before being ejected through the windscreen.

A recent MADYMO application concerns the impact between the side structure of a trailer and a cyclist. The risk of overriding the cyclist and the potential of different side structure geometries attached to the trailer to prevent such overriding, could be assessed quite well by means of mathematical simulations. Figure 12 shows the kinematics obtained from such a simulation.

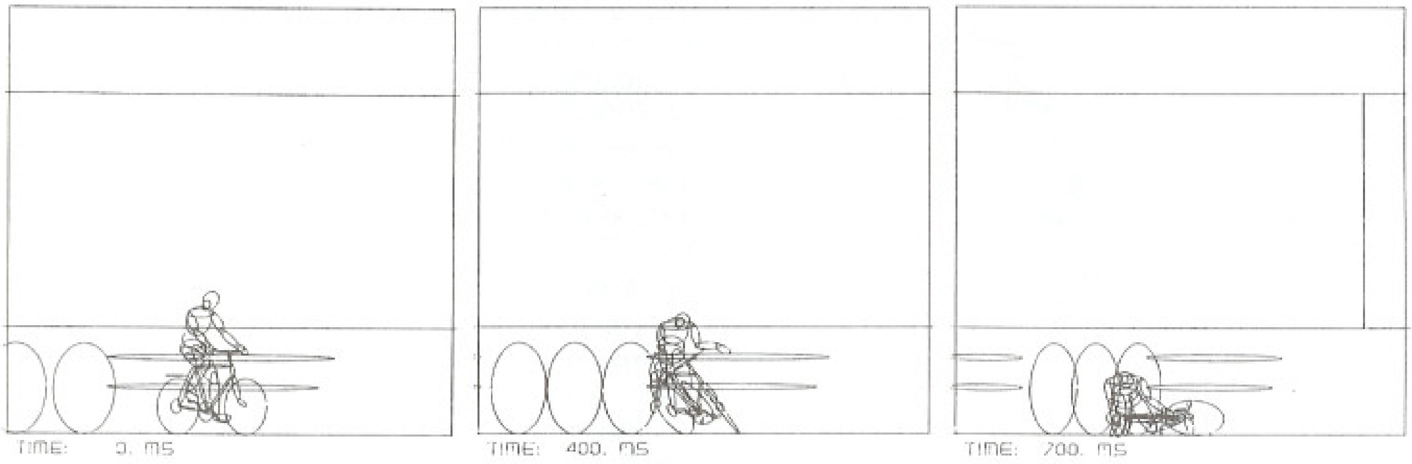


Fig. 12 Accident involving a trailer and a cyclist.

DISCUSSION

Since its appearance on the market the MADYMO program has been continuously modified and improved. In its present form the program appears to be a very useful tool for the simulation and analysis of human body behaviour during a crash or impact. The validation of the program in various applications is an on-going activity.

The newly developed multibody module makes MADYMO more user-friendly, efficient and versatile. Other application areas such as ergonomics and vehicle dynamics can also be considered. The inclusion of tire models in MADYMO is anticipated.

A further inclusion of finite elements within MADYMO in addition to the membrane elements implemented for airbag simulations is anticipated. This will allow the modelling of certain parts of the dummy, for instance the ribs of EUROSID, with a detailed FEM mesh which provides the analyst with information on local deflections and deformations. The coupling with the explicit finite element codes can then be employed to determine the behaviour of the vehicle structure during a full scale crash with MADYMO performing the calculations for the dynamic behaviour of the crash victim. If local interior deformations are of interest, for instance kneebolster deformation during a sled test, the finite elements within MADYMO can be applied in the future as well.

Another important area of further development is the field of powerful and user-friendly pre- and postprocessors. As a first step in this development a postprocessor, time-histories and animations, for MADYMO has been developed. In conjunction with the postprocessor a preprocessor is being developed. The interactive preprocessor will be able to generate a MADYMO input file, perform graphical positioning of the dummy and display MADYMO input functions.

Validation of simulation results is usually carried out by means of experiments using crash dummies. Studies reporting model verification using human volunteers or human cadaver tests appear to be limited. In most cases they only deal with the behaviour of certain body segments such as the thorax or neck. A major step forward will have been made once mathematical models reach a stage where they offer a more realistic representation of the human body than current crash test dummies.

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