Modifications to the Neck, Chest and Pelvis Description of the Hybrid-III Dummy in MADYMO.

Gert Nilson
Department of Injury Prevention
Chalmers University of Technology
S-412 96 Göteborg, Sweden.

ABSTRACT

This paper describes new mathematical formulations, in the MADYMO-format, of the neck and the upper and lower torso elements of the Hybrid-III dummy. The modifications are assumed to improve the mathematical predictions of experimental results.

Like the dummy neck the suggested mathematical neck has five pivots, whose elastic properties have been established through measurements on the mechanical neck. The energy-dissipating properties have been tuned to obtain a response in agreement with the calibration requirements on the mechanical neck.

In addition to the improved correspondence with mechanical tests, the more detailed neck representation is assumed to improve the understanding of the neck response to various impacts. Furthermore, it has the potential to increase the biofidelity of the Hybrid-III dummy, at least indirectly, since it can link between results obtained from mechanical tests and results from simulations with the present, two-pivot neck, which has previously been shown to have a higher degree of biofidelity in comparison with the mechanical neck.

The upper torso has been made flexible by means of two connected elements, and the relevant properties of this system have been tuned to meet the calibration requirements on the mechanical chest.

For the lower torso, finally, a contact contour that well resembles the corresponding contour of the mechanical dummy has been designed. Since the lower torso is heavy as well as exposed to very high forces during a crash, a correct contact contour in this area is considered to be essential for obtaining a proper response from the mathematical model.

INTRODUCTION

When trying to improve safety for car occupants, dummies with the adequate human properties replace the occupant that undergo crash tests. Performance criteria for the dummies are stated in the Federal Motor Vehicle Safety Standards (FMVSS) in the USA. To ensure its compliance with the regulations, each dummy used for crash simulation purposes is calibrated on a regular basis.

The mechanical properties of a dummy, as well as the relevant conditions in a crash test, can also be described mathematically. Mathematical simulations are often used to predict the results from mechanical experiments, in order to reduce the number of crash tests necessary to evaluate the potential injury reducing benefits of various designs of cars or protective systems.

General mathematical models for crash victim simulation purposes have been developed since the beginning of the 1970s [Prasad, 1984]. The most general and widely used models today are the Mathematical Dynamic Model (MADYMO), developed by TNO in the Netherlands, and the CALSPAN 3D model (CAL3D), originally developed by CALSPAN Corporation in the United States. Both of the models provide the users with a database, which contains descriptions of the most commonly used crash-test dummies in the appropriate format. The descriptions are based on extensive measurements on the dummies (TNO, 1990).

However, for some parts of the Hybrid-III dummy (Foster *et al.*, 1977), which is the most common dummy for frontal impact testing, the descriptions have proven to be too simplified to adequately describe the properties of the counterparts of mechanical dummy. Such parts are, for instance, the neck, the upper torso, and the lower torso.

A major part of the fatal as well as the severe and the serious injuries sustained by car accident victims consists of head injuries. Since protective systems, such as the seat-belt or the air-bag, act primarily on the torso, the neck determines the motion of the head until head contact with the car interior occurs. To adequately model the mechanical properties of the neck is therefore essential in crash tests and crash victim simulations. However, neither of the two public descriptions of the Hybrid-III dummy (TNO, 1990 and 1991) has a neck that complies with the requirements on the mechanical neck. On the other hand, Wismans and Spenny (1983 and 1984), Wismans *et al.*, (1986 and 1987) and Mendis *et al.* (1989) have shown that a two-pivot neck, such as the neck described in the MADYMO Databases (TNO, 1990 and 1991), has the potential to well predict the response to various impacts of volunteer and human cadaver necks. Considering the fact that the Hybrid-III neck has been criticised for a lack of biofidelity, e.g. Seemann *et al.* (1986) have found significant differences between the response of the Hybrid-III neck and that of human volunteer necks, this potential biofidelity of a mathematical neck could accommodate for evaluation of the difference in response to various impacts between the Hybrid-III neck and a human neck. This provides, however, that also a "dummy-fidelic" mathematical neck is at hand. A detailed model of the Hybrid-III neck could also improve the understanding of the neck response to various impacts, according to Deng (1989), who developed a detailed model of the Hybrid-III neck in the CAL3D-format. Deng established the relation between the neck angular displacement and the moments in the neck joints, up to moments of approximately 30 Nm. However, in the requirements about twice as high a moment is stated for the occipital condyle. Hjolman and Barne (1987) measured the angle-moment relation up to a sufficient level.

In the first of the two Hybrid-III datadecks released by the TNO (TNO, 1990 and 1991) the chest is described as one, rigid element. This means it cannot possibly meet the requirements of chest deflection that are stated for the mechanical dummy. In the second release chest deflection has been accomplished by an additional system, a sternum, which is attached to the original chest with springs and dampers.

For the lower torso both databases (TNO, 1990 and 1991) suggest a single, wide contact contour. However, many car seats of today have a complex design, comprising a mix of load-carrying and compliant structures, whose details cannot be recognized by such a simple contour. Due to the load from the lap-belt and the knee-panel, there is a very high contact force between the lower torso element and the seat in most crash tests. Moreover, the element mass is a considerable part of the entire dummy mass and it is located in the same region as the centre of gravity of the dummy. Hence, a correct calculation of the time-histories of the lower torso is essential for a successful crash victim simulation, although the accelerations and displacements of the lower torso itself may not be of primary interest. When submarining is studied these measurements are, in addition, of particular interest, since the angle between the belt and the pelvis, which has been shown to be a good measure of the risk of submarining, can be obtained with higher precision in mathematical simulations than in other kinds of experiments (Håland and Nilson, 1991).

The aim of this work has been to find descriptions of the neck, and the upper torso, of the Hybrid-III dummy in the MADYMO format, that make the model comply with existing crash-test regulations. Furthermore, it has been to modify the description of the lower torso, in order to accommodate for modelling of complex interactions between the lower torso and the seat.

MATERIALS AND METHODS

Neck

The mechanical dummy neck consists of four aluminium plates, separated by rubber (Foster *et al.*, 1977). Hjolman and Barne (1987) present the angle-moment relation for the neck segments in static bending (Table 1) as well as in dynamic bending at various velocities. No further neck measurements have been made in this work, which can as pertains to the neck be described as a test of the usefulness of the results of Hjolman and Barne.

Table 1. Angle vs. moment for the segments of the Hybrid-III neck in static bending. The values for the top segment differ from those of the three lower.

Top segment, loading		*Top segment, unloading*		*Lower segments, loading*		*Lower segments, unloading*	
Angle(rad.)	Moment (Nm)	Angle(rad.)	Moment (Nm]	Angle (rad.)	Moment (Nm)	Angle (rad.)	Moment (Nm)
0	0	0	0	0	0	0	0
0.1047	20	0.1745	20.9	0.01745	15	0.1047	24.6
0.1396	30	0.1885	30.8	0.05236	33	0.1396	35.4
0.1745	54	0.2007	38.5	0.1571	76	0.1745	46.2
0.2094	100			0.2094	104	0.2094	62.6
0.2443	172			0.2443	132	0.2443	89.2
				0.2618	151		
				*0.35	302.7		
				**0.45	1000		

* Value obtained after extrapolation. **Value inserted to account for contact between adjacent aluminium-plates.

Two different tests were undertaken to evaluate this neck description, the calibration test and a previously validated frontal impact test in 48 kmph (30 mph), in which the new neck description replaced the one from MADYMO Databases (TNO, 1990). Since Hjolman and Barne (1987) did not suggest any values for the MADYMO input parameters joint damping and joint friction, preliminary values were applied to the model and varied until the neck responded in agreement with the calibration requirements. The final values were then used in the second test. For simplicity, the same friction and damping coefficients were applied to all elements.

In the first test, the calibration procedure for the mechanical neck was reproduced in MADYMO. Thus, the neck was attached to a pendulum, which after a free fall was braked to stop in its vertical position with a braking force of 3.5 kN plus 0.1 kNs/m (Fig. 1). In the mechanical experiments this force is accomplished by the crushing of a so called honeycomb material. For comparison, two two-pivot necks (MADYMO Databases 1990 and 1991) were tested under the same conditions. The requirements regard the head rotation and the moment around the occipital condyle. For both these parameters the peak value, the time of the peak, and the decay time to zero have to lie within certain intervals (Table 2).

The angle-moment relation for the lower segments proved to be insufficient in the second test, since the peak moment exceeded the highest moment measured by Hjolman and Barne (1987). To deal with this, the measured values were extrapolated by means of a fifth-order polynomial, which was first fitted to the measured values, and then used to predict the angle-moment relation for exceeding angles. However, the extrapolation was considered to be valid only as long as the resistance to bending of the neck arises merely from deformation of rubber. The aluminium-plates in the neck have a radius of 42.5 mm and are separated with 22.0 mm of rubber. Thus, when the angle between two adjacent segments reaches 0.47 radians, the plates will come into contact. For angles near this value the angle-moment relation was supposed to be more progressive than predicted by the polynomial (Table 1).

The frontal impact test had previously been validated against data from a mechanical sled-test (Nilson, 1991). In the present study the test was run twice, first with the original two-pivot neck (MADYMO Databases, 1990), then with the five-pivot neck introduced above. For each run the trajectory of the centre of gravity of the head and the time-history of the resultant head acceleration were compared to the corresponding data from the sled-test.

Upper torso

The performance criteria for the dummy chest are based on a test in which a 23.5 kg pendulum impacts the upper torso at 6.7 m/s when the dummy sits on the floor with the arms straight in a right angle to the torso. These conditions were reproduced in MADYMO (Fig. 2).

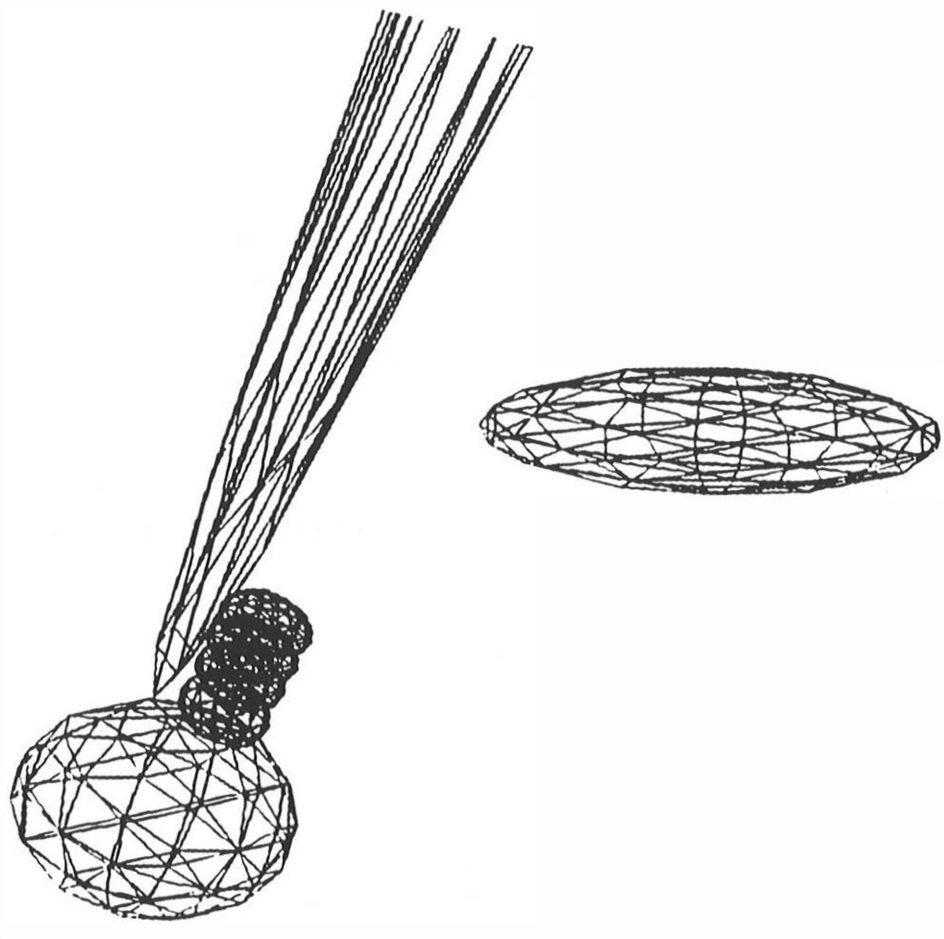

Figure 1. Graphics from the mathematical modelling of the calibration of the Hybrid-III neck. The neck is attached to a pendulum at its lower end and to the Hybrid-III head at its upper end. The pendulum has a velocity prior to impact of 7.0 ± 0.1 m/s. After impact, the pendulum is braked to stop with a constant force of 3.5 kN plus a damping of 0.1 kNs/m The figure shows the pendulum with the five-pivot neck and the head just before impact.

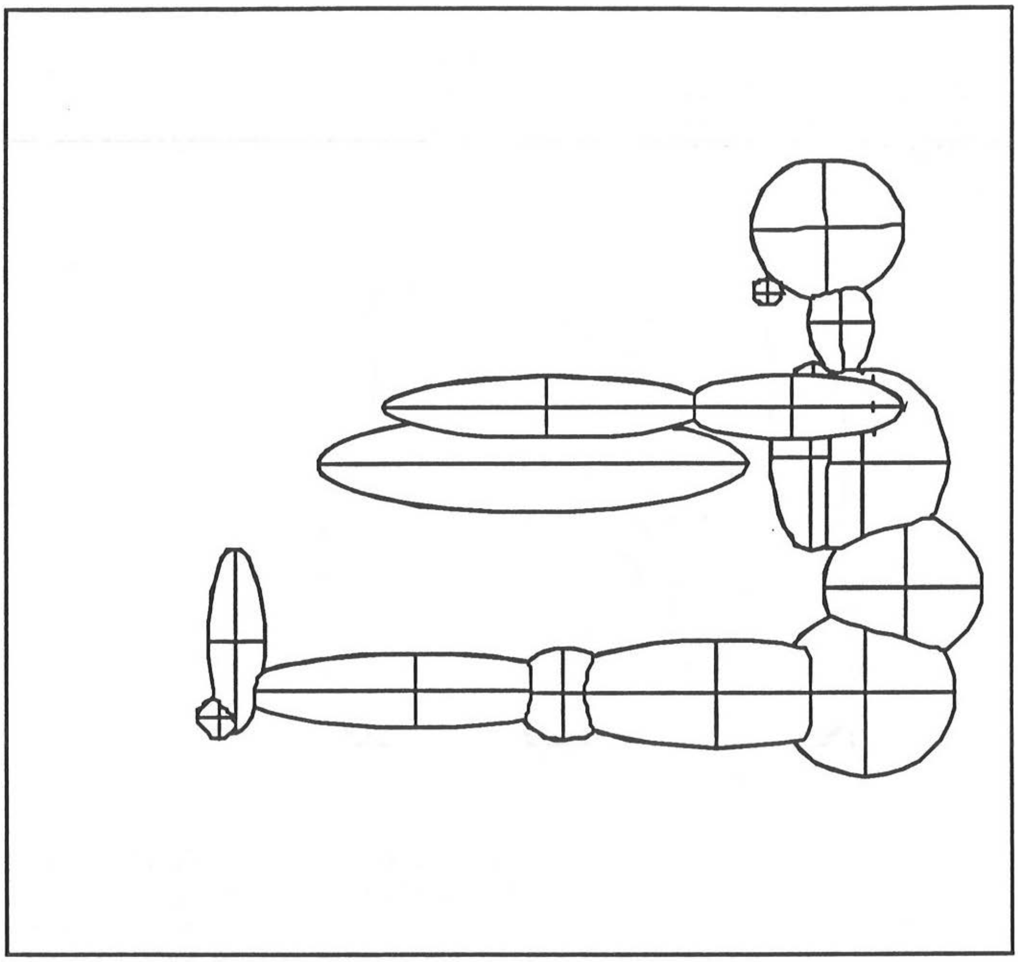

Figure 2. Calibration process for the chest of the Hybrid-III dummy. A 23.5 kg pendulum impacts the dummy chest at 6.7 m/s. The dummy sits on the floor with the arms straight in a right angle to the torso.

Chest deformation properties were accomplished by dividing the upper torso into two parts. The two elements were connected with a hinge joint at the point where the neck is connected to the torso. Then five parameters were varied until the dummy response met the requirements: the elastic torque; the damping in the joints; the friction in the joints; the mass distribution; and the moment of inertia of the outer element, which represented the sternum. The total mass was constant and equal to the mass of the upper torso element in the MADYMO Database (TNO, 1990). Since the proper mass rate was found to be approximately 30 to one, the moment of inertia of the heavier element was supposed not to differ from the value suggested for the entire upper torso in the database. To make sure that the new chest design would work under real testing conditions, it was used in a simulated sled-test, where it replaced the description from the database (TNO, 1990).

Lower torso

The lower torso was modified in two steps. First two extra ellipsoids were attached to the lower torso element of the Hybrid-III dummy, in order to reproduce the parts of the aluminium pelvis (Fig. 3) that are interacting with the seat. This modification was used in a recent study by Nilson (1991).

During the design process it was also found that the outer contour of the lower torso strongly affected the calculated dummy kinematics. Therefore, this contour also was modified (Fig. 3). As can be seen in Fig. 3, the new contour has a high visual resemblance with the corresponding contour of the mechanical dummy. Thus, the part of the contact contour of the lower torso that interacts with the seat comprises 1) an outer third-degree ellipsoid, which accounts for the interaction between the dummy and the seat at low contact forces and, 2) two inner, small ellipsoids, which account for the interaction between the dummy and the seat at high contact forces and for contacts with devices such as the submarine-beam.

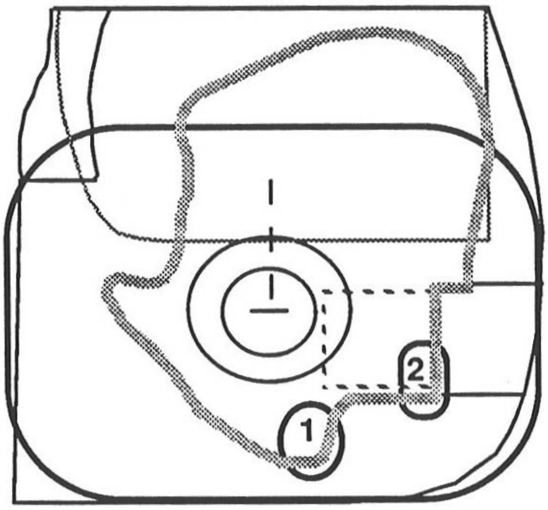

Figure 3. Modified contact contour for the lower torso. The frontal ellipsoid (1) has a circular cross-sectional area in the sagittal plane. Its centre has the x- and z-coordinates (-0.009, -0.054) [mm] with respect to the femur joints, and its radii is 25 mm. The rear ellipsoid (2) has its centre at (-0.073, -0.031) and has the shape of a hyperellipsoid (4th degree) with semi-axes of 10 (x) and 20 (z) mm. The outer contour is a third-degree ellipsoid with x, y and z semi-axes of 127, 183 and 92 mm, respectively (in the figure, this contour is represented by a rectangle with rounded corners). Together these contours describe the parts of the lower torso that interacts with the seat. The ellipsoid-contours lie approximately 5 mm outside the contour of the actual pelvis, since the soft parts of the element will have a certain thickness even under very high loads. The thin lines represent the contours of the undeformed pelvic flesh, the grey contour represent the stiff, aluminium pelvis.

RESULTS

Neck

It was found that with a coefficient of damping of 2.3 Nms/rad., to account for the dynamic properties, and a coefficient of friction of 5.0 Nm, to account for energy dissipation that is not velocity-dependent, the static bending data obtained by Hjolman and Barne (1987) (Table 1) was sufficient to make the mathematical neck meet the requirements (Table 2).

The results from the second test are shown in Figs. 4 and 5. In this test the performance of the new five-pivot neck in a simulated frontal impact sled-test is compared to that of the two-pivot neck suggested in MADYMO Databases (1990). Fig. 4 shows the time-histories of the resultant linear acceleration of the centre of gravity of the head. Fig. 5 shows the trajectory of the centre of gravity of the head obtained in the mechanical sled-test as well as in each of the mathematical duplications of the test.The only difference between the simulations is the description of the neck.

Table 2: Results from pendulum test of the five-pivot neck with joint damping=2.3 Nms/rad and joint friction=5.0 Nm, and from a similar test with the two-pivot necks from MADYMO Databases (1990 and 1991). Within brackets are given the calibration requirements.

Parameter	Five-pivot neck (new)	Two-pivot (1990)	Two-pivot (1991)	(Requirements)
Pendulum velocity at time zero [m/s]:	7.05	7.03	7.05	(6.89 - 7.13)
Maximum momentum - occipital condyle [Nm]:	104.8	67.5	59.8	(88.2 - 108.5)
Momentum peak time [ms]:	54.9	64.1	56.7	(47.0 - 58.0)
Momentum decay time to zero [ms]:	97.3	96.2	99.5	(97.0 - 107.0)
Maximum head rotation [°]:	71.3	79.4	67.6	(64.0 - 78.0)
Head rotation peak time [ms]:	59.9	68.9	62.4	(57.0 - 64.0)
Head rotation decay time to zero [ms]:	123.0	135.0	115.7	(113.0 - 128.0)

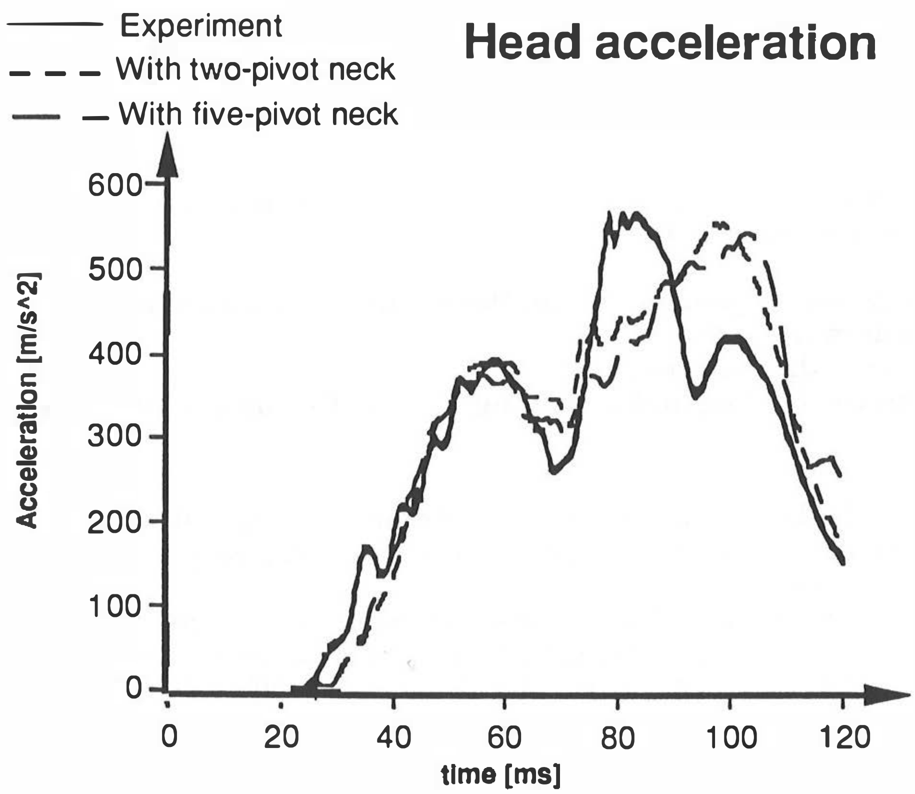

Figure 4. Resultant acceleration of the centre of gravity of the head, measured in the sled-test (solid line), and from the simulations of the sled test (dashed lines).

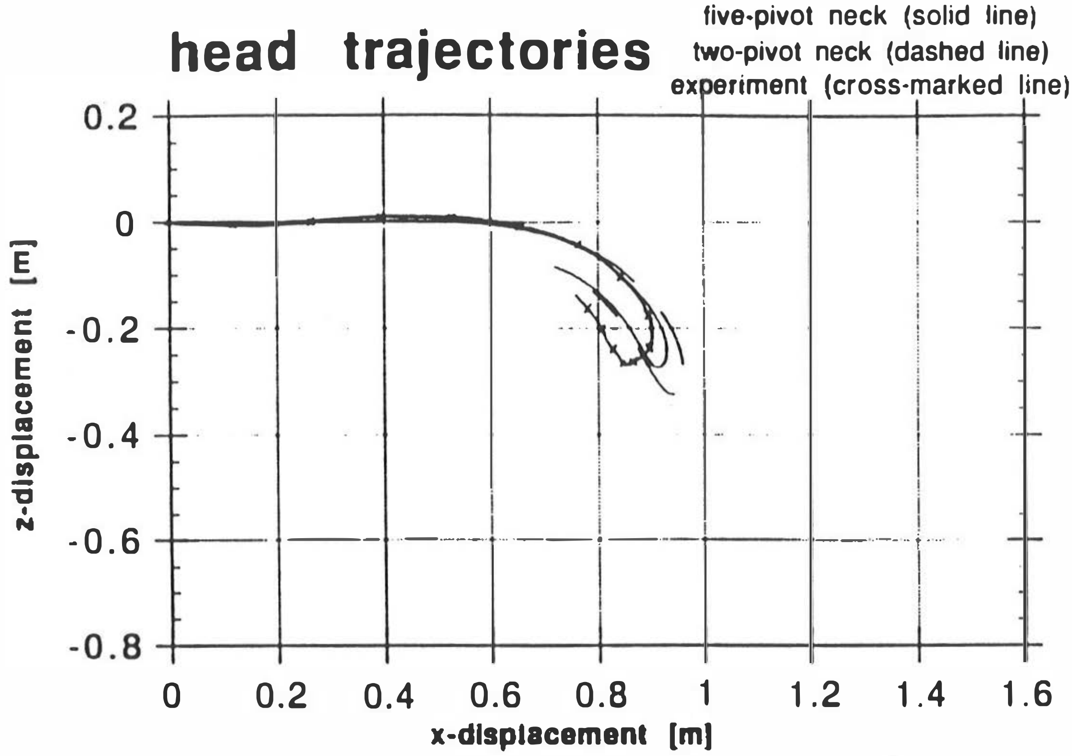

Figure 5. Trajectories of the centre of gravity of the head, obtained in the sled-test (cross-marked line), and in the simulations of this test. The five-pivot neck (solid line) seems to better duplicate the mechanical neck response than the two-pivot neck (dashed line).

Upper torso

The performance criteria for the deflection of the chest of a Hybrid-III dummy regard the following output parameters (Fig. 6):

- Maximum force between the pendulum and the sternum (measured as the deceleration of the pendulum times the mass).
- Maximum deflection of the sternum, and
- Hysteresis between the loading and unloading slope of the force-curve (measured as above).

With the listed set (Table 3) of input parameters the implemented sternum met all three requirements, and the force-deflection curve as a whole was very similar to a typical from an ordinary test (Fig. 6).

When used in a simulated sled-test, the new design proved to improve the prediction of the resultant acceleration of the centre of gravity of the chest, in comparison with the single-element description from the MADYMO Databases (TNO, 1990) (Fig. 7).

Lower torso

In the absence of calibration requirements, there are only qualitative results to illustrate the effect of the modified contact contour of the lower torso. Fig. 8 shows the difference in trajectory in the xz-plane for the centre of gravity of the head when the contact contour for the lower torso is modified.

Table 3. Appropriate input parameters for the sternum.

Parameter	Value	
Mass	0.5	[kg]
Moment of inertia	0.009	[kgm^2]
Spring constant	1550	[Nm/rad.]
Damping coefficient	9.5	[Nms/rad.]
Friction coefficient	0.5	[Nm]

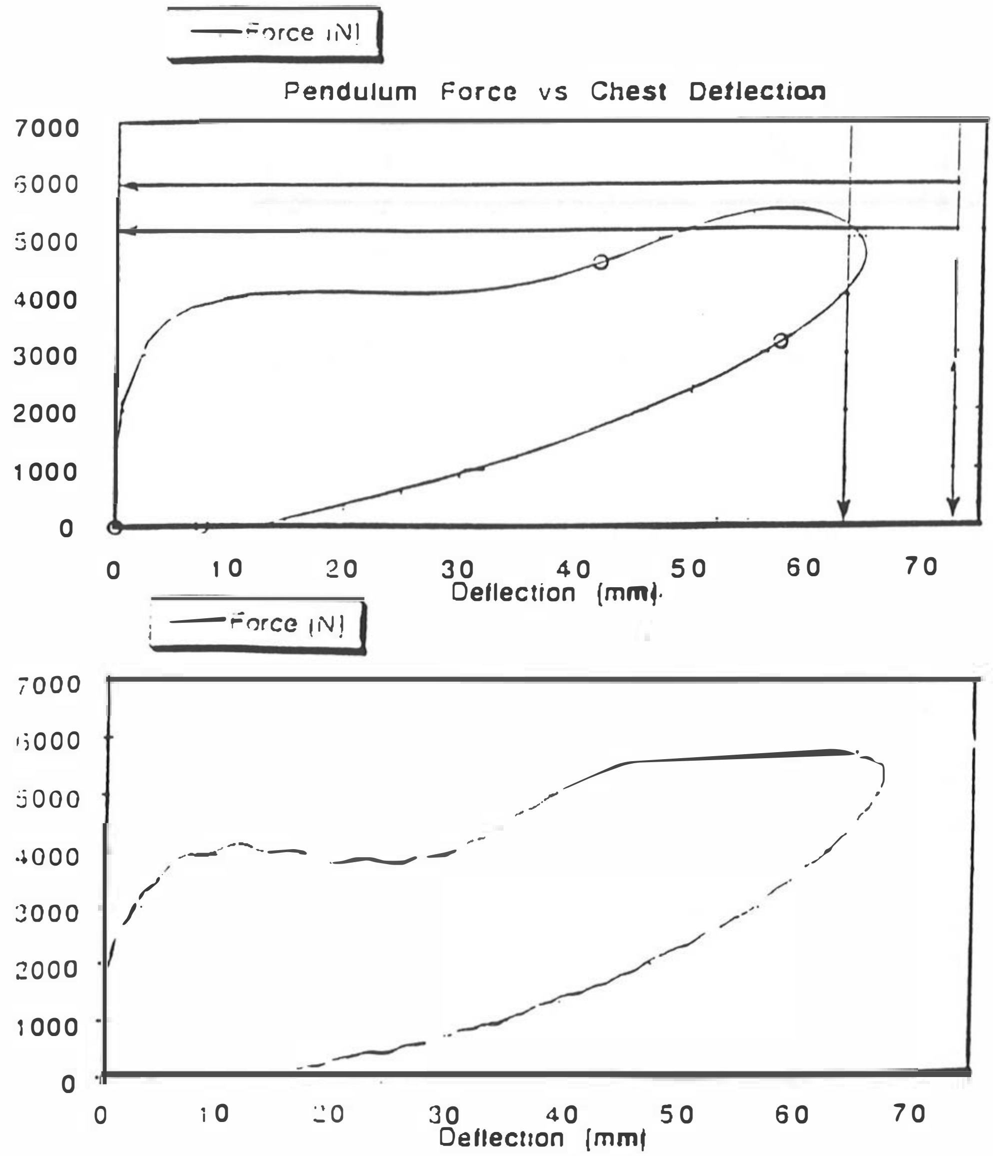

Figure 6. Results from the mathematical modelling of the calibration of the Hybrid-III chest (upper) and from a similar test performed with the mechanical dummy (lower). The requirements of maximum pendulum force and maximum chest deflection are indicated with arrows in the upper figure. As can be seen, the hysteresis, on which the third requirement is based, is also very well reproduced in the mathematical model.

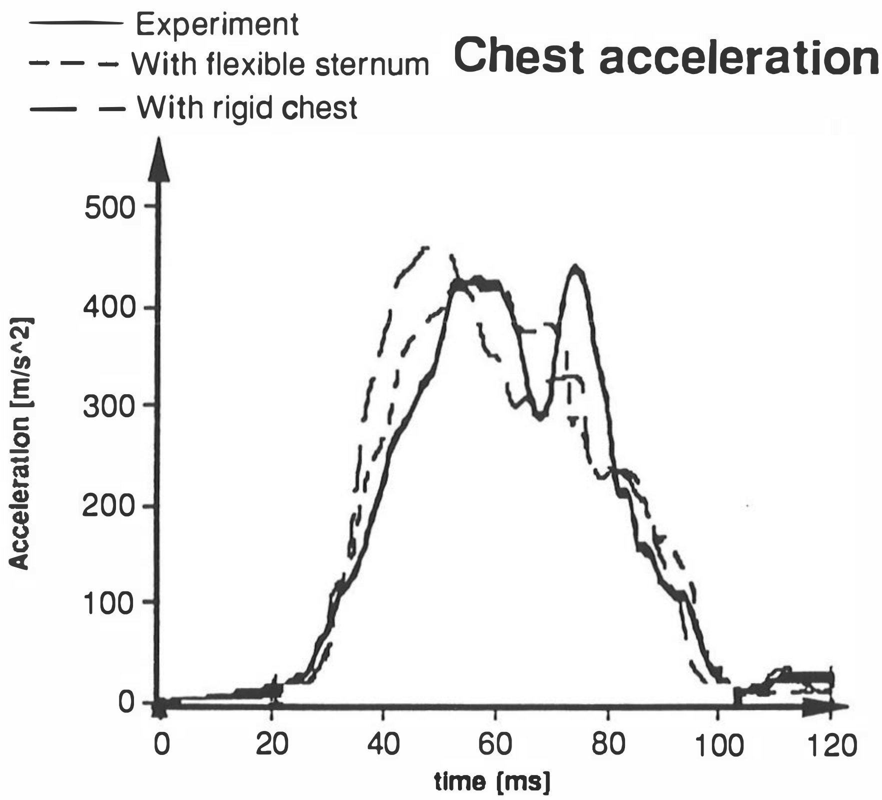

Figure 7. Resultant acceleration of the centre of gravity of the chest, measured in the sled-test (solid line), and from the simulations of the sled test (dashed lines).

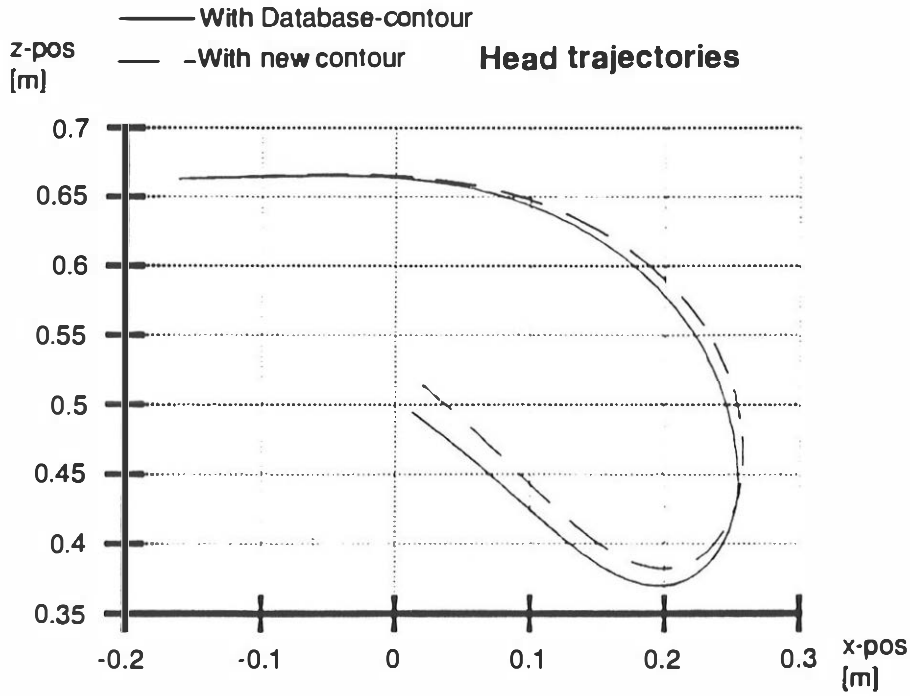

Figure 8. Trajectories of the centre of gravity of the head when the pelvis has an outer contact contour as suggested in the database (solid line) and when the modified contour is used (dashed line). All other parameters are identical between the tests.

DISCUSSION

Neck

In a series of contributions to the Stapp Car Crash Conference 1983 through 1987, Wismans and Spenny, later Wismans *et al.*, have shown that a two-pivot neck, such as the neck described in the MADYMO Databases, has the potential to well predict the response to various impacts of volunteer and human cadaver necks. However, in order to model the rotation of the head with respect to the chest correctly, a two-pivot neck must have a lower resistance to bending in its joints than the mechanical neck, since the latter can bend in more than two points. Consequently, in the calibration test both two-pivot necks have a maximum moment around the occipital condyle that is much too low to comply with the standards. The neck description from MADYMO Databases (1990) also has too slow an angular response. This is no reason why the necks could not respond like the dummy neck in many other relevant aspects. The results from the simulated sled-test show that the response of the 1990 neck-version is fair, both when compared to the five-pivot neck and to the mechanical dummy neck. Unfortunately, the 1991 description of the Hybrid-III dummy is so different from the previous version that the necks cannot be compared in a simple way, such as swopping them while maintaining a fix residual dummy description. This is the reason why the five-pivot neck was compared only to the neck of 1990 in the simulated sled-test. A comparison with the two-pivot neck of 1991 would have required at least one extra validation study, which was not possible within the time-frames of this study. Since the two two-pivot necks responded similarly in the calibration tests there is, however, reason to believe that also the two-pivot neck of 1991 would have performed well in the simulated sled-test.

Nevertheless, since much work with mathematical models has the aim to guide and aid experimental testing, access to a neck that can predict dummy response in detail is sometimes preferable. The four-element neck described here complies with the standards, without any extra arrangements such as a chin to torso contact. It also seems to better predict the acceleration and trajectory of the head in simulated sled-tests, although the model could be further improved, for instance by a more careful positioning of the point where the neck should be attached to the torso. Altogether, this means the new neck should improve the correspondence between results from simulations and results from experimental testing with the Hybrid-III dummy. Access to a mathematical neck that reproduces the properties of a human neck would then accommodate for establishing the difference in response to various impacts between the dummy neck and the human neck, and according to Wismans and Spenny (1983 and 1984), Wismans *et al.*, (1986 and 1987) and Mendis *et al.* (1989), many important properties of such a neck could be included in a fairly simple neck-model.

Another reason for using a more detailed neck model in mathematical simulations is that it may improve the understanding of the neck behaviour in a car crash, since any parameter that determines the neck response is obtainable in the mathematical model. This fact is discussed by Deng (1989).

Since the physical neck consists of five rubber parts separated by aluminium-plates, a five-pivot neck appears to be a natural mathematical description. This description was also used by Deng (1989). The segments are identical, except for the top segment, which has additional rubber parts. Consequently, in the report by Hjolman and Barne (1987), there is one angle-moment relation for the uppermost joint and another for the four lower. Despite this, the same damping and friction properties were applied to all five joints in the neck system. The reason is that the neck met the requirements already with this simple approach. Nevertheless, since the performance criteria accept a range of values for the neck response, there ought to be other coefficients of friction and damping with which the mathematical neck also would fulfil the requirements. Thus, a more refined tuning to obtain an even better resemblance with a specific dummy neck is possible. Since there is significant scatter between different necks, the simple approach presented here is assumed to do just as well in the general case. Deng (1989) also measured the angle-moment relation for the neck, but in a lower range than Hjolman and Barne (1987). However, the measurements overlap, and in the region of overlap the results obtained by Deng are similar to the results obtained by Hjolman and Barne.

Hjolman and Barne (1987) stated that their major reason for not suggesting any damping and friction coefficients was that their results were intended to be used in a model that allowed the bending moment to be given as a function of both angle and bending velocity. They also stated that they found no simple relation between the neck response at different bending velocities, such that it could be expressed by a linear coefficient of damping.

Upper torso

This work has shown that chest compliance, such that the mathematical Hybrid-III dummy meets the performance criteria for the mechanical dummy, can be achieved with a simple model of the upper torso.

The fact that the two chest elements are connected in one point means that the sternum is rotating instead of translating relative to the upper torso. This does not correspond very well with the mechanical dummy design. However, the fraction of the restraining effect of the shoulderbelt is in proportion to the angle circumscribed (in the plane perpendicular to the contact surface) in an arbitrary part of the contact area. Thus, a large part of the shoulderbelt-force is applied in the "clavicle" area, since there the belt makes an abrupt turn of nearly 90 degrees. In this region the dummy is virtually undeformable, which means that little error is introduced if the shoulder-belt is acting in a point that is fixed with respect to the upper torso element. The other important area is the lower edge of the ribcage, where the belt is re-directed towards the buckle, and in this area the chest deflection of the mathematical model presented in this paper correlates well to that of the mechanical dummy.

The dummy with a modified upper torso has been used in standard frontal impact simulations, in which it works properly. The modification proved to affect not only the upper torso response but also that of the head and the lower torso.

When modelling chest-to-airbag impacts, the relation between the contact surface of the sternum and the contact surface of the rest of the upper torso, as well as the shape of the surfaces, is important. The reason is that for the chest deflection to be correctly calculated, both chest elements must carry a realistic proportion of the contact forces. No air-bag calculation is, however, undertaken within this study.

Lower torso

In the absence of objective criteria, the visual resemblance with the original dummy part is the only solid argument to support the appropriateness of the contact contour of the lower torso suggested in this study. This was also the argument applied for the contour in the TNO database (Wismans and Hermans, 1988). However, it is clear that the elliptical cylinder suggested in the database is not sufficient if, for instance, a so called submarine-beam or similar energy-absorbing devices are included in the model, since these devices are small and located at distinct positions and therefore cannot be recognized by one, wide contour. In a work by Bosio (1990) this problem is addressed, but no solution suggested.

The outer contact contour is almost circular in the MADYMO Databases (TNO, 1990). This means that except for forces in the joints to the spine and the upper legs, only the friction force between the dummy and the seat will hinder rotation of the lower torso element. The mechanical dummy has, however, a pronounced "corner" in the rearmost part of the area, which also hinders pelvic rotation. The importance of a correctly designed contact contour is displayed in the comparative runs, which show that a change of the contour affects the head motion significantly. After performing several runs, it seems to me the response of the mathematical dummy is in better agreement with that of the mechanical when the modified contact contour is used.

CONCLUSION

Mathematical representations of the neck and the upper torso of the Hybrid-III dummy that comply with the requirements on the mechanical dummy have been developed. These new representations are assumed to improve the mathematical predictions of experimental results. The modified contact contour for the lower torso is assumed to further improve the correspondence between mathematical and mechanical testing.

The more detailed neck representation is also assumed to improve the understanding of the neck response to various impacts. Furthermore, it has the potential to increase the biofidelity of the Hybrid-III dummy, at least indirectly, since it can link between results obtained from mechanical tests and results from simulations with the present, two-pivot neck, which has previously been shown to have a higher degree of biofidelity in comparison with the mechanical neck.

ACKNOWLEDGEMENTS

This study was sponsored by Electrolux Autoliv AB, Vårgårda, Sweden. I thank Doctor Per Lövsund for help with work planning, Mr. Sven-Erik Svensson and Mr. Claes Jernström, Volvo Car Corporation, for valuable discussions, and the Department of Injury Prevention at the TNO, for providing me with the MADYMO model.

REFERENCES

Bosio, C.: "Simulation of submarining with MADYMO", proceedings of the Second International MADYMO Users' Meeting, TNO Road-Vehicles Research Institute, Delft, The Netherlands, pp 135-170 (1990)

Deng, Y.-C.: "Anthropomorphic Dummy Neck Modeling and Injury Considerations", J of Accident Analysis and Prevention, Vol. 21, No. 1, pp 85-100 (1989)

Foster, J. K., Kortege, J. O., Wolanin, M. J.: "Hybrid III – A Biomechanically Based Crash Test Dummy", Proc. of 21st Stapp Car Crash Conference, SAE P-73, pp 937-1014 (1977)

General Motors Corporation: "Hybrid-III - An Advanced Anthropometric Crash Test Dummy", National Highway Traffic Safety Administration, Washington D. C., USA (1984)

Hjolman, M. and Barne, O.: "Framtagning av matematisk modell för gummihals till krockprovdocka", Department of Machine Elements, Chalmers University of Technology, Göteborg, Sweden (1987) (in Swedish)

Håland, Y. and Nilson, G.: "Seat-Belt Pretensioners to Avoid the Risk of Submarining – A Study of Lap-Belt Slippage Factors", in proceedings of the 13th International Conference on Experimental Safety Vehicle (1991)

Lupker, H.A., and Fraterman, E.: "Status MADYMO Program (1990)", proceedings of the Second International MADYMO Users Meeting, TNO Road-Vehicles Research Institute, Delft, The Netherlands, pp 255-262 (1990)

Mendis, K., Stalnaker, R. L., and Pritz, H. B.: "Multi-Directional Dummy Neck Prototype", proceedings of the 12th International Conference on Experimental Safety Vehicle, pp 645-649 (1989)

Nilson, G: "The Seat-Integrated Safety Belt – A Parametric Study Based on Mathematical Modelling", J of Accident Analysis and Prevention (Submitted) (1991)

Prasad, P.: "An Overview of Major Occupant Simulation Models", proceedings of Government/Industry Meeting & Exposition, Washington, D.C., SAE P-146, pp 1-10 (1984)

TNO Road-Vehicles Research Institute: "MADYMO Databases, Version 4.3", The Netherlands (1990). Upgraded datadeck for the Hybrid-III dummy, distributed separately (1991)

TNO Road-Vehicles Research Institute "MADYMO User's Manual 3D, Version 4.3", The Netherlands (1990)

Wismans, J., and Spenny, C. H.: "Performance Requirements for Mechanical Necks in Lateral Flexion", proceedings of the Twenty-Seventh Stapp Car Crash Conference, SAE P-134, pp 137-148 (1983)

Wismans, J., and Spenny, C. H.: "Head-Neck Response in Frontal Flexion", proceedings of the Twenty-Eighth Stapp Car Crash Conference, SAE P-152, pp 161-172 (1984)

Wismans, J., van Oorschot, H., and Woltring, H. J.: "Omni-Directional Human Head-Neck Response", proceedings of the Thirtieth Stapp Car Crash Conference, SAE P-189, pp 313-331 (1986)

Wismans, J., Philippens, M., and van Oorschot, E.: "Comparison of Human Volunteer and Cadaver Head-Neck Response in Frontal Flexion" proceedings of the 31st Stapp Car Crash Conference, SAE P-202, pp 1-14 (1987)

Wismans, J. and Hermans, J.H.A: "MADYMO 3D Simulations of Hybrid III Dummy Sled Tests", SAE paper no. 880645 (1988)