EINDHOVEN UNIVERSITY OF TECHNOLOGY

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Citation for published version (APA):
Haaster, van, R. M. H. P. (1995). *A combined generator for child multibody models*. (DCT rapporten; Vol. 1995.157). Technische Universiteit Eindhoven.

Document status and date:
Published: 01/01/1995

Document Version:
Publisher's PDF, also known as Version of Record (includes final page, issue and volume numbers)

Please check the document version of this publication:

• A submitted manuscript is the version of the article upon submission and before peer-review. There can be important differences between the submitted version and the official published version of record. People interested in the research are advised to contact the author for the final version of the publication, or visit the DOI to the publisher's website.
• The final author version and the galley proof are versions of the publication after peer review.
• The final published version features the final layout of the paper including the volume, issue and page numbers.

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A combined generator for child multibody models

WFW report 95.157

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Delft, 8 November 1995

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SUMMARY

Children in traffic are a vulnerable group. To verify safety measures for this particular group, such as child seats, crash-dummies can be used by performing sled-test experiments or full-scale experiments. In 1993, TNO Crash-Safety Research Centre, together with Ogle Design Ltd. started to work on a new child dummy: the TNO P1½, representing an 18-month-old child. The anthropometric data is derived from a database called CANDAT (Child ANthropometric DATabase).

Physical experiments are cost expensive as well as time expensive. To overcome these disadvantages, TNO developed an integrated multibody/finite element software package called MADYMO (MAthematical DYnamical MOdels). Child multibody models, aged between 2 and 20 years, can be generated by a software package called GEBOD (GEnerator of BOdy Data) developed by Wright-Patterson Air Force Base. This program is based upon one survey: Snyder 1977. The calculation of the inertial properties is based upon the shape and volume of the ellipsoids that are generated. CANDAT, however, consists of more (recent) data on children, from multiple sources, and the segment masses and segment moments of inertia can be calculated using regression equations, based upon anthropometric surveys.

A combination of CANDAT and GEBOD can be developed; the body length dimensions are based upon more (recent) data, available from CANDAT, and the inertial properties are based upon anthropometric surveys instead of the generated ellipsoids. The generated models can be aged less than 2 years, because data for this age group is available in CANDAT. The program GEBOD is needed, because CANDAT is merely a database, not a program capable of generating multibody models.

In this study, a program is developed that generates an inputfile for GEBOD, consisting of the values of 32 parameters on which the GEBOD models are based. The inertial properties are calculated in a program and are substituted in the GEBOD output file. The arbitrary division of the torso into three segments and calculation of the neck length causes difficulties. From simulations it can be concluded, that the vertical location of the hip joints and the neck length are critical parameters in crash simulations. The combined (improved) program still generates questionable models. Therefore, a newly to be developed program for generating child multibody models can be thought of, that uses CANDAT as data source.

CONTENTS

1 INTRODUCTION

Children in traffic are a vulnerable group, not only as pedestrians or bicyclists, but also as car passengers. Children in a car are often unrestrained, which can be dangerous in case of an accident. By legislation, the automobile industry has been obliged to provide the back seat of cars with reliable belt systems. The belt systems are, nevertheless, not appropriate for all children, especially babies and infants are better protected by child seats in combination with the belt systems. These child restraint systems (CRS) have to be specifically designed for the protection of children. From the early 1960's, TNO developed a series of 5 child dummies; the P0, P3/4, P3, P6 and P10 child dummies. They represent masses and dimensions of children of the following ages: a newborn, 9 months, 3 years, 6 years and 10 years. In 1993, TNO Crash-Safety Research Centre, together with Ogle Design Ltd. started to work on a new child dummy : the TNO P1½, representing an 18-month-old child. The anthropometric data is derived from a database called CANDAT (Child Anthropometric DAtabase) [15, 16]. This database is set up from anthropometry surveys done in the USA and Western Europe in the period 1970-1993 and includes over 90 dimensions. The segment-masses and segment-moments of inertia can be calculated using regression functions with respect to age or body dimensions [3, 6, 7, 8, 12, 14, 15, 16, 19]. Child dummies can be used to verify safety parameters by performing sled-test experiments or full-scale experiments.

It is also possible to simulate these tests using mathematical modelling techniques. For this purpose an integrated multibody/finite element software package called MADYMO (MAthematical DYnamical MOdels) has been developed by the TNO Crash-Safety Research Centre. The multibody module allows the kinematic, dynamic and inverse dynamic analysis of systems of rigid and flexible bodies, interconnected by various types of kinematic joints. Geometry can be assigned to bodies by attaching surfaces, (hyper)ellipsoids or planes, which can also be used for describing contact between bodies.

The geometry and inertial properties of the child multibody models can be derived from CANDAT or they can be generated by a software package called GEBOD (GEnerator of BOdy Data) [1, 4, 9, 10, 17]. In this study the GEBODIII-version is used. GEBOD was originally developed and documented by Baughman in 1983 [1]. Since then additions and improvements have been made to the program [17]. It generates multibody models using regression equations for calculating the body length dimensions, inertial properties and joint locations. CANDAT lacks this information of joint-locations but can directly provide the body length dimensions and inertial properties.

GEBOD can be divided into two parts: 1) one part that calculates body length dimensions, 2) a part that generates a database model with geometry, ellipsoids, etc. The first part could be replaced by data derived from CANDAT. The objective of this report is to determine whether it is possible to combine the database CANDAT and the model generator GEBOD, so that GEBOD can generate a MADYMO multibody model based upon the body length dimensions and inertial properties derived from CANDAT.

Joint characteristics are also calculated by GEBOD, but these results are not discussed in this report, because CANDAT has no data on joint characteristics. This report only discusses the body length dimensions and segment inertial properties of the generated multibody models.

The main reasons to combine CANDAT and GEBOD are: 1) CANDAT has no data on joint locations. For this purpose GEBOD can be used, 2) there is nearly no experience working with GEBOD at TNO Crash-Safety Reasearch Centre. 3) GEBOD generates child models, representing children aged between 2 and 20 years. Data is available in CANDAT for the group less than 2 years. This data can be used to generate models, representing children aged between 0^+ and 20 years, 4) GEBOD is based upon only one anthropometric survey, while CANDAT consists of more data from several (recent) surveys, and 5) GEBOD calculates the inertial properties based upon the dimensions of the generated ellipsoids. The calculation of inertial properties, included in CANDAT, however, is based upon multiple anthropometric surveys.

The program GEBOD and the use of regression equations will be discussed in Chapter 2. Next, the database CANDAT is addressed in Chapter 3. In Chapter 4 the limitations of the use of GEBOD and CANDAT, and the motives to develop a combination of these two are discussed successively. In Chapter 5 the choices that are made to combine GEBOD with CANDAT are addressed and the basic principle on which the program is based, is included. In order to compare the models generated by the original program and the new combined program, some simulations are performed. The set-up of the simulations and the discussion of the results are included in Chapter 6. This report ends with conclusions and recommendations for further research which are presented in Chapter 7.

2 GEBOD

2.1 Introduction

The development of mathematical models, capable of predicting the motion of the human body in a dynamic environment has created a need for data describing human geometry and inertial properties. For that purpose a computer program, called GEBOD, has been developed by Wright-Patterson Air Force Base [1] for generating data sets for human body multibody modelling. It was originally developed to automate the process for generating the body description portion of the Articulated Total Body (ATB) model. In 1989, Vosbeek [17] developed a program to convert GEBOD output into a database for MADYMO. The database contains configuration, geometry, inertia and ellipsoids (ellipses in the 2D case) of a tree structure of rigid bodies that represent the human body.

The program provides data for four human subject types, ie. child (2-19 years), adult human female, adult human male and a human based on user-supplied body dimensions [4]. For this purpose, the program is divided into three parts for generating human body models: 1) adult human male; 2) adult human female and 3) child and user-supplied body dimensions. All the computations for children are based on a set of 32 body measurements (Appendix A [1, 4]). These are used to determine sizes of body segments and the location of joints connecting them. GEBOD has two ways of obtaining values for the required 32 body measurements. These measurements can either be read in from a file or they can be generated by GEBOD using regression equations stored within GEBOD.

2.2 Regression equations

Regression analysis is a method widely used in anthropometry for predicting various body dimensions. The regression equations for adult females and males are based upon weight, stature or both, because this is the information most commonly known about a subject. The child regression equations, however, are based upon age, weight, stature or all three combined. The goal is to use this limited description to achieve the best possible prediction for other body dimensions of a subject.

From now on only the child subject will be discussed, because this data can be compared with the data available from CANDAT. The child regression equations were computed from a survey consisting of data on 3782 children aged two to twenty years from throughout the United States, done by Snyder et al. in 1977 [15]. In the cases where a required dimension was missing from a survey, it was approximated from available measurements (Appendix A).

To indicate the prediction ability of a regression function the R^2-value can be determined, sometimes referred to as the predictive ability score. It measures the percentage reduction in the scope of the predictions errors that is achieved by using the regression equations.
The method of determining the predictive ability of the regression line will be explained in the following three steps [1]:

1. Calculate the prediction error that would result without the use of the regression equation, where Y_i is the observed value and $\bar{Y}$ the mean value :

$$\sum (Y_i - \bar{Y})^2 \qquad i = 1,...,n \tag{2.1}$$

2. Calculate the prediction error that would result from using the regression equation, where $\hat{Y}_i$ is the predicted value :

$$\sum (Y_i - \hat{Y}_i)^2 \qquad i = 1,...,n \tag{2.2}$$

3. The resulting reduction in the prediction-error achieved by using the regression equation predictions rather than the mean value is :

$$R^2 = \frac{\sum (Y_i - \bar{Y})^2 - \sum (Y_i - \hat{Y}_i)^2}{\sum (Y_i - \bar{Y})^2} \tag{2.3}$$

The values of R^2 are always between zero and one. A value of 0 implies that the regression equation is useless in reducing the prediction error and has no predictive ability beyond that provided by using the mean value. A value of 1 implies that there will be no prediction error by using the regression equation. This does not indicate that the predicted results are exact. The R^2-value can't be used as a sole indicator of the effectiveness of the regression equation. If there is an extreme value pulling the regression line toward that value, the R^2-value may be quite high, while the regression equation may not best represent the data. So when using extreme values of stature and/or weight, the predicted results may be questionable [1].

It's remarkable that the R^2-values for almost all child regression equations using all three predictors are greater than 0.9 (Appendix A). The predicted results, using age and the 5-, 50- and 95-percentile values of stature and weight as predictors have been compared to the original data. From Appendix B it can be concluded that the calculated 50-percentile values are predicted with an accuracy of about 1%, while the 5- and 95-percentile values are predicted less accurately (about 4-8 %).

2.3 Body geometry

The appearance of the child multibody models, which is divided into 15 segments, is determined from contact ellipsoid semiaxes and joint locations [3]. The ellipsoids give the child models shape and can describe a contact between the models and planes, other ellipsoids or finite element models. The joints connect segments and serve as pivot points about which motion is allowed. Semiaxes of the contact ellipsoids for the child models are calculated with very straightforward equations using the predicted 32 body parameters (Appendix C [1]). The expressions to determine joint locations for the child models were developed by using the geometric center of each segment (the contact ellipsoid center) as an approximation for its Center of Gravity (CG) [1, 4]. This assumption is necessary, because ATB uses the CG as origin of the local reference system. Once GEBOD has computed the true location of the segment CG's, the joint locations are translated so that they are relative to the CG instead of the ellipsoid center. This is only the case for the torso segments and the foot segments. These expressions for determining the joint locations are also very straightforward. The joint locations were first laid out in a global coordinate system, with axes origin on the floor [1]. From these global locations the expressions for local reference system coordinates were determined. Some examples are included in Appendix D.

The way in which the torso is divided into three segments is somewhat arbitrary. The mid torso or abdomen is defined as extending from the tenth rib landmark to the iliocristale landmark. The upper torso or thorax is defined as being all of the torso above the abdomen, and the lower torso or pelvis being all of the torso below the abdomen [1]. However, none of the available body measurements give tenth rib height. From stereophotometric studies the ratio of thorax height (vertical distance between suprasternale and tenth rib midspine) to abdomen height (vertical distance between tenth rib midspine and right iliocristale) was found to be 4:1 for adults [1, 4]. This result has been used to set the distance between the thorax-abdomen joint and the abdomen-pelvis joint for adults and for children. It is generally known, that for children this ratio might be different.

2.4 Segment masses

The distribution of mass within the human body greatly affects the inertial properties. For simplicity it is assumed that the human body is homogeneous, and thus, each individual segment is homogeneous and has the same density as the other body segments [1, 3]. In order to determine the segment masses of the head, neck, and the limbs, the volumes of the segment ellipsoids are calculated. For the torso segments and the feet GEBOD uses another technique. The segments are represented as right elliptical solids (Figure 2.1) [1]. The torso consists of 4 pieces. The top and bottom are semi-ellipsoids and inbetween are two elliptical frustrums. The feet are also elliptical frustrums. Numerical integration is used to compute these segment masses. First the volume is calculated. Successive approximations are made to the model by stacks of elliptical cylinders. Within each approximation all cylinders are of the same height. Each successive approximation uses more cylinders of lesser height than the previous. When the difference between two approximations drops below a tolerance level, the volume of the combined stack of cylinders is taken as an approximation of the volume of the right elliptical solid. The calculated volumes are multiplied with a density that approximates that of water (an average human body density). The sum of the segment masses is calculated and compared to the total body mass. A weight correction factor can be determined so that the sum of the segment masses equals the total body mass. Since an ellipsoid is completely symmetrical, its CG is located at its center, which agrees with the assumption made in determining the joint locations of the head, neck and limbs. For the torso and the feet, by using right elliptical solids, the CG is calculated and can be used to translate the joints of these segments to the correct locations.

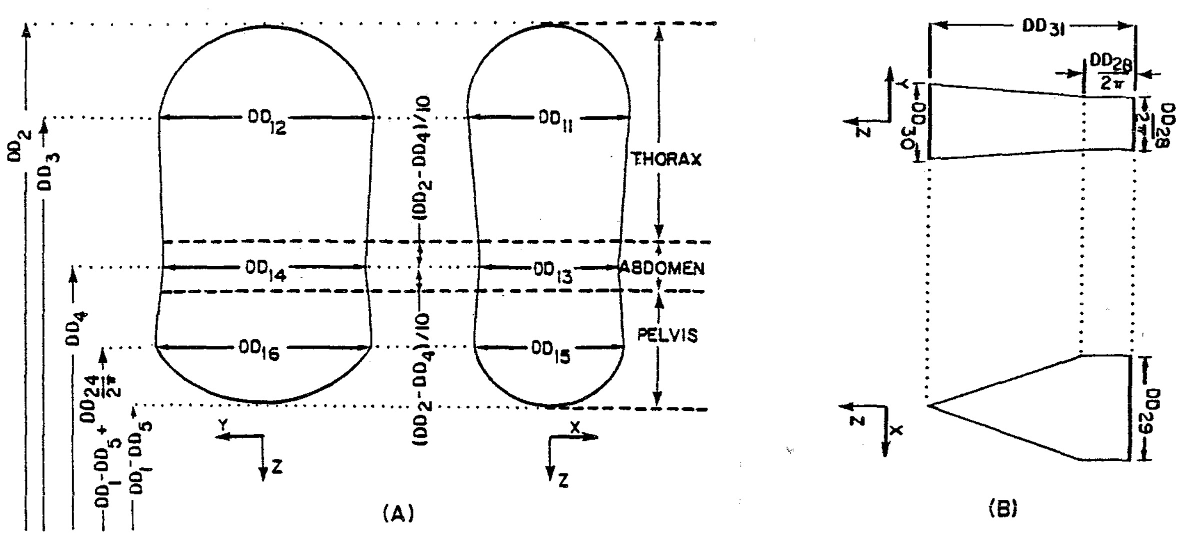

Figure 2.1: (A) Torso right elliptical solid (B) Foot right elliptical solid

2.5 Segment moments of inertia

For calculating the segment moments of inertia the same assumption is made, that the human body is homogeneous, and thus, each individual segment is homogeneous and has the same density as the other body segments. The principal moments of inertia for the head, neck and limbs are determined as the product of the body segment mass *m* and a combination of the squares of the semi axes (*a*, *b* and *c*) [1, 4]:

$$I_{xx} = \frac{m}{5} * (b^2 + c^2)$$
$$I_{yy} = \frac{m}{5} * (a^2 + c^2) \qquad (2.4)$$
$$I_{zz} = \frac{m}{5} * (a^2 + b^2)$$

For the torso segments and the feet GEBOD computes the moments of inertia of a right elliptical solid, based on the numerical integration determined by calculating the segment volume and mass.

3 CANDAT

3.1 Introduction

As a part of the research program for a new generation of child dummies, it was necessary to set up an anthropometry database on children [15]. This database should include information about body length dimensions and inertial properties, such as segment mass, CG and moment of inertia. A survey on data from the USA, the Netherlands and Germany has been conducted at TNO. This data can't be used directly, because they consist of several surveys representing different age groups. For this purpose custom built software [16] is used to select and evaluate the available data.

The collected data has been entered into a database, implemented in Microsoft Excel™. A program called NICELINE [16] has been developed to combine the results from several sources and get a single derived source. With this software it is possible to investigate the relationship between two parameters, usually a particular body segment size as function of age or total body mass. Based on the assumption that growth is a smooth and continuous process [15], a smooth line can be drawn through a number of datapoints. This smoothed data can be used as a new combined source of the specific body dimension. There is also data known of child inertial properties. All this data is collectively known as CANDAT (Child ANthropometric DATabase).

3.2 Body length dimensions

Through the years various surveys have been conducted on child anthropometric data. A considerable amount of information in the form of papers and reports is available at the Crash-Safety Research Centre of TNO. The collection of data has originally been used for two purposes : 1) monitoring the growth of children and determination of factors involved in growth and development and 2) for ergonomics. The TNO Crash-Safety Research Centre, however, mainly uses this collection of data for developing new child dummies. The most recent data have been selected for inclusion in the database CANDAT.

The selected sources are used to compile a list of over 90 parameters. These parameters are put into the database and sorted by an independent parameter, usually body mass or age. Through these datapoints a smooth line is drawn using a non-parametric FFT-filter [11] and low order splines, the GCV-algorithm [18]. The data covers age in the range of 0^+ up to 18 years. Some CANDAT-parameters are not known in this whole range. By using the GCV-algorithm this data can extrapolated to 0^+ years. The extrapolated data can only give an estimate, so caution is needed when using these results [15]. Two examples of this smoothing and extrapolating are given in Figure 3.1.

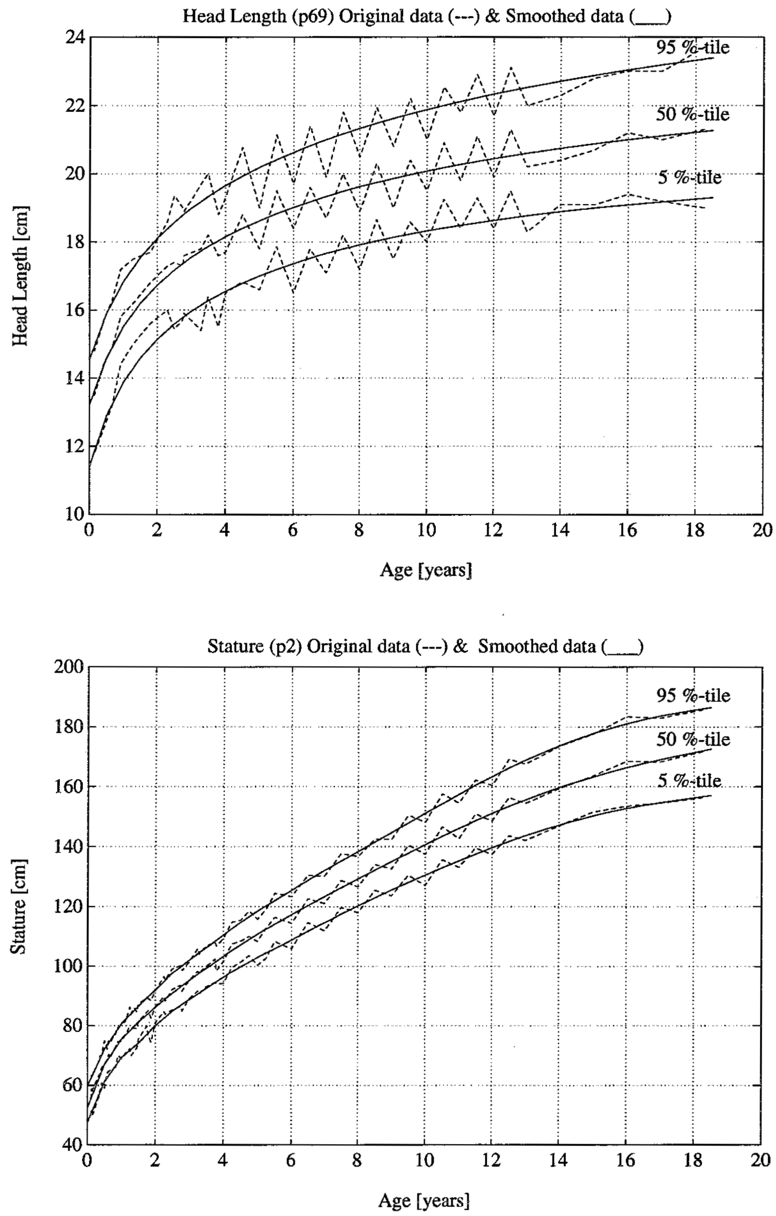

Figure 3.1: Two examples of smoothing body length dimension data

3.3 Segment masses

Through the years there have been several surveys conducted for the calculation of the segment masses. Surveys concerning children and infants in particular are : Jensen [8], Sun & Jensen [14] and Schneider & Zernicke [12]. These first two studies mentioned are based upon the work of Clauser *et al.* [3]; the last study mentioned is based upon the work of Chandler *et al.* [20]. Chandler divided the human body into 14 segments: head, torso, upper arms (2), lower arms (2), hands (2), thighs (2), lower legs (2) and feet (2). The entire neck is included with the torso. Clauser, however, divided the human body into 15 segments. The torso is divided into two segments: lower torso and upper torso. The entire neck has been fused with the head. The 15 segments are: head+neck, lower torso, upper torso, upper arms, forearms, hands, thighs, calves and feet (2).

Jensen [8] presents the segment masses as second order polynomials as function of age in years. These functions are determined for ages 4 to 20. Table 3.1 gives the coefficients of the polynomials of the segment mass relative to the total body mass (proportional segment mass). The proportional segment mass can be found as:

$$m = x_0 + x_1 \cdot t + x_2 \cdot t^2 \tag{3.1}$$

Where t is age expressed in years.

Table 3.1: Coefficients for mass segment proportion according to Jensen [8]

Segment	x_0	x_1	x_2	R^2
head+neck	0.27881	-0.21152E-1	0.53168E-3	0.76
upper torso	0.15837	-0.12533E-2		0.07
lower torso	0.27330			
upper arm	0.02344	0.69558E-3		0.51
forearm	0.01340	0.31268E-3		0.37
hand	0.00880			
thigh	0.04309	0.88978E-2	-0.27425E-3	0.67
calf	0.02177	0.48532E-2	-0.19003E-3	0.31
foot	0.01355	0.14661E-2	-0.71030E-4	0.21
forearm+hand	0.02280	0.26100E-3		0.15
calf+foot	0.03512	0.63207E-2	-0.26119E-3	0.31
torso	0.47620	-0.11928E-1	0.56964E-3	0.14
head/up.arm/torso	0.84359	-0.30346E-1	0.10707E-2	0.60
torso/head	0.75499	-0.33073E-1	0.11010E-2	0.67

Sun & Jensen [14] present the segment masses of infants, aged between 0.18 and 1.5 years as linear regression equations, with exception of the feet. The regression equations give the proportional segment mass, so the real segment mass can be found as the product of the proportional mass and the total body mass. The coefficients of the regression equations (3.2) can be found in Table 3.2.

$$m = a_0 + a_1 \cdot t + a_2 \cdot t^2 + a_3 \cdot t^3 + a_4 \cdot t^4 \tag{3.2}$$

Where t is age expressed in weeks.

Table 3.2: Coefficients for segment mass according to Sun&Jensen [14]

Segment	a_0	a_1	a_2	a_3	a_4	R^2
head+neck	1.31537	1.82805E-2				0.60
neck	6.54286E-2	1.31708E-3				0.34
upper torso	9.23717E-1	2.15418E-2				0.55
lower torso	1.41229	4.99202E-3				0.07
upper arm	1.00717E-1	2.65699E-3				0.36
forearm	1.19954E-1	1.21999E-3				0.20
hand	3.83346E-2	7.86200E-4				0.32
thigh	2.94021E-1	1.01128E-2				0.50
calf	1.60717E-1	4.15153E-3				0.54
foot	1.29924E-1	-1.17758E-2	7.95144E-4	-1.81594E-5	1.41411E-7	0.56

Schneider & Zernicke [12] present the segment masses (m) of infants, aged between 0.04 and 1.5 years as regression equations based on age (A), total body mass (B), segment length (L) or width (W) and segment circumference (C). The equations are given in Table 3.3.

Table 3.3: Regression equations for infants according to Schneider & Zernicke [12]

Segment	Regression equation	R^2
upper arm	$m = 1.2249 \times 10^{-2} \cdot B + 1.3067 \cdot L + 9.8645 \times 10^{-1} \cdot C - 1.9376 \times 10^{-1}$	0.98
forearm	$m = 5.2671 \times 10^{-3} \cdot B + 9.7584 \times 10^{-1} \cdot L + 1.1492 \cdot C - 1.6886 \times 10^{-1}$	0.98
hand	$m = 2.1345 \cdot W - 4.6776 \times 10^{-2}$	0.89
thigh	$m = 6.9126 \times 10^{-2} \cdot A + 2.9582 \cdot L + 3.1541 \cdot C - 6.7217 \times 10^{-1}$	0.96
leg	$m = 6.5138 \times 10^{-3} \cdot B + 1.8158 \cdot L + 1.8743 \cdot C - 3.5460 \times 10^{-1}$	0.98
foot	$m = 2.9331 \times 10^{-3} \cdot B + 1.2405 \cdot L + 1.9337 \cdot W - 1.0250 \times 10^{-1}$	0.81

The positions of the CG's are also known as regression equations [7, 8, 14], but because they are virtually identical to those used in GEBOD, this will not be discussed in this report. For the limbs, head and neck, the positions of the CG is approximately in the ellipsoid center [1].

3.4 Moments of inertia

The moments of inertia can be calculated using the methods of Yeadon & Morlock [19], Jensen [8], Sun & Jensen [14], Hinrichs [6] and Schneider & Zernicke [12]. Only Jensen [8] and Yeadon & Morlock [19] will be discussed in this report, because these two are able to describe the segment moments of inertia for children aged 0^+ to 18 years.

Yeadon & Morlock use information from Chandler *et al.* [20], assuming similar mass distributions for all segments. All segments, with the exception of the torso, are assumed to be symmetrical about their longitudinal axis, so $I_{xx} = I_{yy}$. The moments of inertia can be determined from :

$$I_{zz} = k_1 \cdot p^4 \cdot h \qquad (3.3)$$

$$I_{xx} = I_{yy} = I_{tt} = \frac{1}{2} \cdot I_{zz} + k_2 \cdot p^2 \cdot h^3 \qquad (3.4)$$

where:

I_{ii}= the moment of inertia around principal axis i
p = the (mean) perimeter of the segment
h = the height of the segment (longitudinal)

Table 3.4: Coefficients for moments of inertia according to Yeadon & Morlock [19]

Segment	k_1	k_2
head	0.701	2.33
upper arm	0.979	6.11
forearm	0.810	4.98
hand	1.309	7.68
thigh	1.593	8.12
calf	0.853	5.73
foot	1.001	3.72

For the torso segment the segmental moments of inertia around the three principal axes are given by:

$$I_{xx} = d \cdot w \cdot h \cdot [c_2 \cdot w^2 + c_3 \cdot h^2] \tag{3.5}$$

$$I_{yy} = d \cdot w \cdot h \cdot [c_1 \cdot d^2 + c_3 \cdot h^2] \tag{3.6}$$

$$I_{zz} = d \cdot w \cdot h \cdot [c_1 \cdot d^2 + c_2 \cdot w^2] \tag{3.7}$$

where:

d = depth of segment (anterior-posterior)
w = width of segment (medial-lateral)
c_1 = 49.4
c_2 = 55.0
c_3 = 68.8

Jensen [8] presents the proportional segment radius of gyration as polynomial regression equations. The radius of gyration can be calculated as the product of the proportional radius and the segmenth length. The moment of inertia is defined as:

$$I = m \cdot r^2 \tag{3.8}$$

where:

I = segment moment of inertia
m = segment mass
r = segment radius of gyration

The proportional segment of inertia can be determined from:

$$r = x_0 + x_1 \cdot t + x_2 \cdot t^2 \tag{3.9}$$

The coefficients can be found in Table 3.5. The equations only give values for the transverse axis of gyration, thus the moment of inertia I_{tt}.

Table 3.5: Coefficients for proportional radius of gyration according to Jensen [8]

Segment	x_0	x_1	x_2	R^2
head+neck	0.30750			
upper torso	0.34580			
lower torso	0.34610			
upper arm	0.31939	-0.11138E-2		0.14
forearm	0.29397	-0.85587E-3		0.20
hand	0.23860			
thigh	0.29090			
calf	0.29271	-0.67104E-3		0.22
foot	0.24370			
forearm+hand	0.25947	0.36529E-2	-0.16206E-3	0.18
calf+foot	0.28400			
torso	0.29960			
head/up.arm/torso	0.52813	-0.70247E-2		0.40
torso/head	0.53684	-0.70717E-2		0.43

The methods used to determine segment masses and segment moments of inertia in the combination GEBOD/CANDAT will be mentioned in Chapter 5.

4 LIMITATIONS OF GEBOD AND CANDAT

4.1 Limitations of GEBOD

The program GEBOD is based on only one survey, conducted by Snyder in 1977 [13]. From statistical data collected in the yearbook 1991 of the Dutch Central Bureau of Statistics CBS [2] an increase of 10 mm. in standing height of recruits is found in the period 1980-1990. For this reason it can be interesting to use more of the available data.

In Figure 4.1 on the next page, a comparison of the Snyder survey and GEBOD has been included. When the user chooses to use the child's age as only predictor, the standing height and weight for ages less than 5 years and higher than 15 years are not reflected accurately. To evade this problem CANDAT can be used as input. Another problem occurs, concerning standing height: the sum of the joint locations and segment lengths involved is not equal to the calculated or the specified standing height (+/- 4 %). This problem is reported and will be fixed in future versions of GEBOD.

As can be seen in Chapter 2 and Appendix B, the predicted body length dimensions calculated by using extreme values for body mass and/or standing height as predictors, do not reflect the actual data from the Snyder survey. If these 32 parameters can be determined in another way, without regression equations, the resulting model could be more accurate.

The calculation of the segment masses are not based upon an anthropometric survey. To determine the segment's mass, the volume of the ellipsoid involved is determined [1]. This ellipsoid does not reflect the real shape of the segment and the density may not be the same for all the segments. The moments of inertia are also determined from the shape and mass of the segments, thus the same limitations are present as in the calculation of the segment masses. It appears that the moments of inertia for the feet of young children can become zero, due to an internal error in the calculations.

GEBOD generates child models aged between 2 and 20 years. In CANDAT, data is included with respect to infants and children aged less than 2 years. This data can be used to generate younger child models.

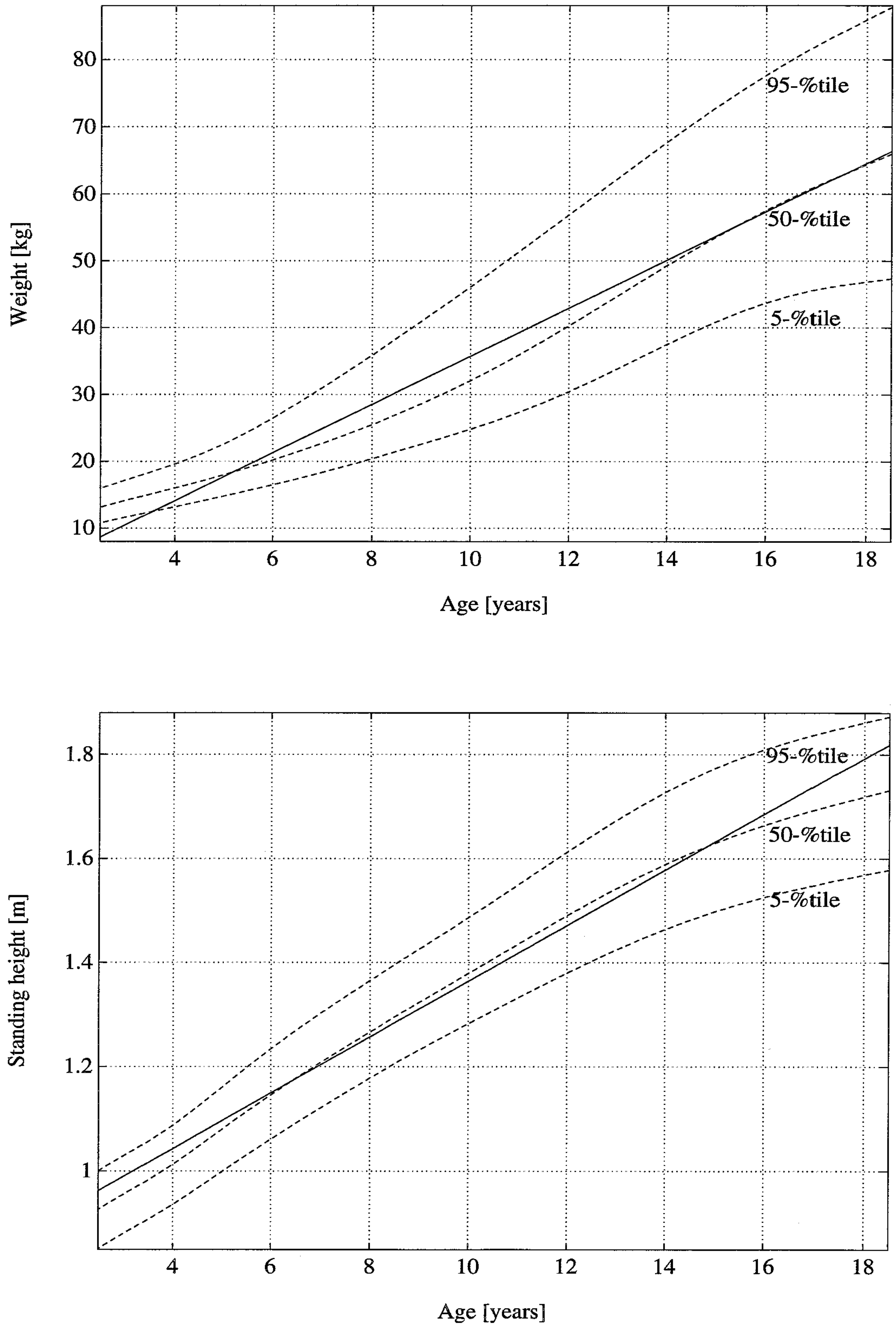

Figure 4.1: A comparison of GEBOD using predictor age and Snyder '77
—— =GEBOD regression equations --- = Snyder '77 data

4.2 Limitations of CANDAT

The database CANDAT is only a set of data, not a program. This is the reason that CANDAT can't be directly used to generate models. To generate child multibody models GEBOD can be used.

To generate a multibody model, a linkage model has to be known. Information on the joint locations is not available. GEBOD can be used to determine this joint locations.

CANDAT is a "hotchpot" of several methods to determine inertial properties and body parameters. A link between these methods on the one side and the smoothed data on the other side is not yet established. To link the separate parts of CANDAT, once more GEBOD can be used.

The definitions for the body parameters are not exactly the same for all the surveys included in CANDAT. This causes fluctuations in the combined data for a specific parameter [15]. This problem can't be solved by using GEBOD.

Another problem occurs, that can't be solved by using GEBOD. The sum of 50-percentile segments will not result in a 50-percentile standing height of a child [15]. The inaccuracy resulting from putting together segments to make a whole will be even greater when using extreme percentile values, such as 5- or 95-percentile. This is because no child is 5- or 95-percentile in all dimensions. As a result, in this study only the 50-percentile values from CANDAT shall be used.

5 COMBINATION OF GEBOD/CANDAT

5.1 Introduction

The CANDAT database contains body length dimensions and inertial properties originally collected for developing a new generation of child dummies [15]. This data, however, can also be used to generate child multibody models for MADYMO. A combination of CANDAT and GEBOD could be possible to achieve this. A possible application can be crash reconstructions, where the child involved can be modelled using the exact length dimensions and inertial properties. In this chapter, the steps that were made will be discussed. The principle of combining GEBOD with CANDAT is schematically reflected in Figure 5.1.

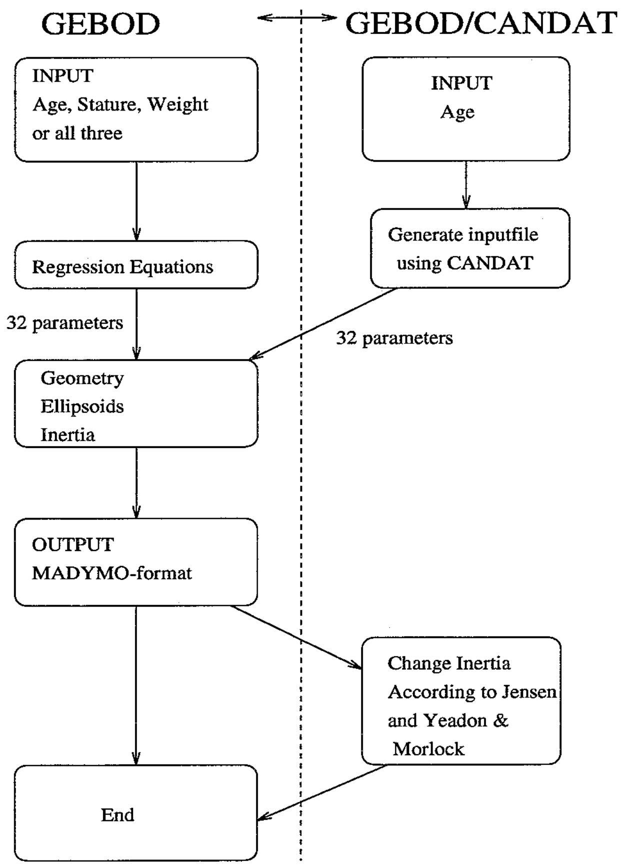

Figure 5.1: Schematic principle of combination GEBOD/CANDAT

5.2 Body length dimensions

As mentioned in Chapter 2, the program GEBOD can generate a child multibody model based upon user-supplied body dimensions [1, 4, 10]. The 32 parameters (Appendix A) can be read in from a file containing this data. The general idea is to generate this inputfile using data derived from CANDAT. For this purpose the program NICELINE [16] is used to smooth and extrapolate the combined data of the 32 parameters from several surveys. The output of this program, a formatted file, containing age, 5-percentile, 50-percentile and 95-percentile values can be read in by a program that generates an inputfile for GEBOD. The user of the combined program GEBOD/CANDAT chooses the age of the child and the program returns the matching values of the required 32 parameters.

The program uses the same parameters as the original GEBOD program. To calculate dimensions, not included in the database, the same assumptions were made as in the original GEBOD version (Appendix A).

5.3 Segment masses

In the past years there have been several surveys on the inertial properties of children (Chapter 3). Only Jensen [8] gives segment masses for children aged 4 to 20 years. The other surveys give segment masses for a smaller group, especially young infants up to 1.5 years. For children aged 0^+ to 4 years, the surveys have been compared. Some examples are included in Figure 5.2. It can be concluded that Jensen's method gives reasonable values for the segment masses, even if the regression equations have in fact not been validated for this group. The choice only to use the method presented by Jensen avoids the effect of discontinuities in the segment masses with respect to age.

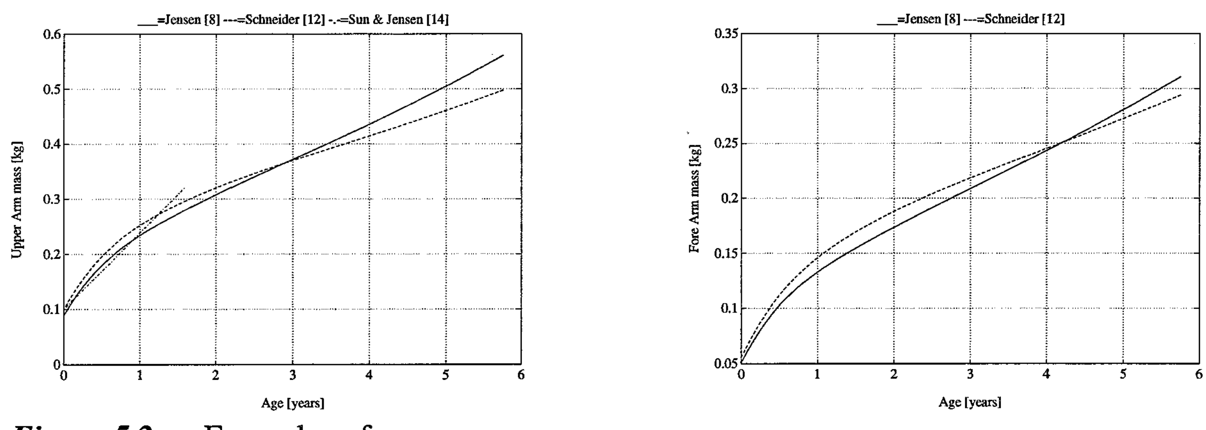

***Figure 5.2*:** Examples of surveys

The difference in segmentation between the GEBOD model and the model used by Jensen causes difficulties. The GEBOD torso is subdivided in 3 segments, while Jensen subdivided the torso in two segments, upper and lower trunk. This problem is solved using the original mass ratio of the three segments generated by GEBOD, that can be calculated after GEBOD has computed all the segment masses. The mass of the total torso according to Jensen is calculated and is then distributed over the three torso segments using this ratio, calculated from the original GEBOD model.

GEBOD determines masses of the head and neck separately. Jensen presents the mass of the head and neck as one segment. The ratio of the GEBOD head and neck mass is determined and is then used to distribute the calculated head/neck mass using Jensen.

The sum of the segment masses will still equal the total body mass, because Jensen presents the segment masses proportionally. The two actions that are taken to get the same segmentation as GEBOD, do not affect the total body mass.

The location of the Center of Gravity (CG) is not altered. The locations calculated by GEBOD do not differ from the locations known from CANDAT.

5.4 Moments of inertia

In order to calculate the segment moments of inertia in transverse direction Jensen [8] can be used. For the limbs and the head/neck, it is assumed that the moment of inertia in x-direction equals the moment of inertia in y-direction. From a comparison of the various surveys known, it can be concluded that Jensen's method gives good results, even for the group aged 0^+ to 4 years, where the equations are not validated. Some examples are included in Figure 5.3 on the next page. To determine the moment of inertia I_{tt}, first the proportional radius of gyration has to be determined using the equations mentioned in Table 3.5. The radius of gyration is found as the product of the proportional radius and the segment length known from CANDAT. The moment of inertia can be found as the product of the segment mass and the squared radius of gyration (Equation 3.8).

The segment moments of inertia in z-direction of the limbs are found using the method of Yeadon & Morlock [19] (Equation 3.3 and Table 3.4)

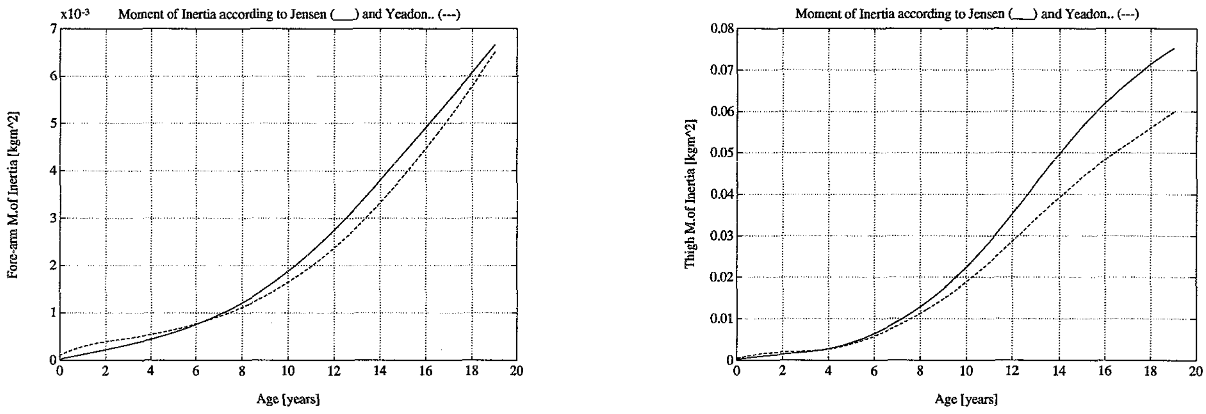

Figure 5.3: Some examples of a comparison of surveys

The moments of inertia of the subdivided torso, the neck and the head should be calculated using the method of Yeadon & Morlock (Equation 3.5, 3.6 and 3.7). The difference in segmentation between GEBOD and the model used by Jensen and Yeadon & Morlock, however, causes the same problems as in the calculation of the segment masses. GEBOD subdivides the torso in three segments, while Yeadon & Morlock do not subdivide the torso. The moments of inertia of the head and the neck are calculated as if it was one segment. This problem is solved by dividing the moments of inertia calculated by GEBOD, by the segment masses calculated by GEBOD and are then multiplied with the segment masses calculated by GEBOD/CANDAT.

As can be seen from Figure 5.1, the segment masses and segment moments of inertia are changed after GEBOD has finished its calculations and has written the MADYMO output file. The original output file is read in by a subroutine and will be written out with the changes made in the inertial properties.

5.5 Conclusions

With the new combined program child multibody models can be generated. A new option in the GEBOD interactive interface has been added: 5) GEBOD/CANDAT child. Some examples of the generated models are included in Figure 5.4 on the next page. From this visualized models, some conclusions can be drawn about the geometry of the models.

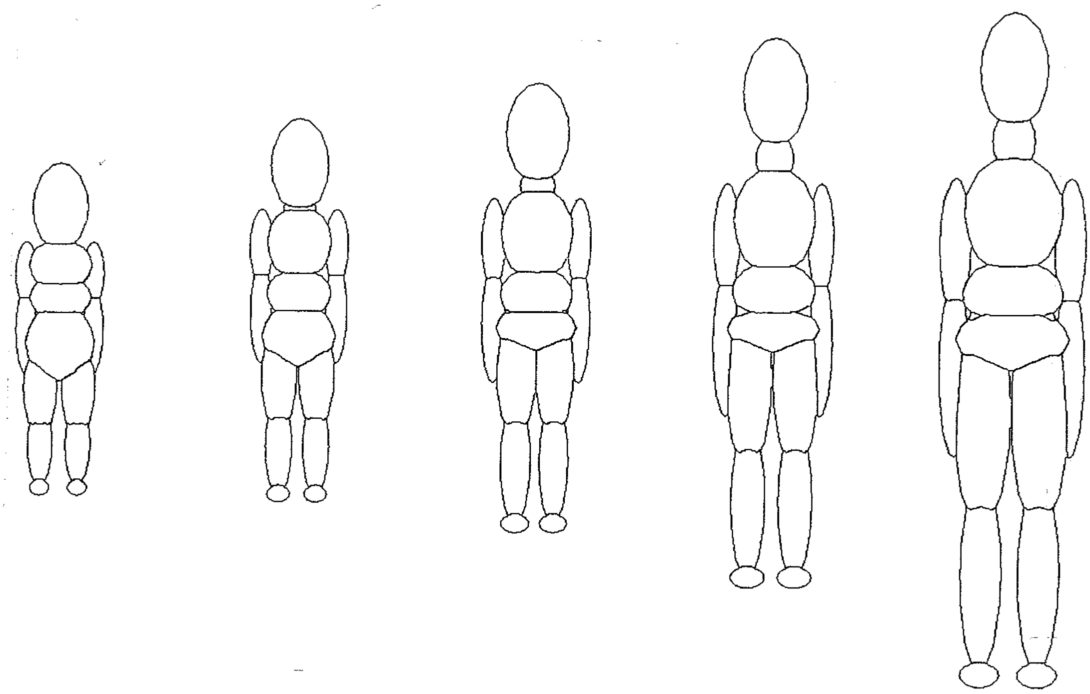

Figure 5.4: Visualization of some generated models, from left to right: 3/4 yrs., 1.5 yrs., 3 yrs., 6 yrs. and 10 yrs.

The subdivision of the torso seems to yield questionable results. For child models, representing children less than 3 years, the ratio of the upper torso segment and the spine(abdomen) segment does not equal the ratio mentioned in Chapter 2 (4:1). The calculation of this geometry is not changed in the combination of GEBOD and CANDAT, thus the reason that this problems arises has to be found in the original subroutines GEBOD uses. This problem can be avoided by including the tenth rib height in CANDAT. None of the surveys, included in CANDAT, give measurements of this parameter. It is recommended, that this parameter will be measured in future surveys, to be used in programs that generate or scale child multibody models.

The neck length of the child models is questionable. Child models, representing children aged 0^+ to 3 years, seem to have a neck which is too short or no neck at all. Child models, representing children aged 8 years and above seem to have a neck that is too long. GEBOD calculates the neck length as the difference between chin height and shoulder height [1, 4]. By evaluating some models generated by GEBOD and the combined program GEBOD/CANDAT, it became clear that the distance between the two neck pivots for child models, representing children less than 5 years, becomes zero and even negative. This is not realistic, but can be explained by looking at the definition of the neck length. The distance between the chin and the shoulders can become zero and negative when looked at real infants. It can be concluded, that the defintion of the neck length GEBOD uses, is not realistic. The neck length, however, is not measured in any of the surveys included in CANDAT, so it is recommended that the neck length will be measured in future surveys and will be used to set the distance between the upper and lower neck pivot.

6 SIMULATIONS

6.1 Description of sled test simulations

Child multibody models now can be generated by the combined program GEBOD/CANDAT. They can be compared to models generated by the original GEBOD and an interim version of the TNO P3-dummy database. From this comparison conclusions can be drawn about the sensitivity of geometry parameters and inertial properties. To do so, an ECE-R44 sled test was simulated, using various child models. The set-up of the simulation can be seen in Figure 6.1.

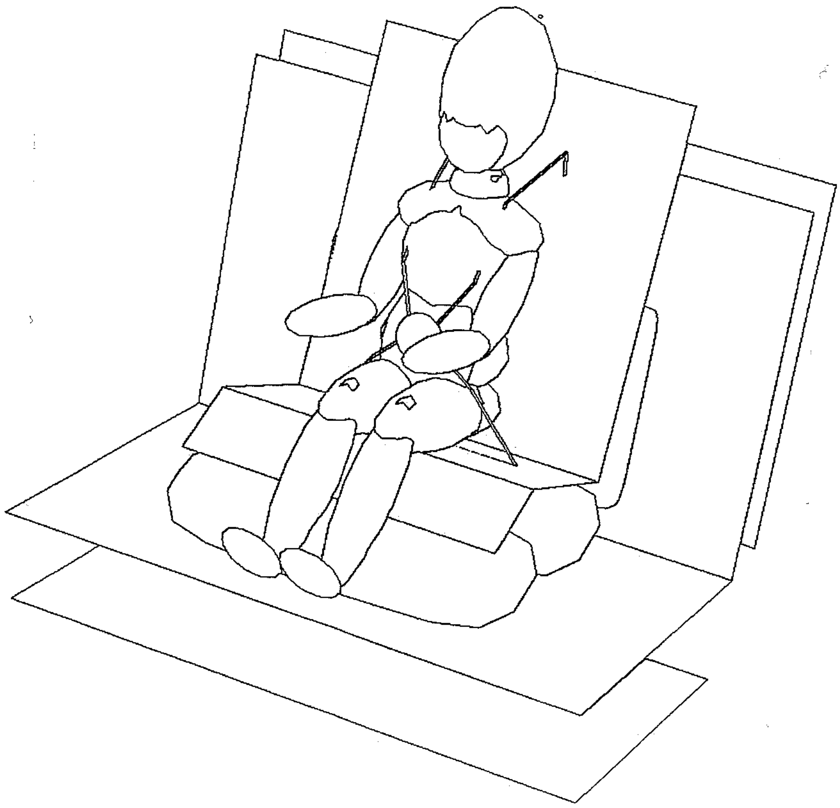

Figure 6.1: Set-up for simulations of the ECE-R44 sled test

The GEBOD/CANDAT and GEBOD models had to be modified to be used in the sled test simulations. An atlas block had to be added in order to use the same joint characteristics as the dummy database. This body is located at the position of the head-neck joint, known from the generated models. The z-position had to be adjusted (+1 cm.), to avoid locking of the flexion-torsion restraint in the neck-atlas block joint. The mass of this extra segment is subtracted from the neck segment, so the total mass still equals the mass calculated by the programs.

Because of the wasp-like shape of the torso (Figure 5.4) generated by GEBOD and GEBOD/CANDAT, an extra ellipsoid (buckle plate) was added to the abdomen segment, to avoid the belly buckle from tilting into the space between the abdomen segment and upper torso segment. The dynamic response of the models will be different if the belly buckle tilts into this space. A chin ellipsoid and a shoulder ellipsoid have been added to the GEBOD/CANDAT and GEBOD models, because the contacts between respectively the chin and upper torso and the shoulder and belts are defined in the dummy database. The chin, shoulder, and the buckle plate have no mass and moments of inertia, so they don't affect the dynamical response because of a change in the inertial properties of the combined ellipsoids.

In Appendix F the results of an ECE-R44 sled test involving a 3 year old GEBOD/CANDAT model, a 3 year old GEBOD model based upon three predictors: age, weight and standing height, and the TNO P3 dummy database are included. A comparison can be made between the GEBOD/CANDAT model, the GEBOD model based upon the same age, weight and standing height as the GEBOD/CANDAT model and the TNO P3-dummy database.

The results of a sled test involving a 3 year old GEBOD/CANDAT model, a 3 year old GEBOD model with the same weight and standing height as the GEBOD/CANDAT model and a GEBOD model based upon one predictor: an age of three years are included in Appendix G. A comparison between the 3 year old GEBOD/CANDAT model and a 3 year old GEBOD model, based only upon age can be made.

In Appendices H, I and J the results of simulations with variations in the 3 year old GEBOD/CANDAT model are carried out. First the location of the hip joint is varied. The results are included in Appendix H. The results of a variation in the location of the shoulder joints are included in Appendix I. In Appendix J the results of a variation in the neck length have been included. To illustrate these variations, figures are included in Appendices H, I and J. In Appendices F and G an overview of the presented results is included. The accelerations and torques simulated, are chosen because these are usually measured in experiments.

6.2 Results

It can be concluded from Appendix F, that the dynamical behaviour of the GEBOD model resembles that of the GEBOD/CANDAT model. The TNO P3-dummy, however, shows a different dynamical behaviour, which is especially apparent in the torques generated at the neck and lumbar spine. A point of discussion can be that the multibody model GEBOD generates is oversimplified. It is expected that the 3-year old dummy database reflects the dynamics of a human child. Thus, the models generated by GEBOD and the combined program GEBOD/CANDAT don't reflect the correct dynamics of human children.

From Chapter 4, it was concluded that child models, representing children aged less than 5 years, have an incorrect standing height and weight when they are based upon age as the only predictor. The dynamical responses of this 3-year old model are different from the CANDAT/GEBOD model and the GEBOD model, based upon the same age, weight and standing height as the CANDAT/GEBOD model, as can be seen in Appendix G.

From the variation in the location of the hip joints, included in Appendix H, it can be concluded that the vertical position (z-direction) has the greatest influence upon the dynamical responses. The responses of the model varied with 'z +2 cm.' and the model varied with 'z -2 cm.' define a corridor that restricts the other responses. It can be concluded, that the vertical position of the joint locations for multibody models have to be determined accurately.

The variation of the location of the shoulder joints, as included in Appendix I, shows almost no variation in the dynamical responses simulated. For future dummy development, it can be concluded, that an accurate location of the shoulder joints is not necessary with respect to the dynamical behaviour. For multibody models it can be concluded, that the shoulder joint locations according to GEBOD are sufficiently accurate.

It is known from injury biomechanics that, with respect to the sustained injuries in a crash environment, the acceleration and trajectory of the head CG are of great importance. The head trajectory and the torques measured in the joints, included in Appendix J, show great variances. Thus the neck length has to be determined accurately. Due to lack of information on this parameter in CANDAT, it is strongly recommended that the neck length (distance between the upper cervical vertebra C1 and the upper thoracic vertebra T1) will be measured in future surveys. A possible way to do this, is to measure the distance between T1 and the tragion (ear opening). This distance is an estimation for the real neck length, but the results will certainly be more accurate than the neck length according to GEBOD.

7 DISCUSSION

7.1 Conclusions

- In this study a combination of the program GEBOD and the database CANDAT was developed. The 32 parameters given in Appendix A can be calculated by GEBOD (2-18 years) or CANDAT (0^{+}-18 years). GEBOD uses linear regression relations to select the 32 parameters, whereas CANDAT uses a non-linear splines approximation, based upon multiple sources. The program GEBOD can be divided into three parts. One part that calculates the 32 parameters by using regression equations, a second part that calculated the geometry (joint locations), the semiaxes of the ellipsoids and the inertial properties, and the last part that makes an ATB-output file that is converted to a MADYMO output file. The first part of GEBOD, the calculation of the 32 parameters is substituted by CANDAT. Therefore the first part of the combined program GEBOD/CANDAT is expected to yield more accurate predictions, in particular for child models, aged less than 5 years.

- A point of discussion is the accuracy of these young models. The neck length is a critical parameter in a crash environment, but the definition of the neck length used by GEBOD is not realistic. The defined ratio of thorax height to abdomen height (4:1) is not found in the young models. This problem lies in the second and/or last part of GEBOD as mentioned here above.

- The combined program uses more anthropometric data on children than the original GEBOD program, which is based upon only one survey. Statistically, better models will be generated by the combined dataset.

- From the results included in Appendix F, a point of discussion arises, whether the models generated by GEBOD and the combined program are oversimplified. All the joint locations have the same anterior-posterior position (x-direction). This results in a straight spine which is not realistic, because the human spine is curved. This has influence upon the dynamics of the torso and thus upon the dynamics of the model as a whole.

- The models generated by GEBOD can be based upon three parameters: age, weight and standing height. In crash reconstructions, a model can be generated that reflect this three parameters of the child involved. With the combined program GEBOD/CANDAT, the models are based upon only one parameter: age. In reconstructions, a model that represents the child involved with the same age, standing height and weight cannot be generated. From the previous point of discussion it can be concluded that even when the model exactly reflects a child of a particular age, standing height and weight, the dynamics of this model does not reflect the dynamics of the child involved.

- The equations of the segment masses and the segment moments of inertia, used in the combined program are based upon anthropometric surveys. The equations GEBOD uses are merely based upon the shape and volume of the ellipsoids. The first method mentioned is preferred, because it is expected to be in accordance with the reality.

- The method developed by Jensen [8] to calculate segment masses and segment moments of inertia can be used in the range of 0^+ to 4 years, where the equations originally have not been validated. In this study, Jensen's method has been validated for this range.

- The locations of the segments' CG that GEBOD calculates, can be used in the child models, because they agree with the locations mentioned in the various surveys [3, 7, 8, 12, 14].

- Although more information is available describing body segment masses, centres of gravity, it is not possible to calculate values for all segments. The subdivision of the torso and the head/neck does not agree with the subdivision used in GEBOD.

- The output GEBOD generates is only a small part of a human multibody model input deck for MADYMO (Appendix E), to be used in a crash or sled test simulation. It takes much effort to build a sled test input file, e.g. the one used in Chapter 5, based upon a model generated by GEBOD.

- The vertical (z-)location of the hip joints and the neck length are critical parameters in crash simulations.

7.2 Recommendations

- The way in which the torso is divided by GEBOD into three segments is somewhat arbitrary. It is recommended, that the position of the tenth rib will be measured in future surveys, so the subdivision of the torso can be based upon measurements.

- The neck length is an important parameter in crash simulations. It is strongly recommended, that this dimension will be measured in future surveys. The distance between T1 and the tragion is a good approximation for the neck length.

- CANDAT can provide data to generate multibody models. A combination with another (newly to develop) multibody model generator can be thought of. The child multibody models that GEBOD generates seem to be too unreliable to be used in crash simulations. The development of a new or altered set-up to calculate joint locations is recommended.

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Appendices

i	Dimension name	Nr. Snyder '77	Nr. CANDAT	R^2-value
-1	Age	101	0	1.0000
0	Weight	1	1	1.0000
1	Standing Height	2	2	1.0000
2	Shoulder Height	61	10	0.9962
3	Armpit Height	62	12	0.9926
4	Waist Height	69	20	0.9843
5	Seated Height	9	3	0.9686
6	Head Length	20	66	0.4631 *
7	Head Breadth	19	67	0.5468 *
8	Head-Chin Height	25	69	0.6808 *
9	Neck Circumference	32	73	0.8882
10	Shoulder Breadth	36	8	0.9460
11	Chest Depth	SEMI(64, 63)	SEMI(13, 15)	0.8682
12	Chest Breadth	64	13	0.9034
13	Waist Depth	SEMI(67, 66)	SEMI(21, 23)	0.6063 *
14	Waist Breadth	66	21	0.8664
15	Buttock Depth	SEMI(72, 71)	SEMI(32, 304)	0.8653
16	Hip Breadth	72	32	0.9477
17	Shoulder-Elbow Length	37	51	0.9736
18	Forearm-Hand Length	41	56	0.9709
19	Biceps Circumference	39	52	0.9203
20	Elbow Circumference	43	57	0.9293
21	Forearm Circumference	43	57	0.9293
22	Wrist Circumference	45	62	0.8446
23	Knee Height	15	40	0.9714
24	Thigh Circumference	77	301	0.9015
25	Upper Leg Circumference	(77 + 81)/2	(301 + 43)/2	0.9316
26	Knee Circumference	(77 + 81)/2	(301 + 43)/2	0.9316
27	Calf Circumference	81	43	0.9380
28	Ankle Circumference	83	46	0.8741
29	Ankle Height	85	302	0.5992 *
30	Foot Breadth	87	249	0.8687
31	Foot Length	86	248	0.9380

(*) Regression equation with $R^2 \leq 0.9$

Note : SEMI(a, b) is one axis length of an ellipse; b=circumference and a=other axis length

0	1	1	1	2	2	2	10	10	10	3	3	3	66	66	66	67	67	67
	Snyder children survey 1977																	
age	weight			Stature			Shoulder height			Seated height			Head length			Head breadth		
	5th	50th	95th	5th	50th	95th	5th	50th	95th	5th	50th	95th	5th	50th	95th	5th	50th	95th
2.75	11.3	14	17.1	85.7	93.4	100.8	66.6	72	79.3	50.2	54.6	58.8	16.1	17.4	18.4	12.5	13.4	14.4
4	13.1	16	19.6	93.9	101.4	109.1	72.3	78.2	84.2	53.7	57.5	61.5	16.8	17.9	18.9	12.8	13.6	14.5
5	15.1	17.9	22.1	100.6	108.5	115.8	77.4	84.2	90.4	56	60.5	64.9	16.6	18.1	19.2	13.1	13.7	14.7
6	16.1	20	25.6	105.8	114.5	123.7	84.3	90	97.5	58.1	63.3	67.7	16.7	18.1	19	13.1	13.9	14.8
10	24.8	31.9	45.5	127.1	137.6	148.3	102.8	111	119.8	66.7	72.1	76.9	17.6	18.5	19.6	13.5	14.3	15.1
15	40.2	54.2	72.1	151.5	163.6	177.6	122.1	132.4	142	78.3	84.8	92.8	18	19.2	20.1	13.9	14.8	15.8
18.25	45.6	65.4	86.5	156.4	171.8	185.7	125.2	138.2	152.5	81.8	89.3	96.5	17.6	19.4	20.8	14.2	15.1	16.3
	GEBOD results using age, weight and stature																	
2.75	11.3	14	17.1	85.7	93.4	100.8	64.84	71.55	78.01	51.39	54.29	57.13	17.44	17.73	18.02	13.47	13.61	13.75
4	13.1	16	19.6	93.9	101.4	109.1	71.99	78.53	85.25	54.58	57.44	60.44	17.58	17.87	18.18	13.57	13.71	13.87
5	15.1	17.9	22.1	100.6	108.5	115.8	77.83	84.72	91.09	57.24	60.23	63.16	17.71	18.01	18.32	13.66	13.81	13.97
6	16.1	20	25.6	105.8	114.5	123.7	82.37	89.95	97.98	59.3	62.67	66.39	17.77	18.12	18.51	13.72	13.89	14.11
10	24.8	31.9	45.5	127.1	137.6	148.3	100.9	110.1	119.4	68.17	72.49	77.58	18.12	18.57	19.14	14.05	14.3	14.7
15	40.2	54.2	72.1	151.5	163.6	177.6	122.2	132.8	145	78.99	84.59	91.26	18.55	19.17	19.9	14.52	14.94	15.45
18.25	45.6	65.4	86.5	156.4	171.8	185.7	126.5	139.9	152	81.81	89.15	96.12	18.4	19.22	20	14.62	15.19	15.77
	Difference = (Snyder-GEBOD)/Snyder * 100%																	
2.75	*	*	*	*	*	*	2.64%	0.63%	1.63%	-2.37%	0.57%	2.84%	-8.32%	-1.90%	2.07%	-7.76%	-1.57%	4.51%
4	*	*	*	*	*	*	0.43%	-0.42%	-1.25%	-1.64%	0.10%	1.72%	-4.64%	0.17%	3.81%	-6.02%	-0.81%	4.34%
5	*	*	*	*	*	*	-0.56%	-0.62%	-0.76%	-2.21%	0.45%	2.68%	-6.69%	0.50%	4.58%	-4.27%	-0.80%	4.97%
6	*	*	*	*	*	*	2.29%	0.06%	-0.49%	-2.07%	1.00%	1.94%	-6.41%	-0.11%	2.58%	-4.73%	0.07%	4.66%
10	*	*	*	*	*	*	1.85%	0.81%	0.33%	-2.20%	-0.54%	-0.88%	-2.95%	-0.38%	2.35%	-4.07%	0.00%	2.65%
15	*	*	*	*	*	*	-0.08%	-0.30%	-2.11%	-0.88%	0.25%	1.66%	-3.06%	0.16%	1.00%	-4.46%	-0.95%	2.22%
18.25	*	*	*	*	*	*	-1.04%	-1.23%	0.33%	-0.01%	0.17%	0.39%	-4.55%	0.93%	3.85%	-2.96%	-0.60%	3.25%

69	69	69	73	73	73	21	21	21	32	32	32	51	51	51	56	56	56
head height			neck circumference			Torso breadth (waist, umbili			Torso breadth (hip, trochar			Shoulder to elbow			Forearm-hand		
5th	50th	95th	5th	50th	95th	5th	50th	95th	5th	50th	95th	5th	50th	95th	5th	50th	95th
15.7	17.3	19	21.5	23.9	25.5	14.3	16	17.9	16.5	17.9	20	16.3	18.5	20.9	21.8	24.4	27.3
16.5	17.7	19.3	21.8	24.2	26.3	14.8	17.1	18.7	16.9	18.6	20.3	18.4	20.1	22.3	24.4	26.5	29.5
16.6	17.8	19	22.8	24.8	27.1	15.8	17.8	19.5	17.6	19.5	21.1	19.7	21.8	23.9	26.2	28.4	31
16.5	18.4	19.7	23.4	25.6	27.9	15.9	18.1	21	18.6	19.9	22.2	21.1	23.2	25.5	27.6	30	33.3
18	19.5	21	24.7	27.8	31.4	18.1	21.4	26.3	22	23.7	27.5	26.2	28.5	31.6	33.2	36.5	40.4
19.1	20.7	22.8	28.5	31.7	35.4	21.7	26.1	29	27.1	31.2	34.4	31.6	34.5	37.6	39.9	44.1	48.7
19	21.3	23.7	29.7	34.3	40.2	23.5	27.5	32.9	30.6	32.4	36.3	32.3	35.5	39.6	40.9	46.1	51.9
16.97	17.4	17.82	23.39	24.06	24.79	16.28	16.81	17.42	17.14	17.75	18.43	16.86	18.55	20.17	22.23	24.44	26.57
17.31	17.73	18.18	23.79	24.49	25.32	16.78	17.35	18.06	18.04	18.68	19.45	18.69	20.33	22.02	24.45	26.6	28.83
17.61	18.04	18.49	24.2	24.91	25.84	17.27	17.84	18.67	18.84	19.49	20.36	20.18	21.92	23.52	26.27	28.54	30.67
17.81	18.12	18.88	24.43	25.34	26.57	17.61	18.37	19.47	19.47	20.31	21.46	21.35	23.26	25.28	27.66	30.18	32.87
18.75	19.42	20.26	26.15	27.68	30.42	19.79	21.19	23.86	22.78	24.22	26.83	26.12	28.43	30.77	33.47	36.56	39.87
19.94	20.86	21.96	29.08	31.92	35.52	23.41	26.16	29.67	27.69	30.39	33.82	31.6	34.26	37.33	40.22	43.93	48.27
20.09	21.31	22.49	29.9	33.88	38.07	24.86	28.75	32.89	29.87	33.67	37.67	32.76	36.14	39.19	41.45	46.22	50.61
-8.09%	-0.58%	6.21%	-8.79%	-0.67%	2.78%	-13.85%	-5.06%	2.68%	-3.88%	0.84%	7.85%	-3.44%	-0.27%	3.49%	-1.97%	-0.16%	2.67%
-4.91%	-0.17%	5.80%	-9.13%	-1.20%	3.73%	-13.38%	-1.46%	3.42%	-6.75%	-0.43%	4.19%	-1.58%	-1.14%	1.26%	-0.20%	-0.38%	2.27%
-6.08%	-1.35%	2.68%	-6.14%	-0.44%	4.65%	-9.30%	-0.22%	4.26%	-7.05%	0.05%	3.51%	-2.44%	-0.55%	1.59%	-0.27%	-0.49%	1.06%
-7.94%	1.52%	4.16%	-4.40%	1.02%	4.77%	-10.75%	-1.49%	7.29%	-4.68%	-2.06%	3.33%	-1.18%	-0.26%	0.86%	-0.22%	-0.60%	1.29%
-4.17%	0.41%	3.52%	-5.87%	0.43%	3.12%	-9.34%	0.98%	9.28%	-3.55%	-2.19%	2.44%	0.31%	0.25%	2.63%	-0.81%	-0.16%	1.31%
-4.40%	-0.77%	3.68%	-2.04%	-0.69%	-0.34%	-7.88%	-0.23%	-2.31%	-2.18%	2.60%	1.69%	0.00%	0.70%	0.72%	-0.80%	0.39%	0.88%
-5.74%	-0.05%	5.11%	-0.67%	1.22%	5.30%	-5.79%	-4.55%	0.03%	2.39%	-3.92%	-3.77%	-1.42%	-1.80%	1.04%	-1.34%	-0.26%	2.49%

57	57	57	62	62	62	40	40	40	46	46	46	249	249	249	248	248	248
Elbow circumference			Wrist circumference			Knee height			Ankle circumference			Foot breadth			Foot Lenght		
5th	50th	95th	5th	50th	95th	5th	50th	95th	5th	50th	95th	5th	50th	95th	5th	50th	95th
13.9	15.7	17.4	9.9	11.2	12.7	23.7	26.9	30.6	13.1	14.8	16.4	5.3	6	6.8	13	14.7	16.4
14.3	15.8	17.7	10.2	11.4	13	26.7	29.8	33.1	13.4	14.8	16.7	5.8	6.4	7.1	14.6	16	17.7
15	16.4	18.5	10.5	11.6	13.2	29.2	32.2	35.6	13.9	15.3	17	6	6.8	7.5	15.5	17	18.4
15.1	16.9	19.1	10.9	12.1	13.3	31.5	34.7	38.3	14.5	15.8	17.6	6.3	7	7.8	16.2	17.8	19.8
17.4	19.4	22.7	11.6	13.3	16.1	39.4	43.5	48.1	15.6	18.5	21.4	7.3	8.3	9.1	19.6	21.6	23.6
20.5	23.4	27.5	13.5	15.2	17	46.7	51.5	56.8	18.5	21.2	23.4	8.3	9.5	10.9	22.4	24.7	27.5
21.2	26.2	29.8	13.1	16.4	19.3	47.2	52.8	60	18.8	22	26.1	8.5	9.9	11.6	22.2	25.2	28.7
15.15	15.76	16.44	11.04	11.44	11.88	24.39	27.43	30.35	14.3	14.92	15.58	5.817	6.219	6.617	13.68	15	16.26
15.52	16.17	16.95	11.23	11.65	12.14	27.34	30.3	33.32	14.68	15.32	16.05	6.155	6.552	6.975	14.86	16.15	17.47
15.91	16.56	17.45	11.43	11.85	12.4	29.74	32.86	35.71	15.05	15.7	16.5	6.441	6.856	7.275	15.84	17.19	18.44
16.13	16.98	18.16	11.52	12.06	12.78	31.56	34.98	38.56	15.26	16.07	17.11	6.643	7.117	7.651	16.55	18.04	19.62
17.82	19.29	22	12.33	13.22	14.78	38.92	42.98	46.97	16.68	17.96	20.08	7.573	8.199	8.985	19.5	21.3	23.14
20.75	23.54	27.1	13.76	15.38	17.42	47.1	51.64	56.85	18.95	21.17	23.95	8.741	9.597	10.63	22.81	24.89	27.29
21.64	25.57	29.72	14.05	16.31	18.67	48.11	53.84	58.92	19.45	22.53	25.72	8.911	10.05	11.15	23.08	25.72	28.11
-8.99%	-0.38%	5.52%	-11.52%	-2.14%	6.46%	-2.91%	-1.97%	0.82%	-9.16%	-0.81%	5.00%	-9.75%	-3.65%	2.69%	-5.23%	-2.04%	0.85%
-8.53%	-2.34%	4.24%	-10.10%	-2.19%	6.62%	-2.40%	-1.68%	-0.66%	-9.55%	-3.51%	3.89%	-6.12%	-2.37%	1.76%	-1.78%	-0.94%	1.30%
-6.07%	-0.98%	5.68%	-8.86%	-2.16%	6.06%	-1.85%	-2.05%	-0.31%	-8.27%	-2.61%	2.94%	-7.35%	-0.82%	3.00%	-2.19%	-1.12%	-0.22%
-6.82%	-0.47%	4.92%	-5.69%	0.33%	3.91%	-0.19%	-0.81%	-0.68%	-5.24%	-1.71%	2.78%	-5.44%	-1.67%	1.91%	-2.16%	-1.35%	0.91%
-2.41%	0.57%	3.08%	-6.29%	0.60%	8.20%	1.22%	1.20%	2.35%	-6.92%	2.92%	6.17%	-3.74%	1.22%	1.26%	0.51%	1.39%	1.95%
-1.22%	-0.60%	1.45%	-1.93%	-1.18%	-2.47%	-0.86%	-0.27%	-0.09%	-2.43%	0.14%	-2.35%	-5.31%	-1.02%	2.48%	-1.83%	-0.77%	0.76%
-2.08%	2.40%	0.27%	-7.25%	0.55%	3.26%	-1.93%	-1.97%	1.80%	-3.46%	-2.41%	1.46%	-4.84%	-1.52%	3.88%	-3.96%	-2.06%	2.06%

The equations for calculating the semiaxes of the contact ellipsoids are :

Segment	X semiaxis	Y semiaxis	Z semiaxis
Pelvis	$DD_{15}/2$	$DD_{16}/2$	$(DD_4+DD_5-DD_1-0.1(DD_2-DD_4))/2$
Abdomen	$DD_{13}/2$	$DD_{14}/2$	$(DD_2-DD_4)/10 + DD_9/\pi$
Thorax	$DD_{11}/2$	$DD_{12}/2$	$.45*(DD_2-DD_4)$
Neck	$DD_9/2\pi$	$DD_9/2\pi$	$(DD_1-DD_8-DD_2+DD_9/2\pi)/2$
Head	$DD_6/2$	$DD_7/2$	$(DD_8+DD_9/2\pi/2$
Thigh	$(DD_{24}+DD_{25})/4\pi$	$(DD_{24}+DD_{25})/4\pi$	$(DD_1-DD_5-DD_{23}+(DD_{24}+DD_{26})/\pi)/2$
Calf	$DD_{27}/2\pi$	$DD_{27}/2\pi$	$(DD_{23}-DD_{29}+DD_{28}/2\pi)/2$
Foot	$DD_{29}/2$	$DD_{30}/2$	$DD_{31}/2$
Upper arm	$DD_{19}/2\pi$	$DD_{19}/2\pi$	$DD_{17}/2$
Forearm	$DD_{21}/2\pi$	$DD_{21}/2\pi$	$DD_{18}/2$

With DD_i the i-th parameter according to GEBOD (Appendix A).

The equations for calculating the joint locations were first laid out in a global coordinate system, with origin on the floor (Figure 5). A spherical joint concept was developed to determine joint locations relative to limb segments :

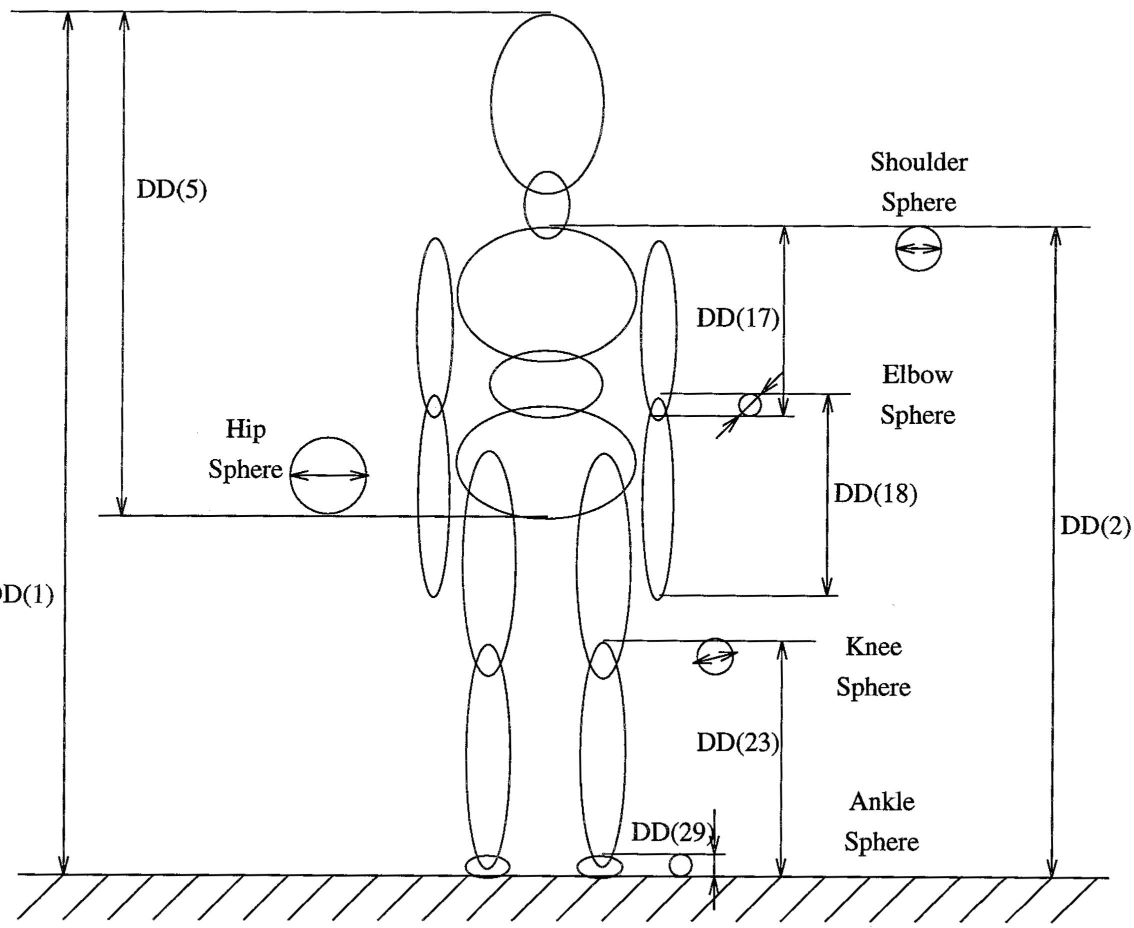


Figure 5: Joint locations in a global coordinate system

Radii of these spheres are as follows :

Shoulder Sphere	: $DD_{19}/2\pi$
Elbow Sphere	: $DD_{20}/2\pi$
Hip Sphere	: $DD_{24}/2\pi$
Knee Sphere	: $DD_{26}/2\pi$
Ankle Sphere	: $DD_{28}/2\pi$

From these global locations the expressions for local reference system coordinates were determined. With these equations the joint locations relative to the two connecting segments can be calculated (necessary for ATB-format). The results will be converted into MADYMO-format, which is different from these results. Some examples of the original equations to calculate z-coordinates, used for ATB-output are :

Joint	Relative to	Z
Abdomen-Pelvis	Pelvis	$(DD_1-DD_5-DD_4+(DD_2-DD_4)/10)\ /2$
	Abdomen	$(DD_2-DD_4)/10$
Thorax-Abdomen	Abdomen	$-(DD_2-DD_4)\ /10$
	Thorax	$9*(DD_2-DD_4)\ /20$
Neck-Thorax	Thorax	$-9*(DD_2-DD_4)\ /20$
	Neck	$(DD_1-DD_8-DD_2-DD_9/2\pi)\ /2$
Head-Neck	Neck	$-(DD_1-DD_8-DD_2-DD_9/2\pi)\ /2$
	Head	$(DD_8+DD_9/2\pi)\ /2$
Right Shoulder	Thorax	$-(DD_2-DD_3-DD_{19}/2\pi)$
	Right upper arm	$-(DD_{17}-DD_{20}/\pi)\ /2$
Left Hip	Pelvis	$(DD_4-(DD_2-DD_4)/10-DD_1+DD5-DD_{24}/\pi)\ /2$
	Left thigh	$-(DD_1-DD_5-DD_{23}+DD_{26}/\pi)\ /2$
Left Knee	Left thigh	$(DD_1-DD_5-DD_{23}+DD_{24}/\pi)\ /2$
	Left calf	$-(DD_{23}-DD_{29}+DD_{28}/2\pi-DD_{26}/2\pi)\ /2$
Left Ankle	Left calf	$(DD_{23}-DD_{29}-DD_{28}/2\pi)\ /2$
	Left foot	$-(DD_{31}-DD_{28}/\pi)\ /2$

...

With DD_i the i-th parameter according to GEBOD (Appendix A). The results are the coordinates relative to the segment Center of Gravity.

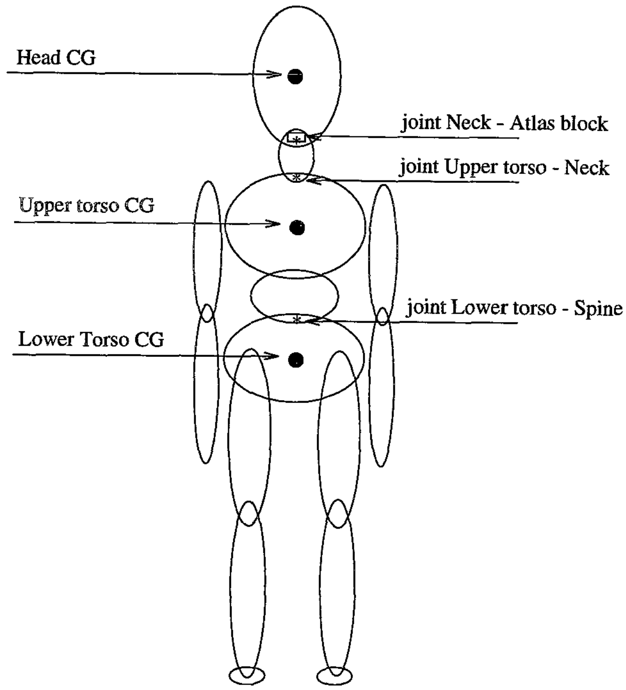
```
SYSTEM
Example output GEBOD/CANDAT
CONFIGURATION
 5  4  3  2  1
 7  6  3  2  1
 9  8  3  2  1
12 11 10  1
15 14 13  1
-999
GEOMETRY
   0.000E+00  0.000E+00  0.000E+00   +
   0.000E+00  0.000E+00 -0.500E-01   LOWER TORSO
   0.000E+00  0.000E+00  0.000E+00   +
   0.000E+00  0.000E+00  0.300E-01   SPINE
   0.000E+00  0.000E+00  0.600E-01   +
   0.000E+00  0.000E+00  0.110E+00   UPPER TORSO
   0.000E+00  0.000E+00  0.230E+00   +
   0.000E+00  0.000E+00  0.100E-01   NECK
   0.000E+00  0.000E+00  0.200E-01   +
   0.000E+00  0.000E+00  0.110E+00   HEAD
   0.000E+00  0.100E+00  0.180E+00   +
   0.000E+00  0.000E+00 -0.800E-01   UPPER ARM LEFT
   0.000E+00  0.000E+00 -0.170E+00   +
   0.000E+00  0.000E+00 -0.120E+00   LOWER ARM LEFT
   0.000E+00 -0.100E+00  0.180E+00   +
   0.000E+00  0.000E+00 -0.800E-01   UPPER ARM RIGHT
   0.000E+00  0.000E+00 -0.170E+00   +
   0.000E+00  0.000E+00 -0.120E+00   LOWER ARM RIGHT
   0.000E+00  0.500E-01 -0.400E-01   +
   0.000E+00  0.000E+00 -0.100E+00   UPPER LEG LEFT
   0.000E+00  0.000E+00 -0.230E+00   +
   0.000E+00  0.000E+00 -0.110E+00   LOWER LEG LEFT
   0.000E+00  0.000E+00 -0.240E+00   +
   0.600E-01  0.000E+00 -0.200E-01   FOOT LEFT
   0.000E+00 -0.500E-01 -0.400E-01   +
   0.000E+00  0.000E+00 -0.100E+00   UPPER LEG RIGHT
   0.000E+00  0.000E+00 -0.230E+00   +
   0.000E+00  0.000E+00 -0.110E+00   LOWER LEG RIGHT
   0.000E+00  0.000E+00 -0.240E+00   +
   0.600E-01  0.000E+00 -0.200E-01   FOOT RIGHT
-999
INERTIA
 0.225E+01  0.678E-02  0.486E-02  0.860E-02
 0.111E+01  0.233E-02  0.182E-02  0.375E-02
 0.482E+01  0.248E-01  0.245E-01  0.164E-01
 0.356E+00  0.304E-03  0.304E-03  0.203E-03
 0.318E+01  0.111E-01  0.134E-01  0.831E-02
 0.511E+00  0.251E-02  0.251E-02  0.198E-03
 0.458E+00  0.284E-02  0.284E-02  0.170E-03
 0.511E+00  0.251E-02  0.251E-02  0.198E-03
 0.458E+00  0.284E-02  0.284E-02  0.170E-03
 0.153E+01  0.163E-01  0.163E-01  0.314E-02
 0.784E+00  0.647E-02  0.647E-02  0.664E-03
 0.359E+00  0.645E-03  0.645E-03  0.413E-03
 0.153E+01  0.163E-01  0.163E-01  0.314E-02
 0.784E+00  0.647E-02  0.647E-02  0.664E-03
 0.359E+00  0.645E-03  0.645E-03  0.413E-03
-999
ELLIPSOIDS
 1      0.770E-01  0.990E-01  0.450E-01   +
        0.000E+00  0.000E+00 -0.490E-01   2.   0  0  0.   LOWER TORSO
 2      0.750E-01  0.860E-01  0.650E-01   +
        0.000E+00  0.000E+00  0.300E-01   2.   0  0  0.   SPINE
 3      0.880E-01  0.860E-01  0.113E+00   +
        0.000E+00  0.000E+00  0.121E+00   2.   0  0  0.   UPPER TORSO
```

```
  4     0.400E-01  0.400E-01  0.500E-01   +
        0.000E+00  0.000E+00  0.100E-01   2.   0  0  0.   NECK
  5     0.910E-01  0.690E-01  0.113E+00   +
        0.000E+00  0.000E+00  0.110E+00   2.   0  0  0.   HEAD
  6     0.280E-01  0.280E-01  0.112E+00   +
        0.000E+00  0.000E+00 -0.800E-01   2.   0  0  0.   UPPER ARM LEFT
  7     0.260E-01  0.260E-01  0.144E+00   +
        0.000E+00  0.000E+00 -0.120E+00   2.   0  0  0.   LOWER ARM LEFT
  8     0.280E-01  0.280E-01  0.112E+00   +
        0.000E+00  0.000E+00 -0.800E-01   2.   0  0  0.   UPPER ARM RIGHT
  9     0.260E-01  0.260E-01  0.144E+00   +
        0.000E+00  0.000E+00 -0.120E+00   2.   0  0  0.   LOWER ARM RIGHT
 10     0.470E-01  0.470E-01  0.177E+00   +
        0.000E+00  0.000E+00 -0.100E+00   2.   0  0  0.   UPPER LEG LEFT
 11     0.360E-01  0.360E-01  0.157E+00   +
        0.000E+00  0.000E+00 -0.110E+00   2.   0  0  0.   LOWER LEG LEFT
 12     0.870E-01  0.350E-01  0.220E-01   +
        0.820E-01  0.000E+00 -0.200E-01   2.   0  0  0.   FOOT LEFT
 13     0.470E-01  0.470E-01  0.177E+00   +
        0.000E+00  0.000E+00 -0.100E+00   2.   0  0  0.   UPPER LEG RIGHT
 14     0.360E-01  0.360E-01  0.157E+00   +
        0.000E+00  0.000E+00 -0.110E+00   2.   0  0  0.   LOWER LEG RIGHT
 15     0.870E-01  0.350E-01  0.220E-01   +
        0.820E-01  0.000E+00 -0.200E-01   2.   0  0  0.   FOOT RIGHT
-999
END SYSTEM
```

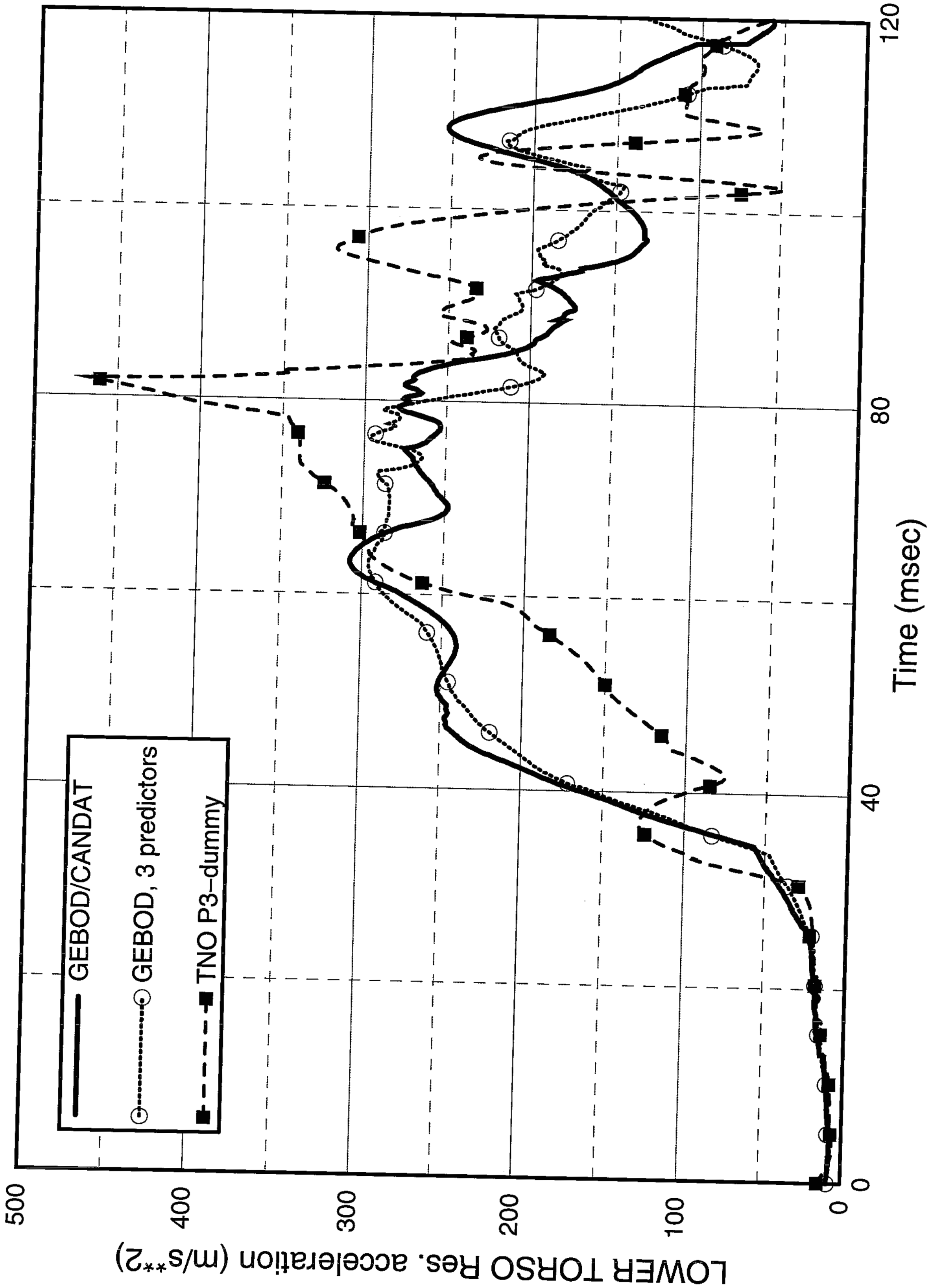
Appendix F

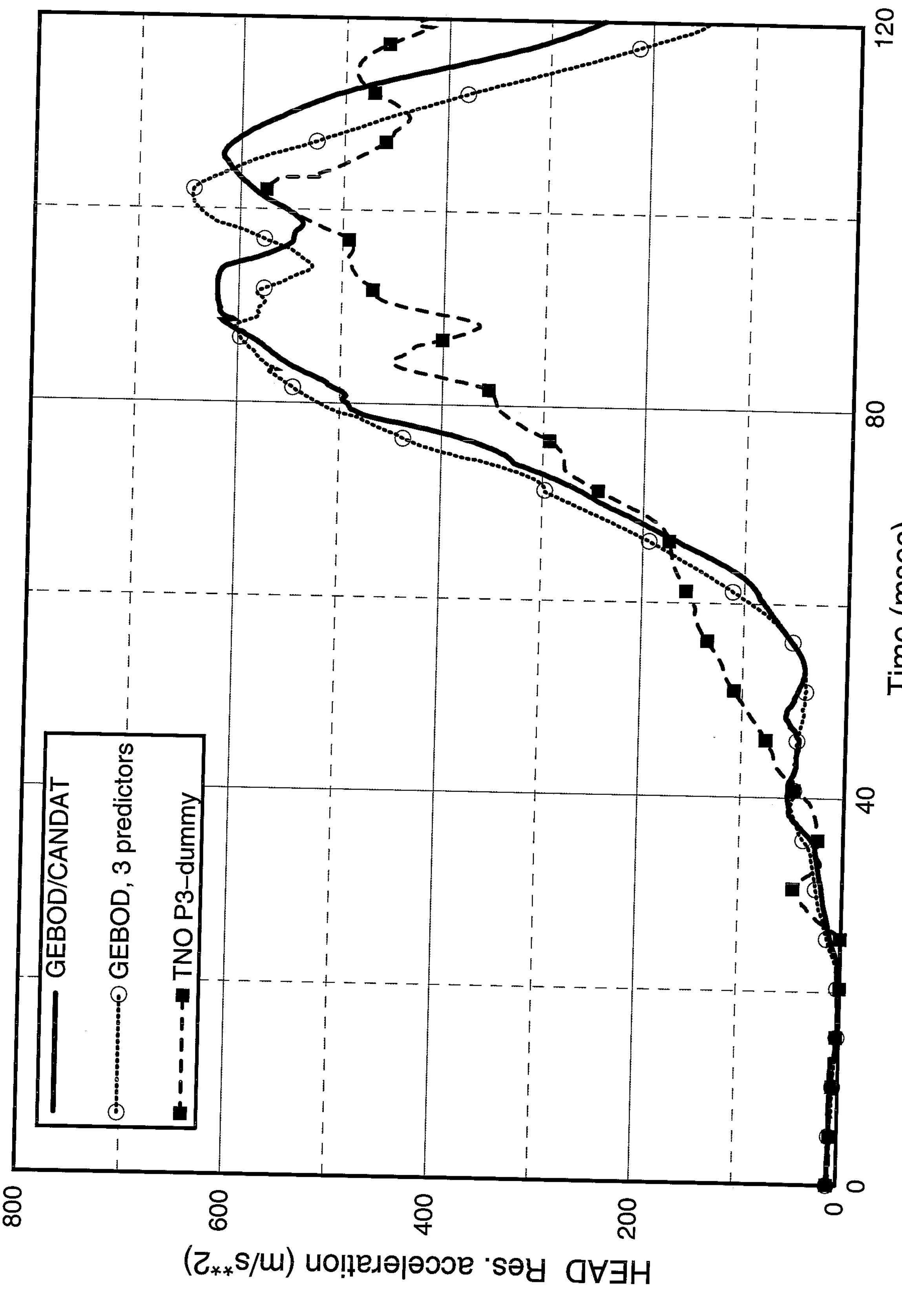
On the following pages, the results of 3 simulations of a sled test involving a restrained 3 year old child are included. The simulations consist of :

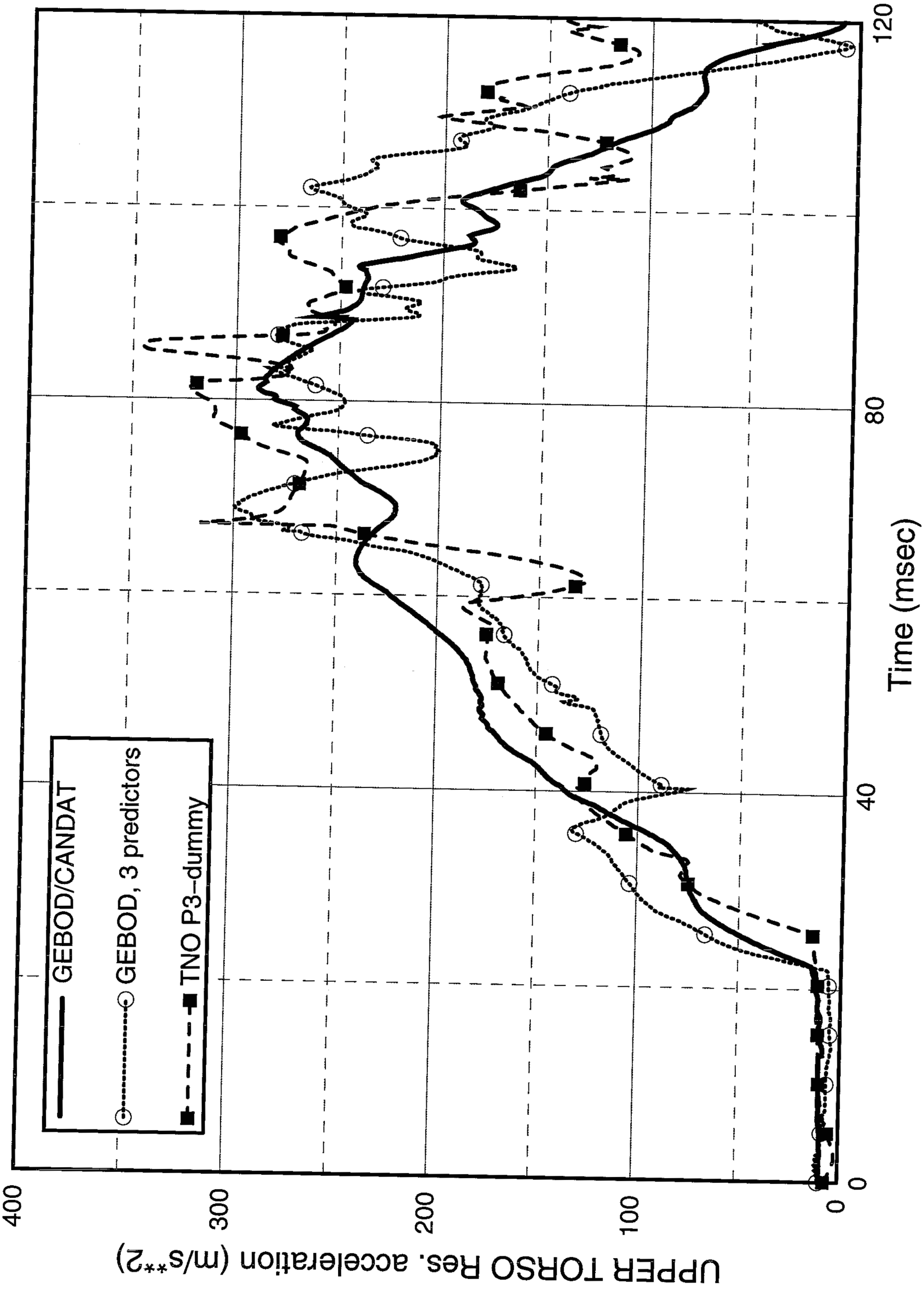
1) A 3-year old child multibody model generated by the combination GEBOD/CANDAT.
2) A 3-year old child multibody model generated by GEBOD using all three predictors : age, weight and standing height.
3) The TNO P3-dummy database.

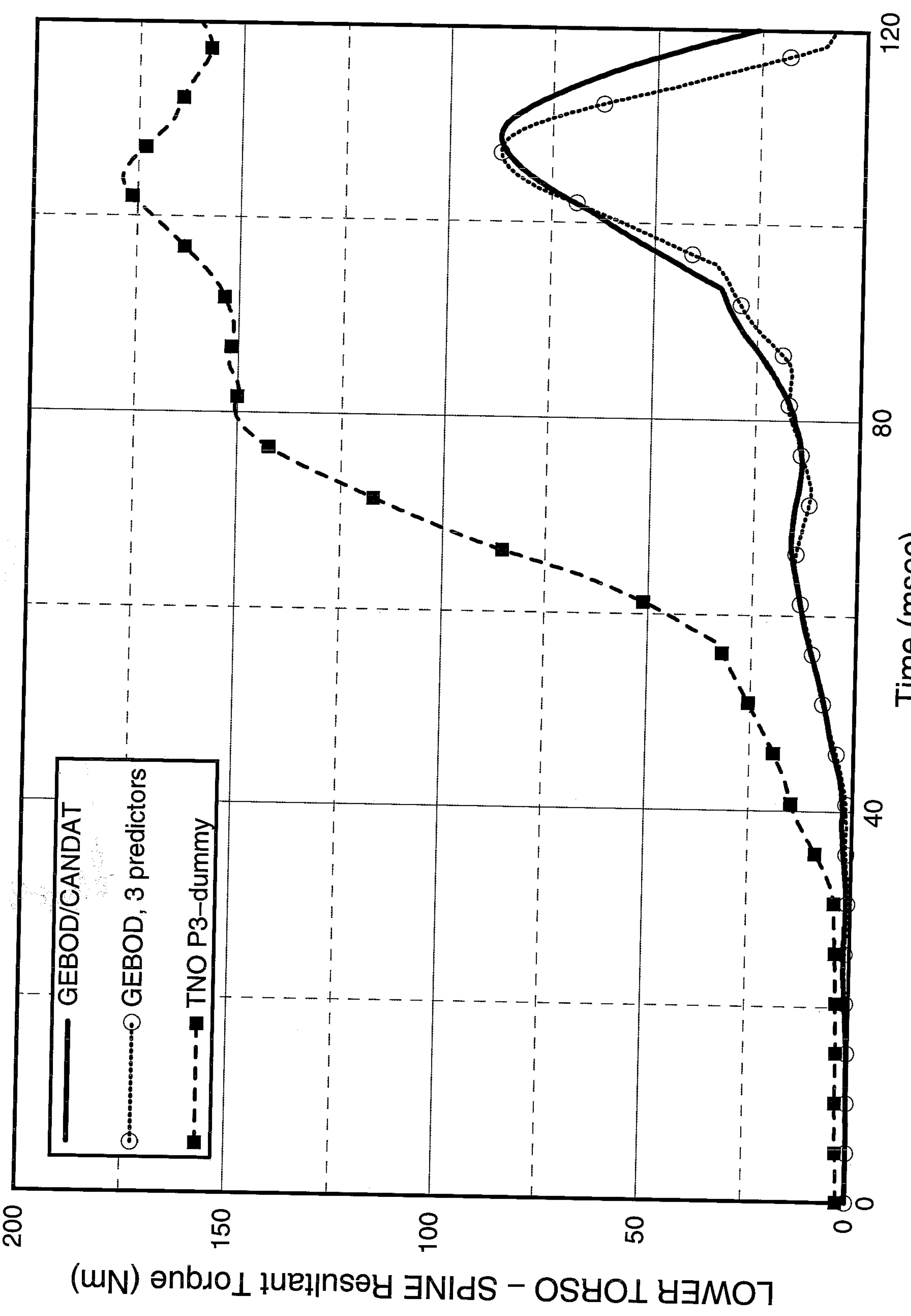


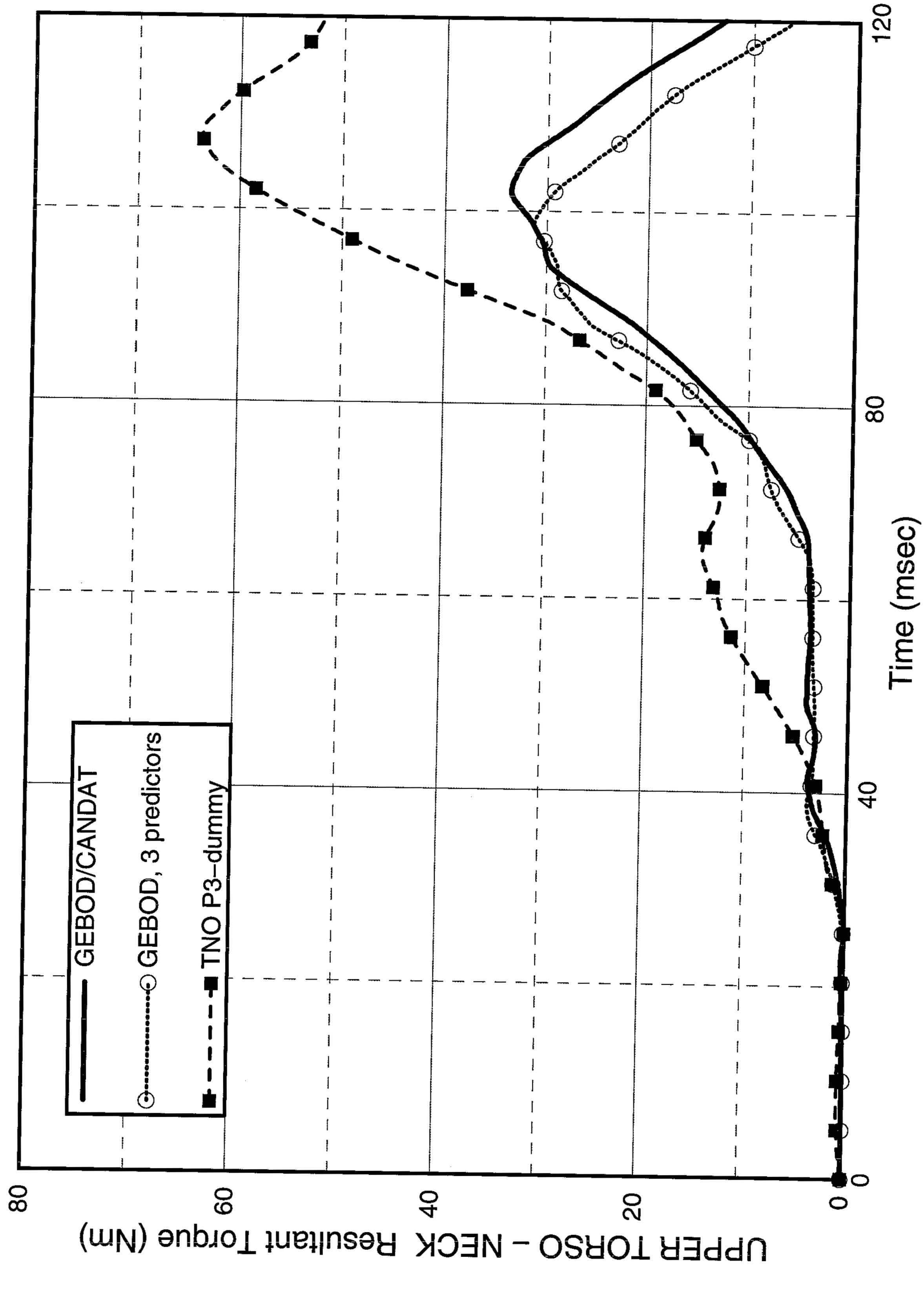
The following results are presented :

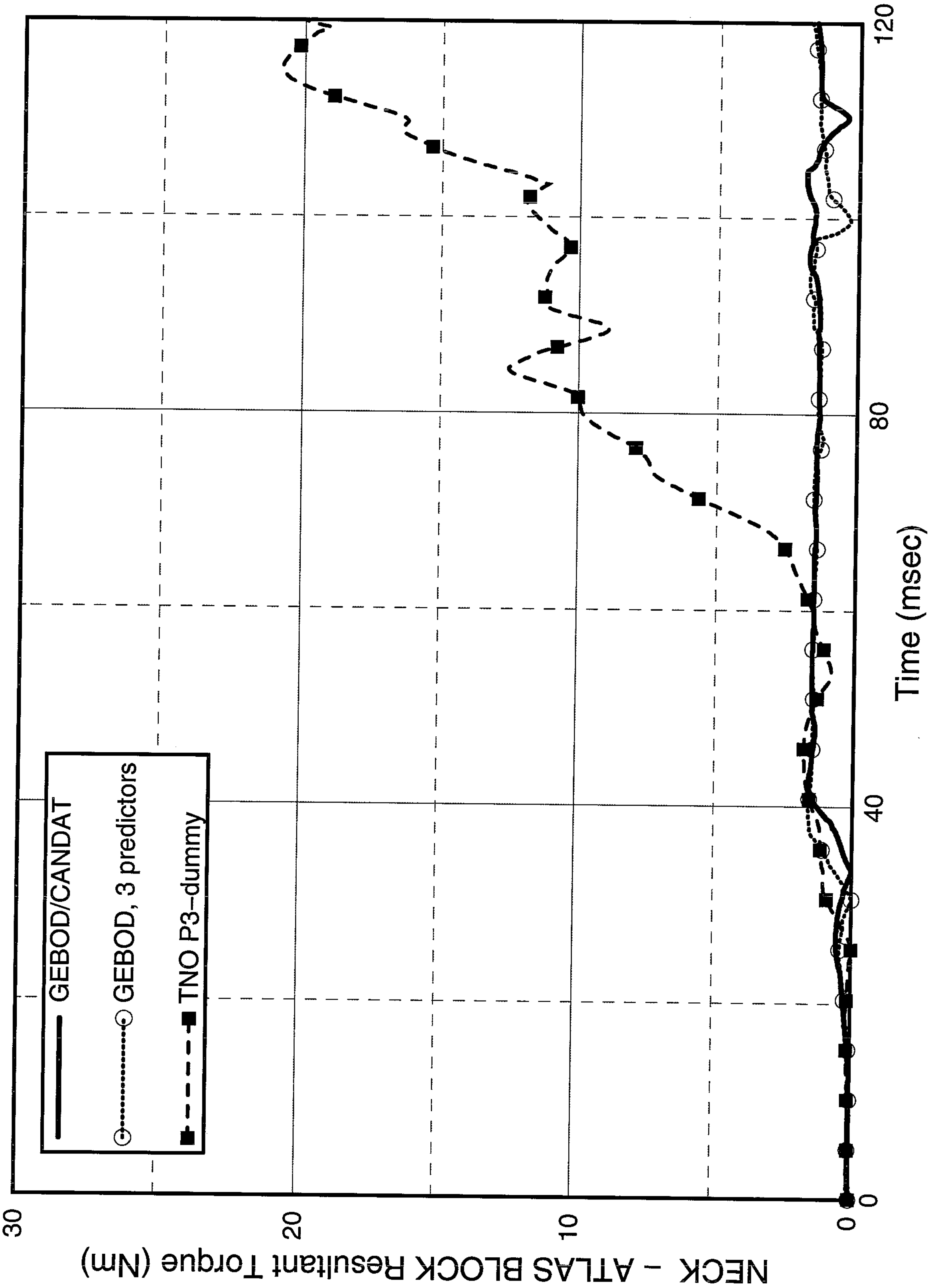

GEBOD/CANDAT
GEBOD, 3 predictors
TNO P3–dummy
Time (msec)
0
40
80
120
LOWER TORSO Res. acceleration (m/s**2)
0
100
200
300
400
500

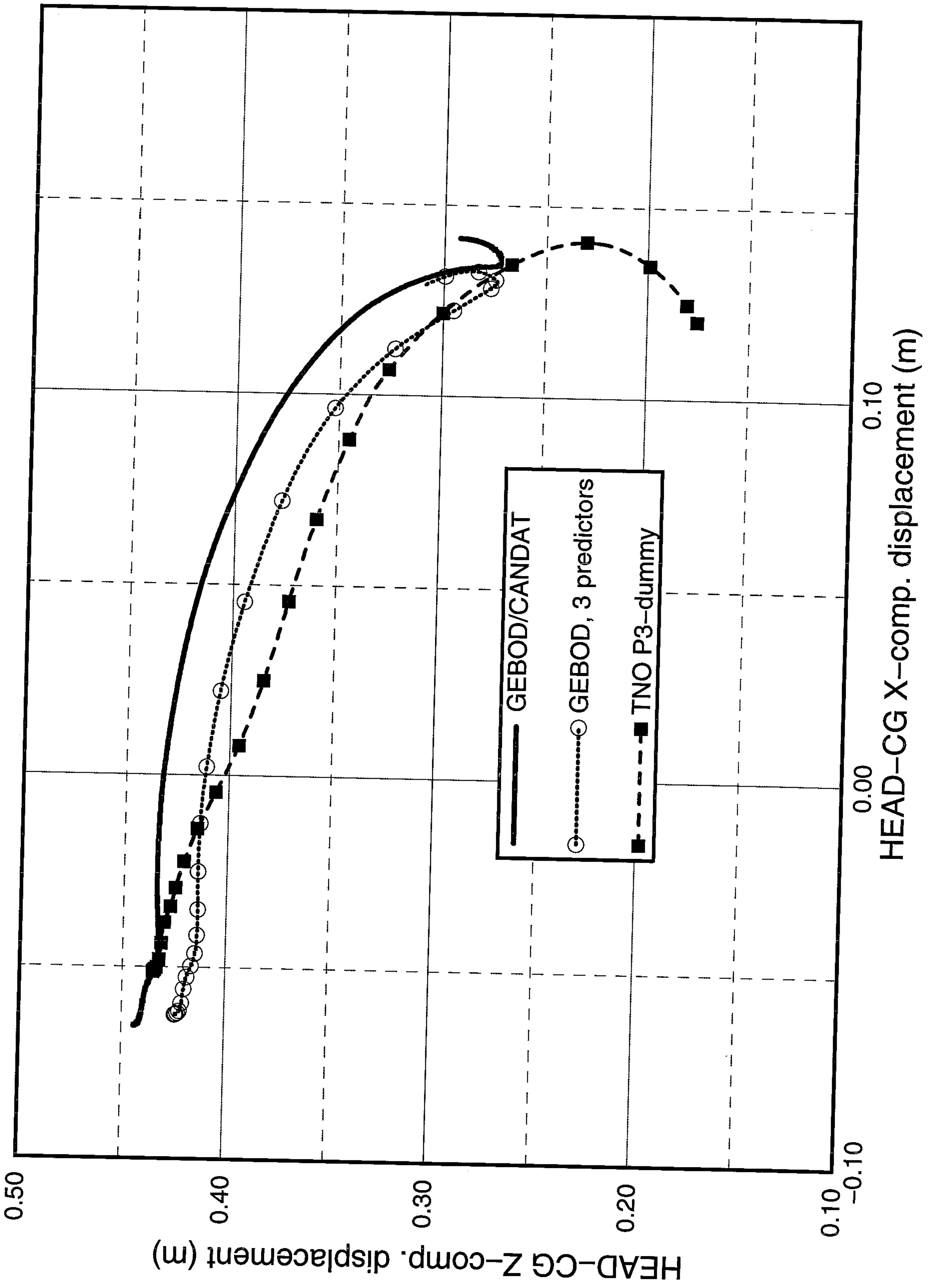

GEBOD/CANDAT
GEBOD, 3 predictors
TNO P3-dummy
HEAD Res. acceleration (m/s**2)
Time (msec)
0
200
400
600
800
0
40
80
120


GEBOD/CANDAT
GEBOD, 3 predictors
TNO P3–dummy
UPPER TORSO Res. acceleration (m/s**2)
Time (msec)
0
100
200
300
400
0
40
80
120


GEBOD/CANDAT
GEBOD, 3 predictors
TNO P3–dummy
Time (msec)
LOWER TORSO – SPINE Resultant Torque (Nm)
0
40
80
120
0
50
100
150
200


GEBOD/CANDAT
GEBOD, 3 predictors
TNO P3–dummy
0
40
80
120
Time (msec)
0
20
40
60
80
UPPER TORSO – NECK Resultant Torque (Nm)

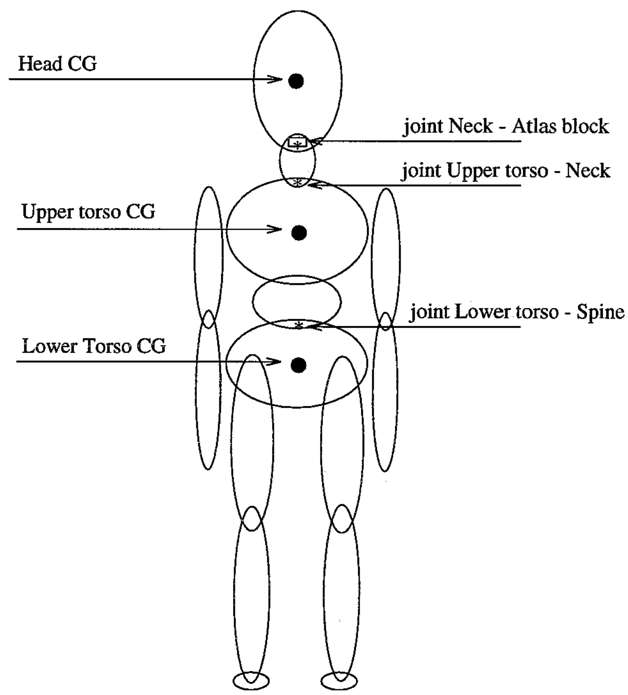

GEBOD/CANDAT
GEBOD, 3 predictors
TNO P3–dummy
Time (msec)
NECK – ATLAS BLOCK Resultant Torque (Nm)
0
40
80
120
0
10
20
30


GEBOD/CANDAT
GEBOD, 3 predictors
TNO P3–dummy
HEAD–CG X–comp. displacement (m)
HEAD–CG Z–comp. displacement (m)
–0.10
0.00
0.10
0.10
0.20
0.30
0.40
0.50

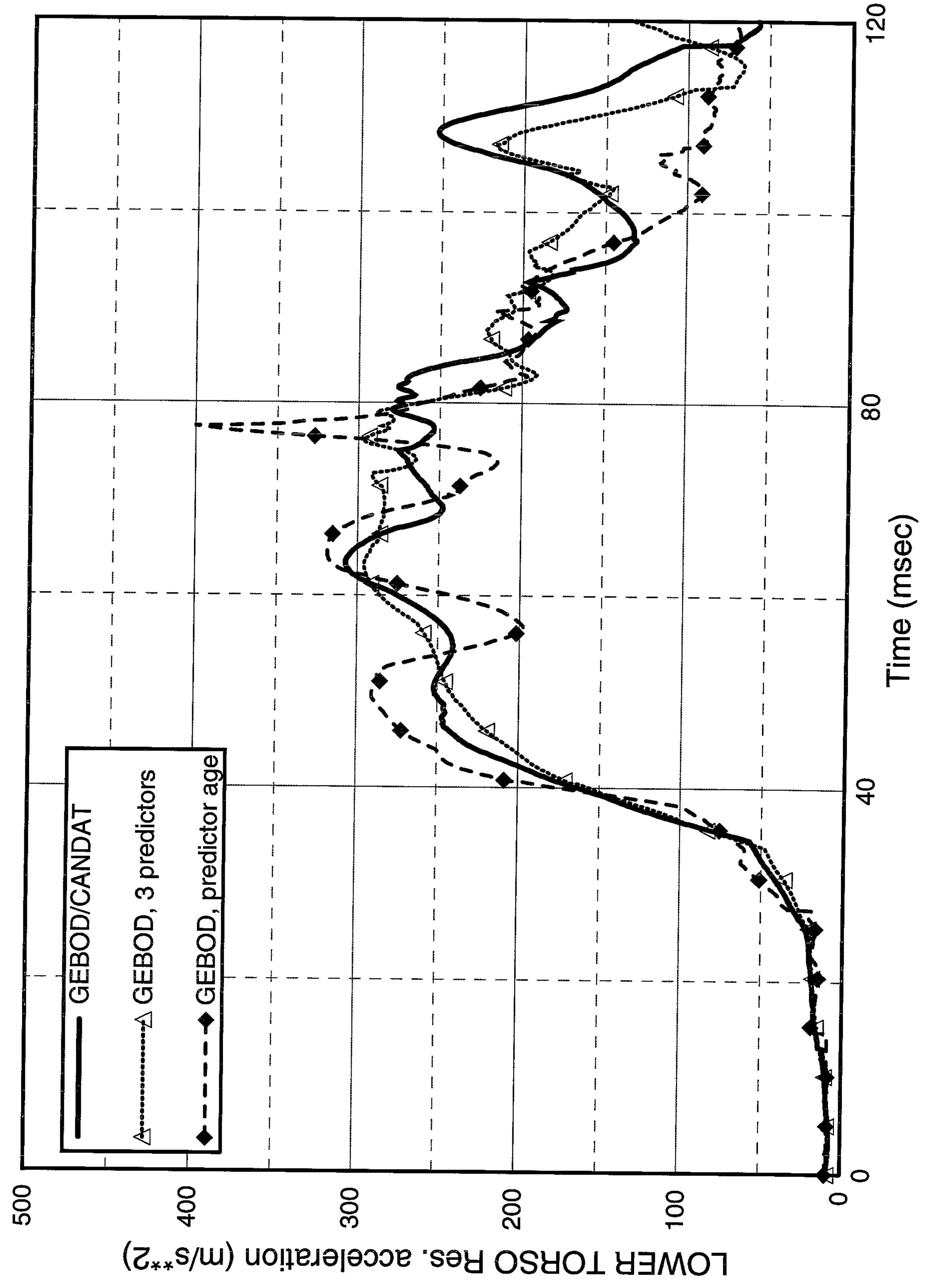
Appendix G

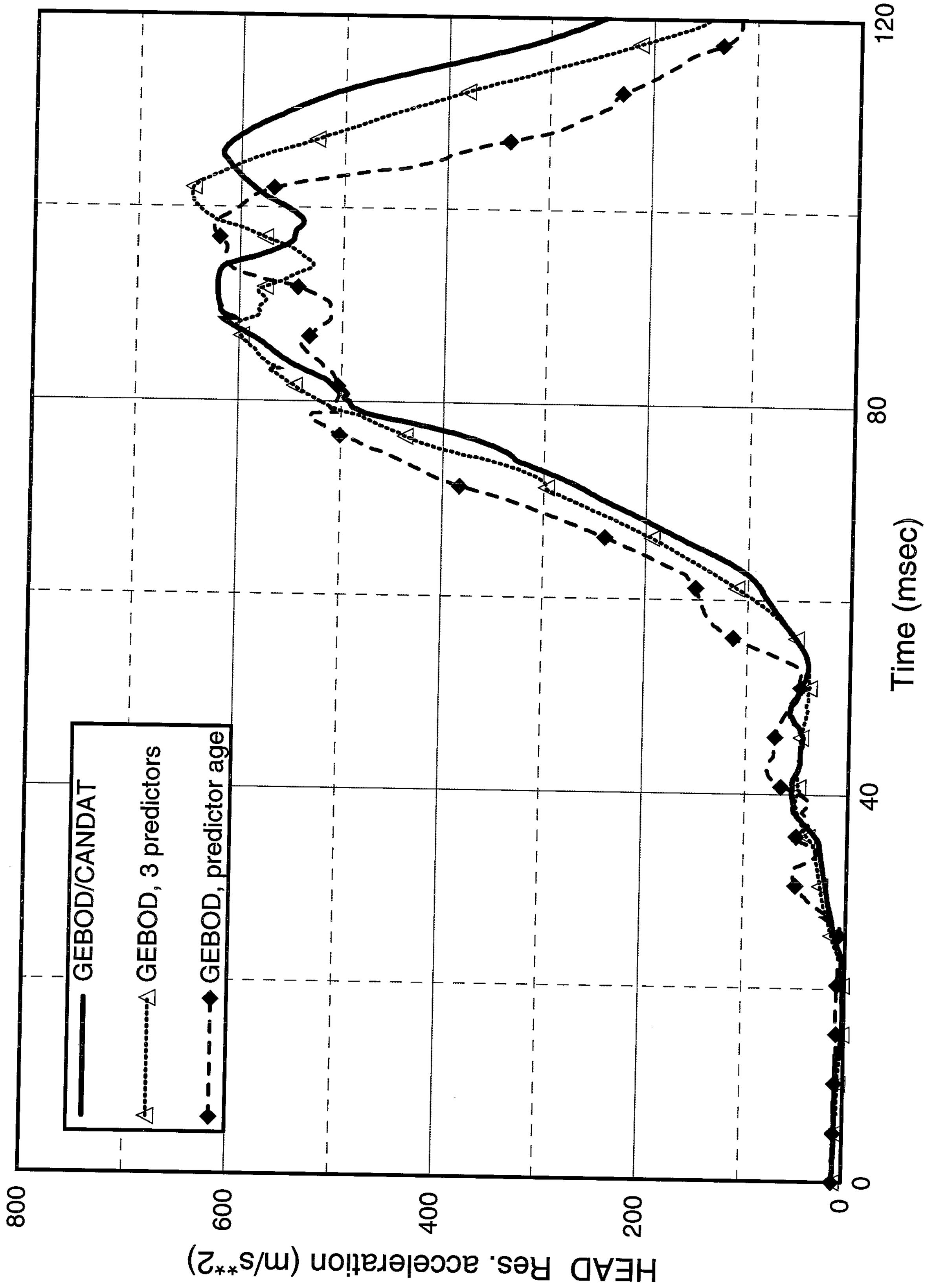
On the following pages, the results of 3 simulations of a sled test involving a restrained 3 year old child are included. The simulations consist of :

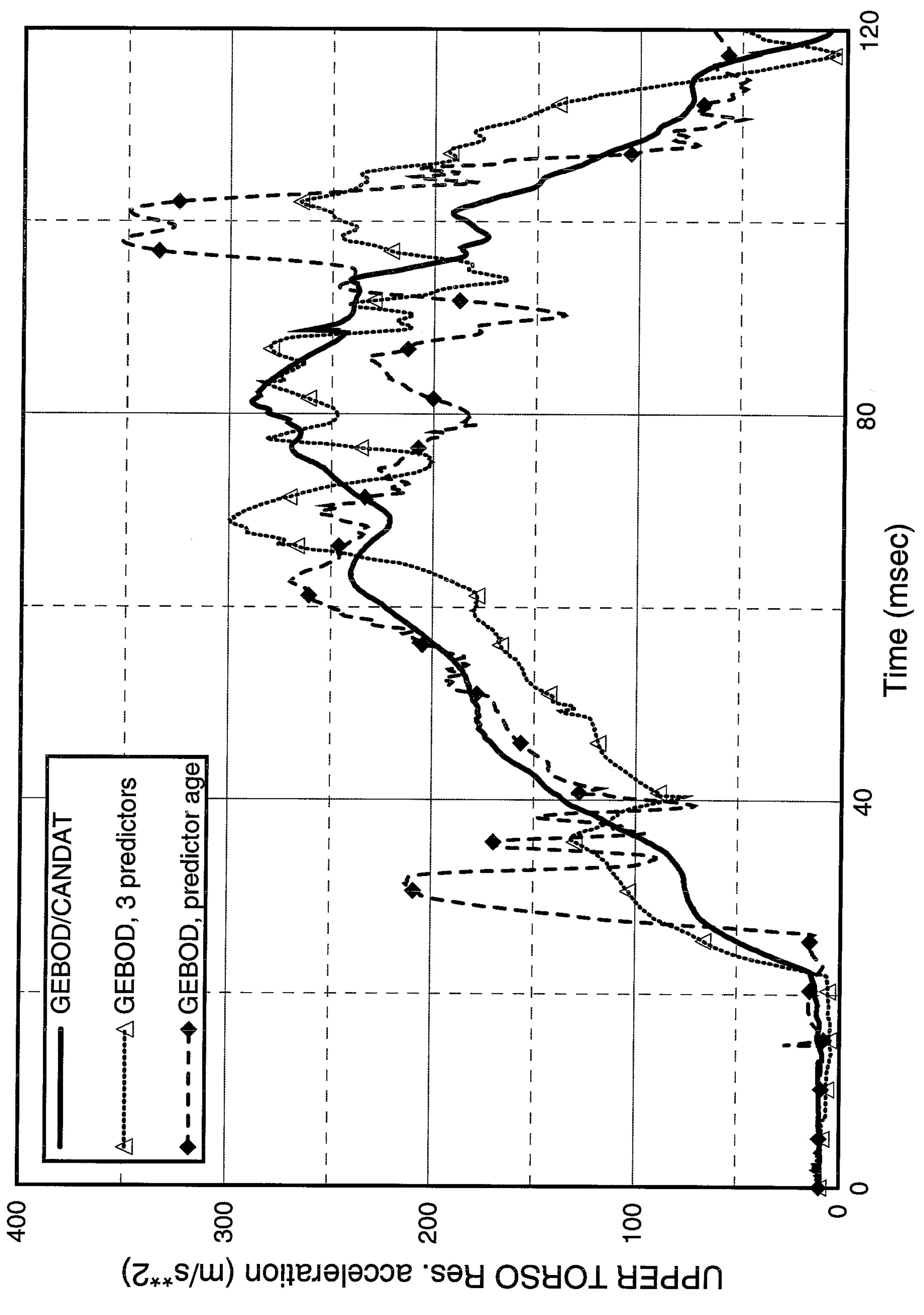
1) A 3-year old child multibody model generated by the combination GEBOD/CANDAT.
2) A 3-year old child multibody model generated by GEBOD using all three predictors : age, weight and standing height.
3) A 3-year old child multibody model generated by GEBOD using age as only predictor.

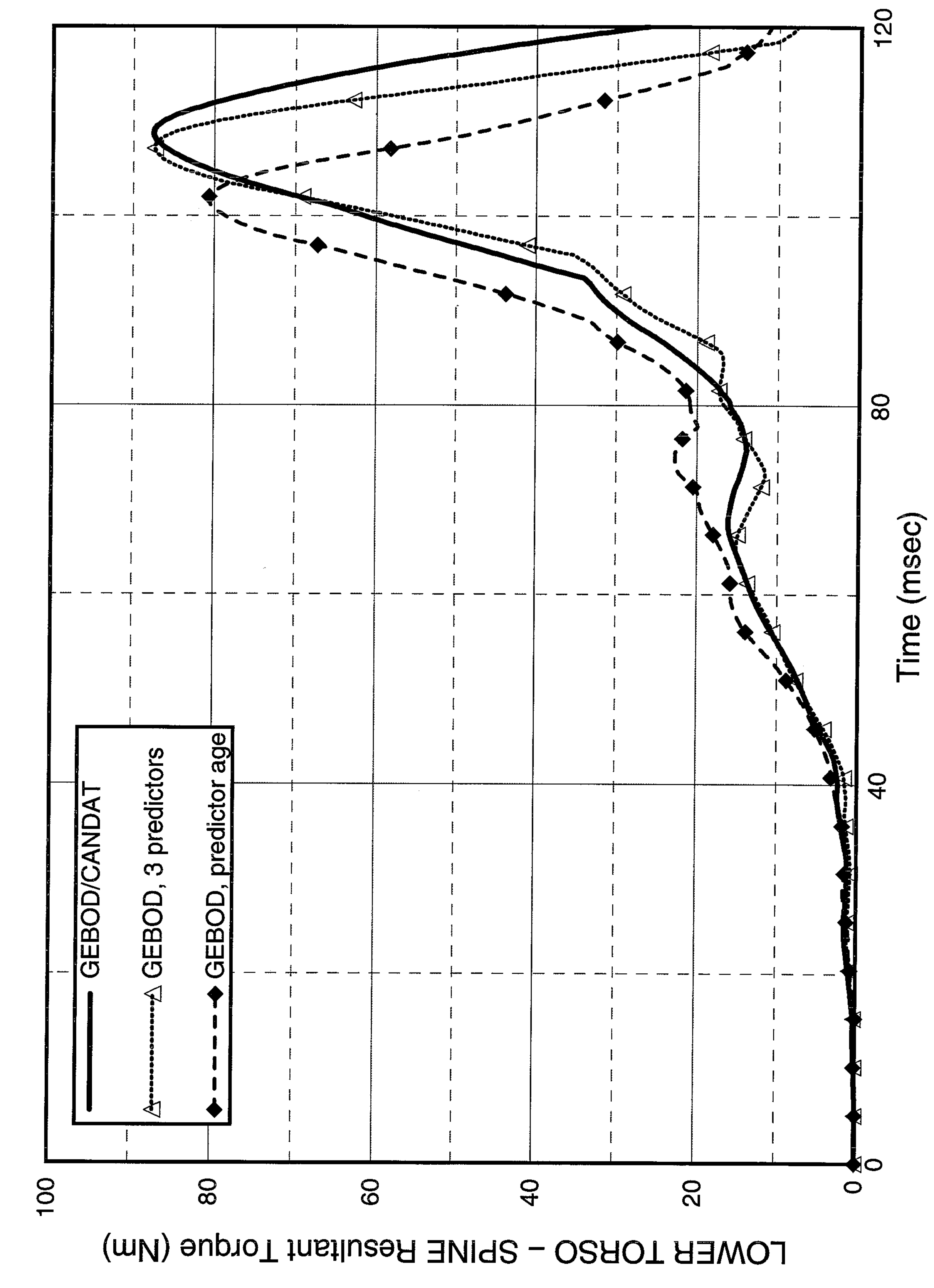


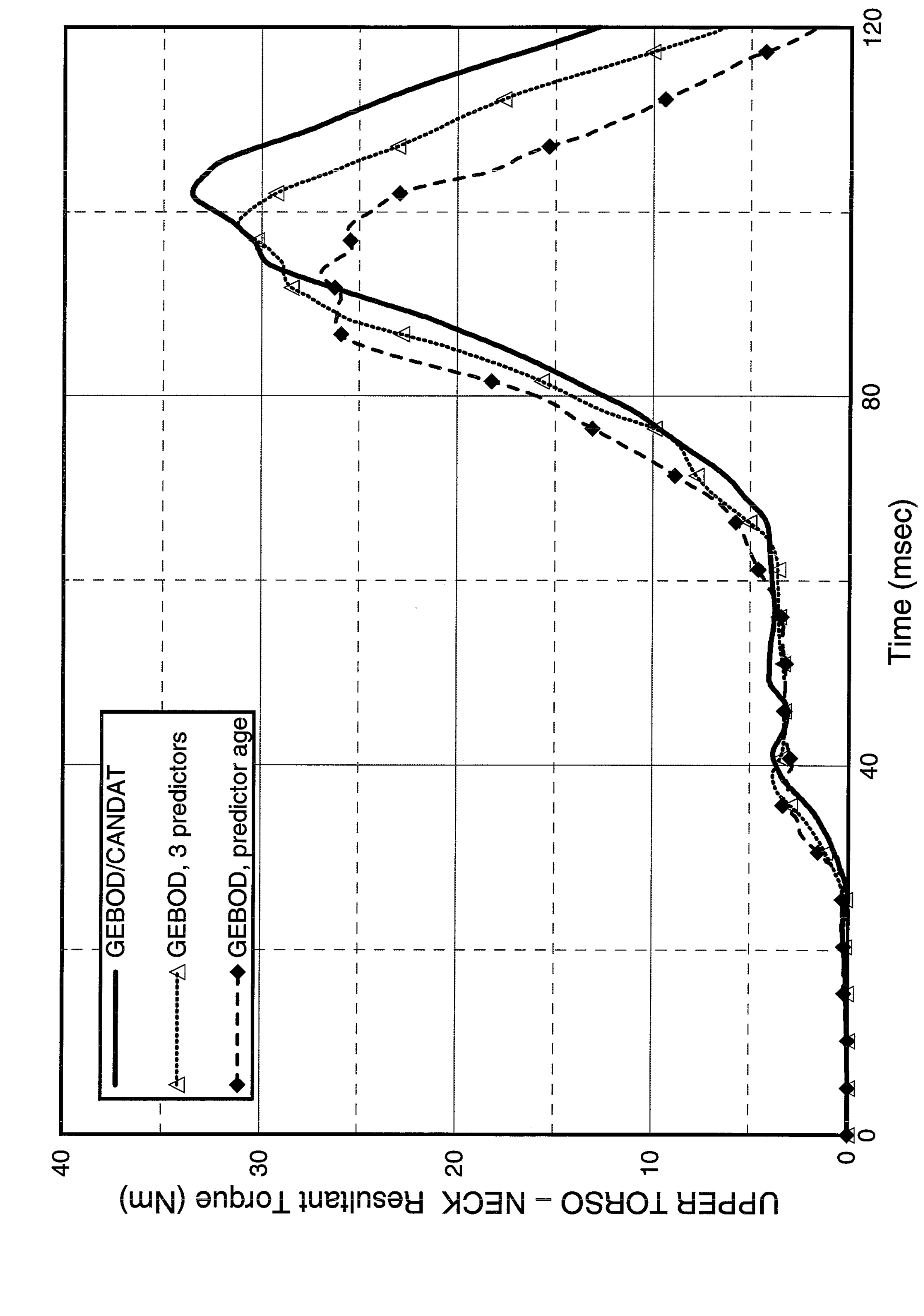
The following results are presented :

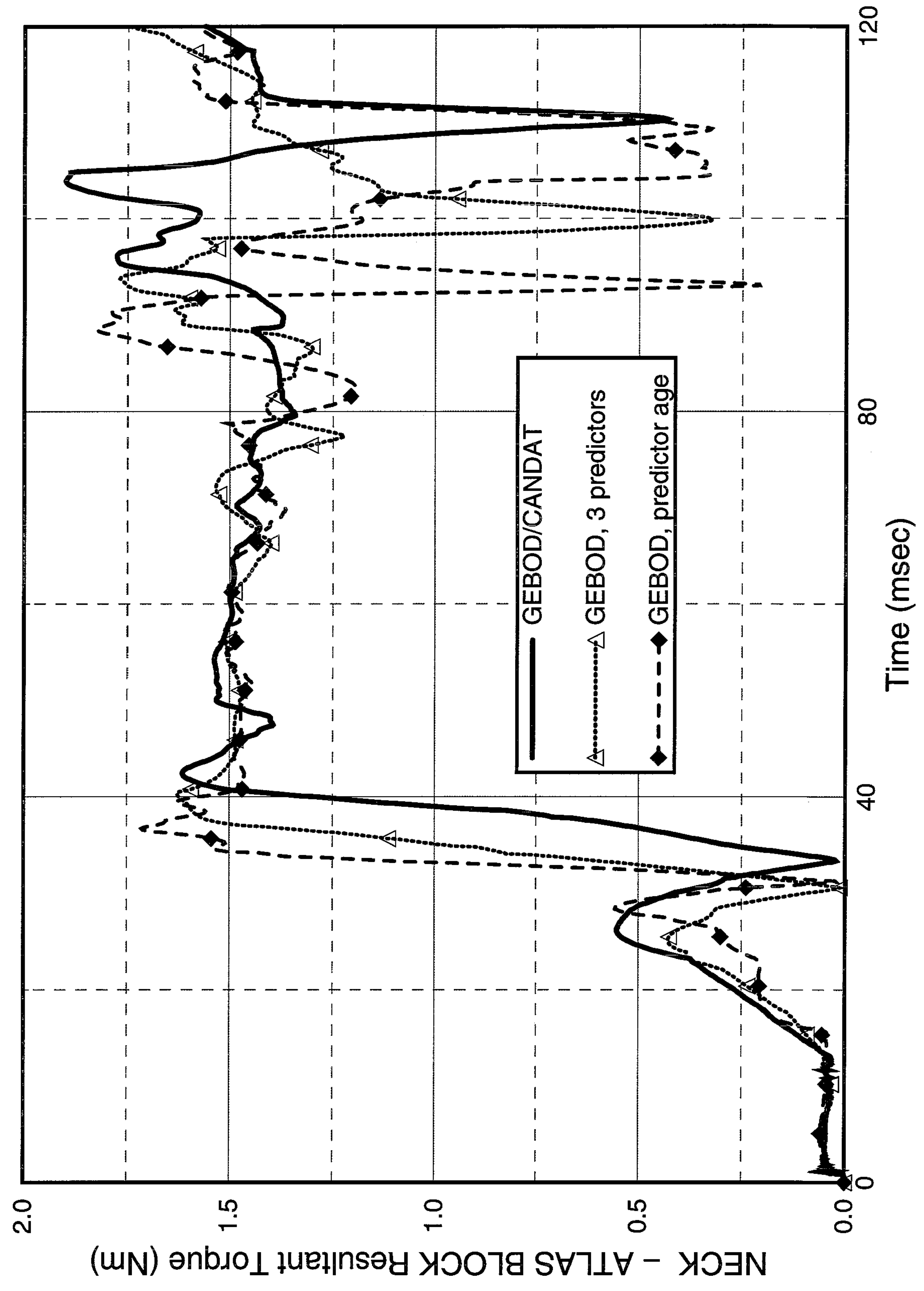

GEBOD/CANDAT
GEBOD, 3 predictors
GEBOD, predictor age
LOWER TORSO Res. acceleration (m/s**2)
Time (msec)
0
100
200
300
400
500
0
40
80
120

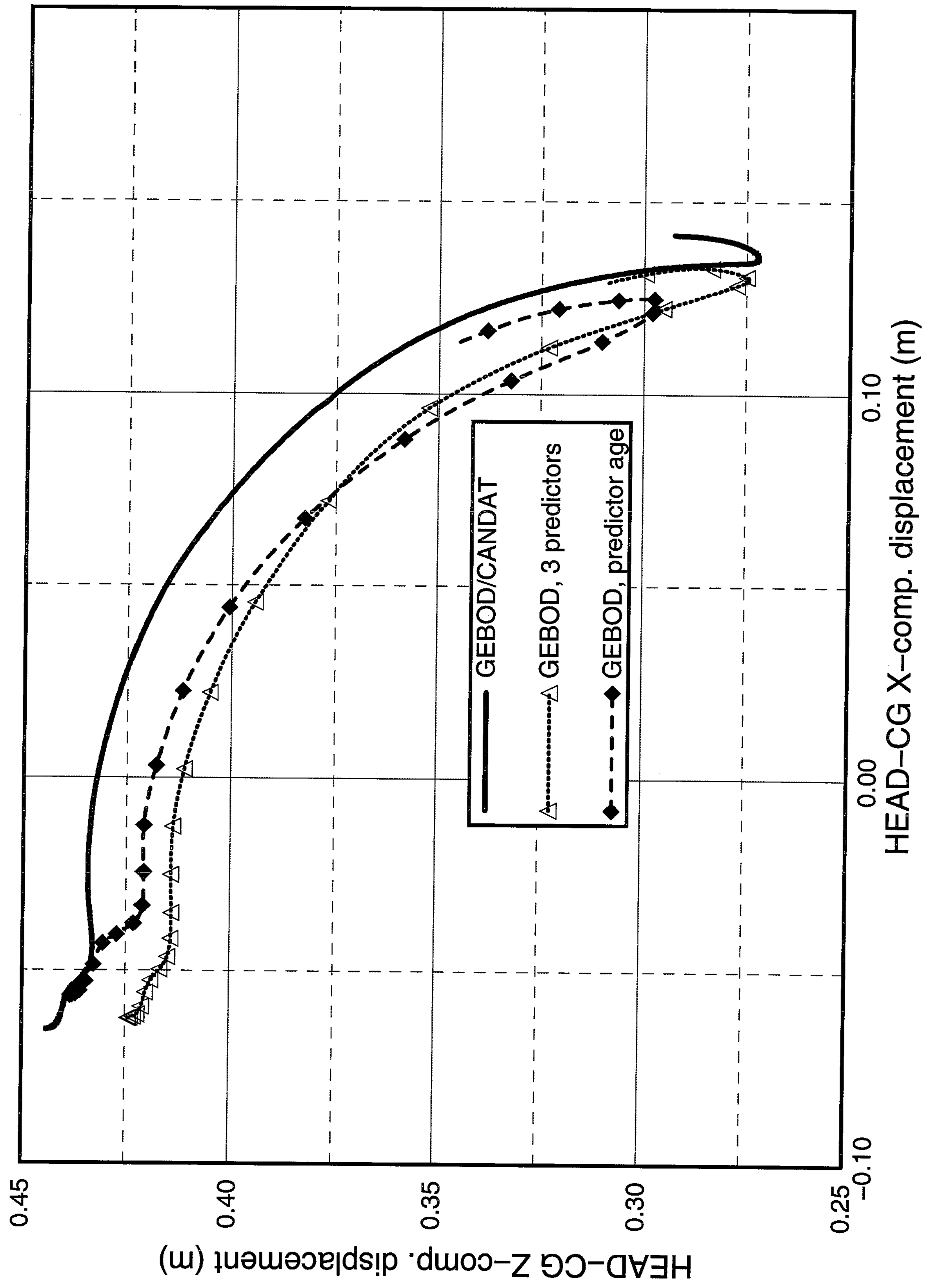

GEBOD/CANDAT
GEBOD, 3 predictors
GEBOD, predictor age
HEAD Res. acceleration (m/s**2)
0
200
400
600
800
Time (msec)
0
40
80
120


GEBOD/CANDAT
GEBOD, 3 predictors
GEBOD, predictor age
UPPER TORSO Res. acceleration (m/s**2)
Time (msec)
0
100
200
300
400
0
40
80
120


GEBOD/CANDAT
GEBOD, 3 predictors
GEBOD, predictor age
LOWER TORSO – SPINE Resultant Torque (Nm)
Time (msec)
0
20
40
60
80
100
0
40
80
120

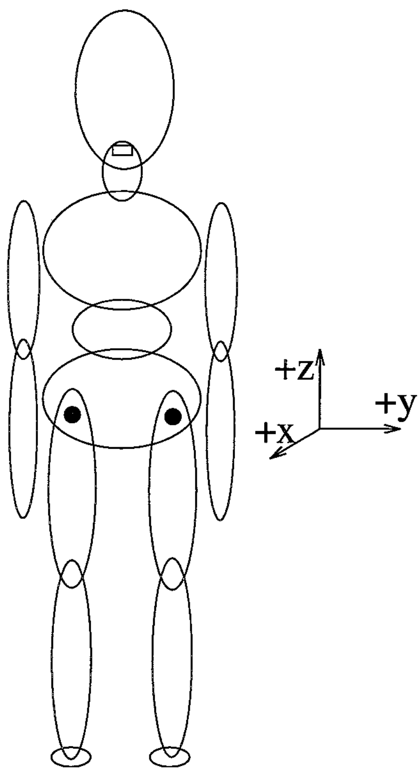

GEBOD/CANDAT
GEBOD, 3 predictors
GEBOD, predictor age
Time (msec)
UPPER TORSO – NECK Resultant Torque (Nm)
0
10
20
30
40
0
40
80
120


NECK – ATLAS BLOCK Resultant Torque (Nm)
Time (msec)
GEBOD/CANDAT
GEBOD, 3 predictors
GEBOD, predictor age
0.0
0.5
1.0
1.5
2.0
0
40
80
120

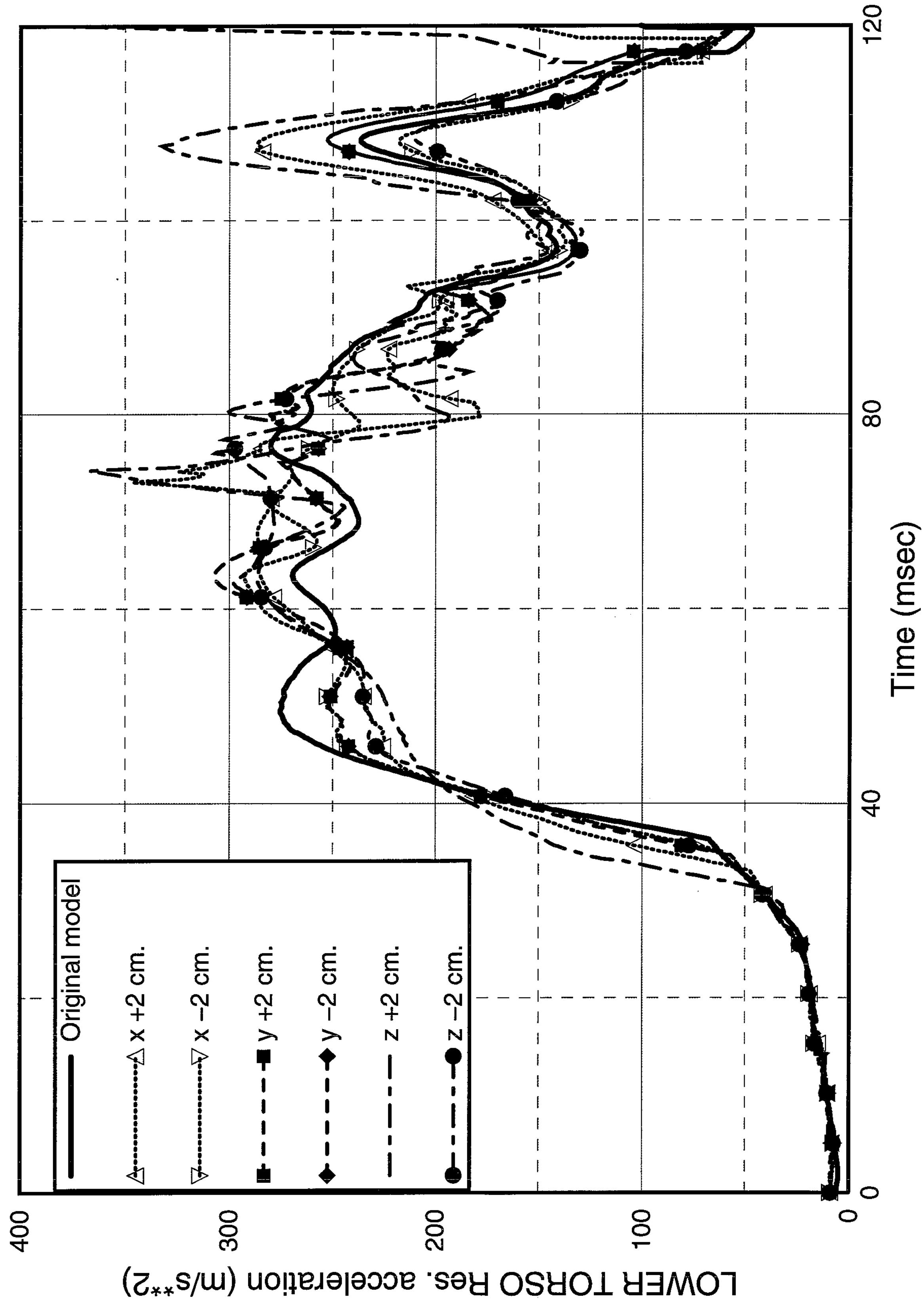

GEBOD/CANDAT
GEBOD, 3 predictors
GEBOD, predictor age
HEAD–CG X–comp. displacement (m)
HEAD–CG Z–comp. displacement (m)
−0.10
0.00
0.10
0.25
0.30
0.35
0.40
0.45

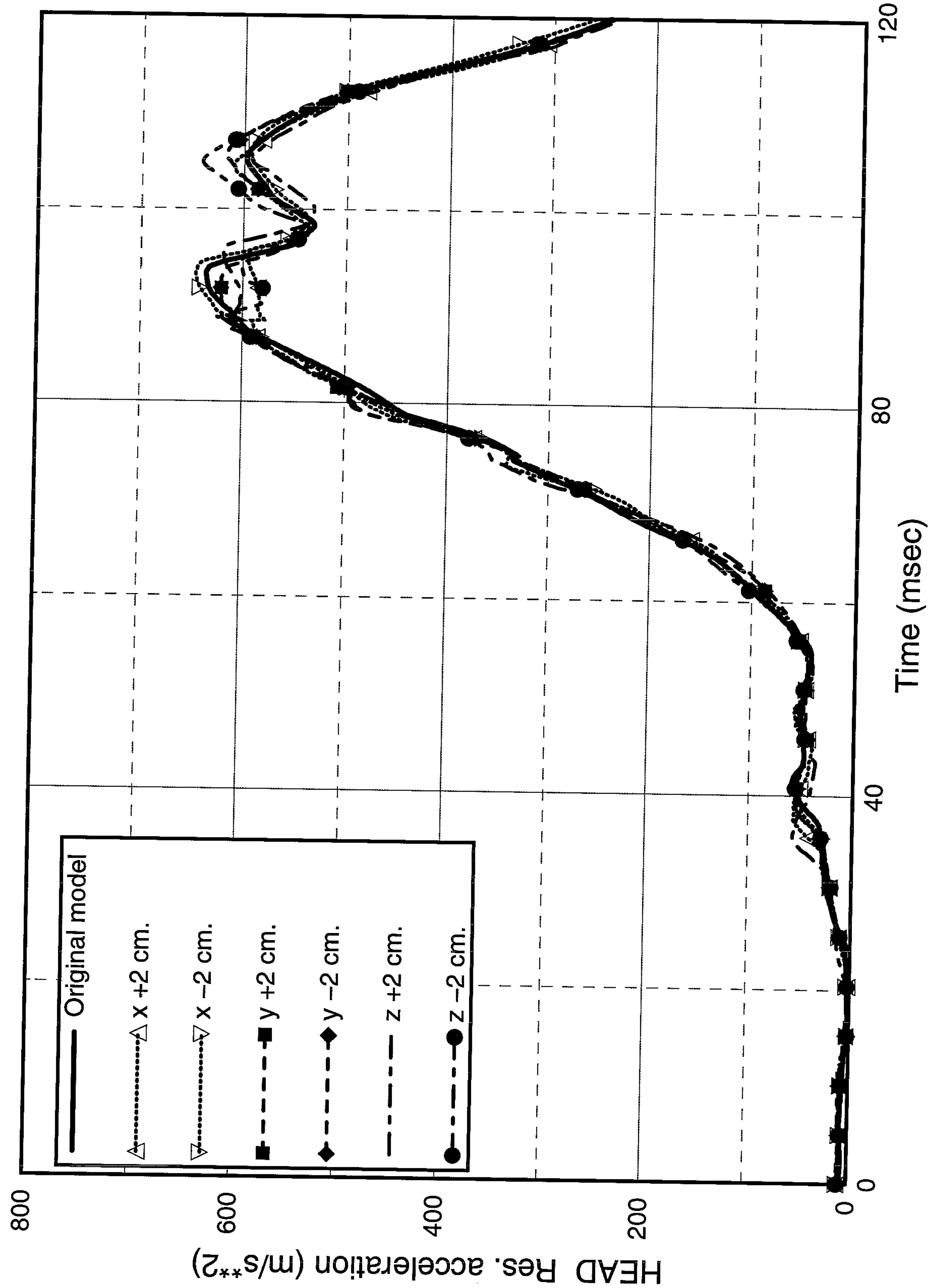
Appendix H

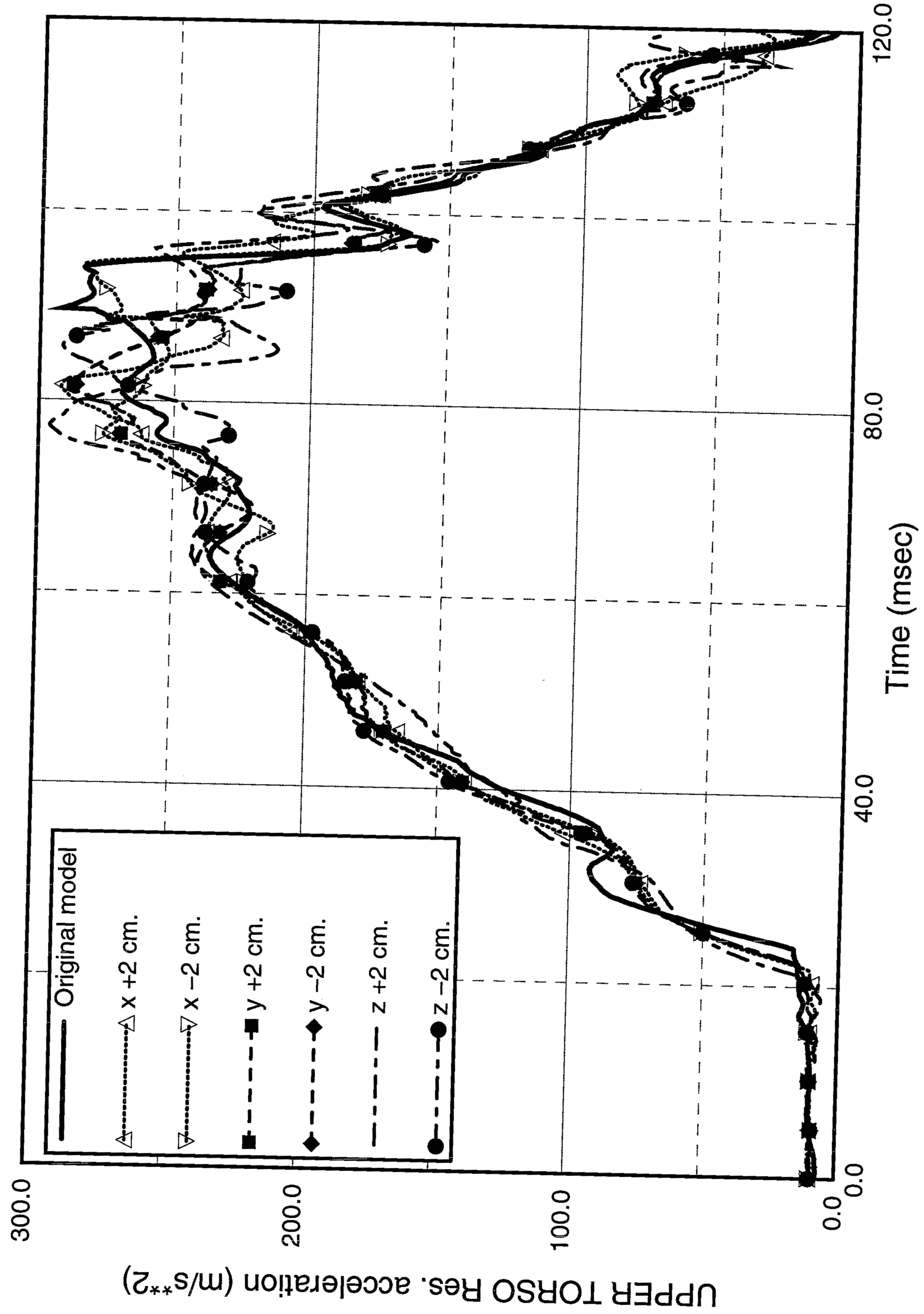
On the following pages, the results of 7 simulations of a sled test involving a restrained 3 year old child multibody model, generated by the combination GEBOD/CANDAT are included. The simulations consist of the original model and 6 variations in the location of the hip joints. The + x-direction, + y-direction and the + z-direction are shown in the figure below.

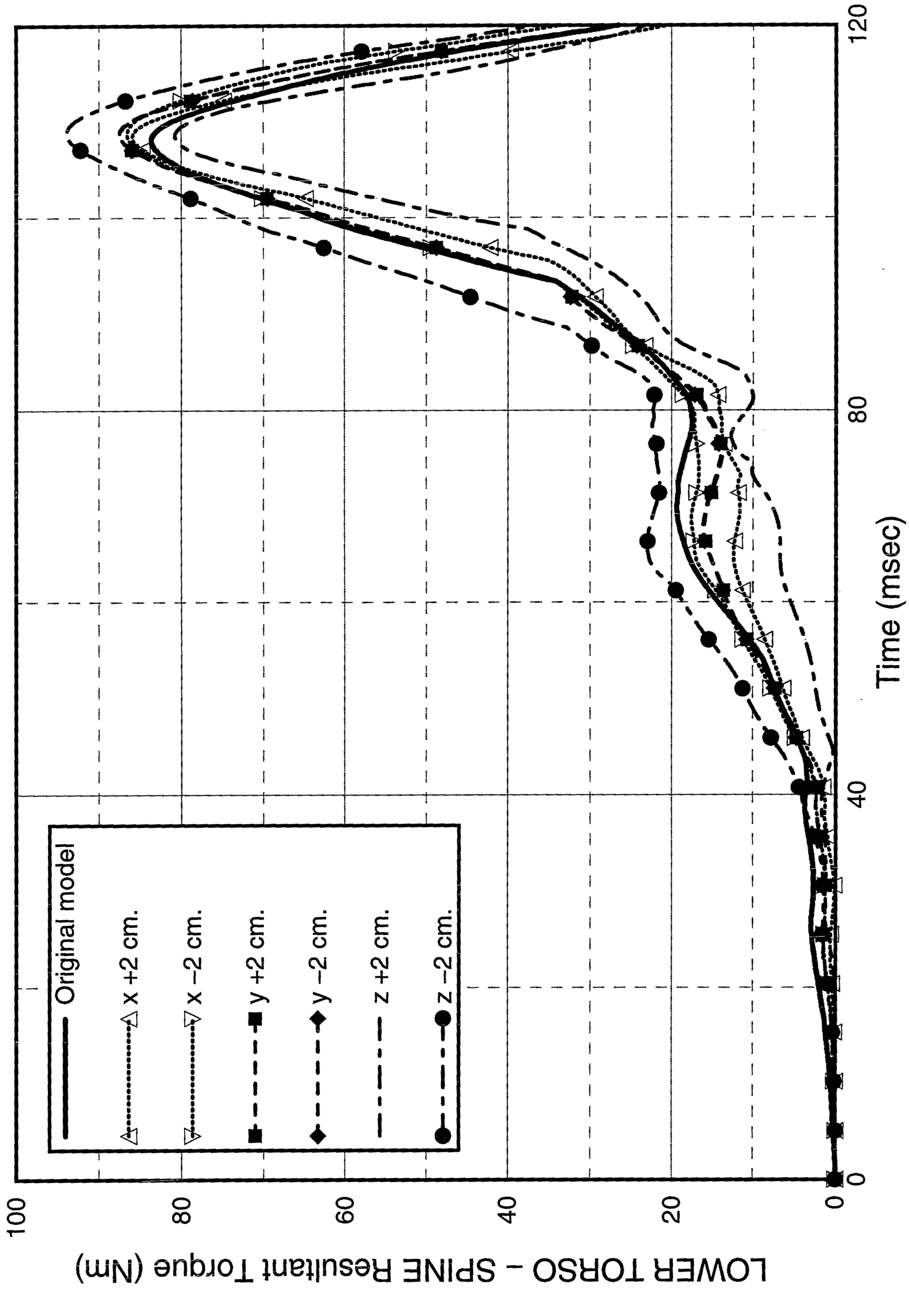


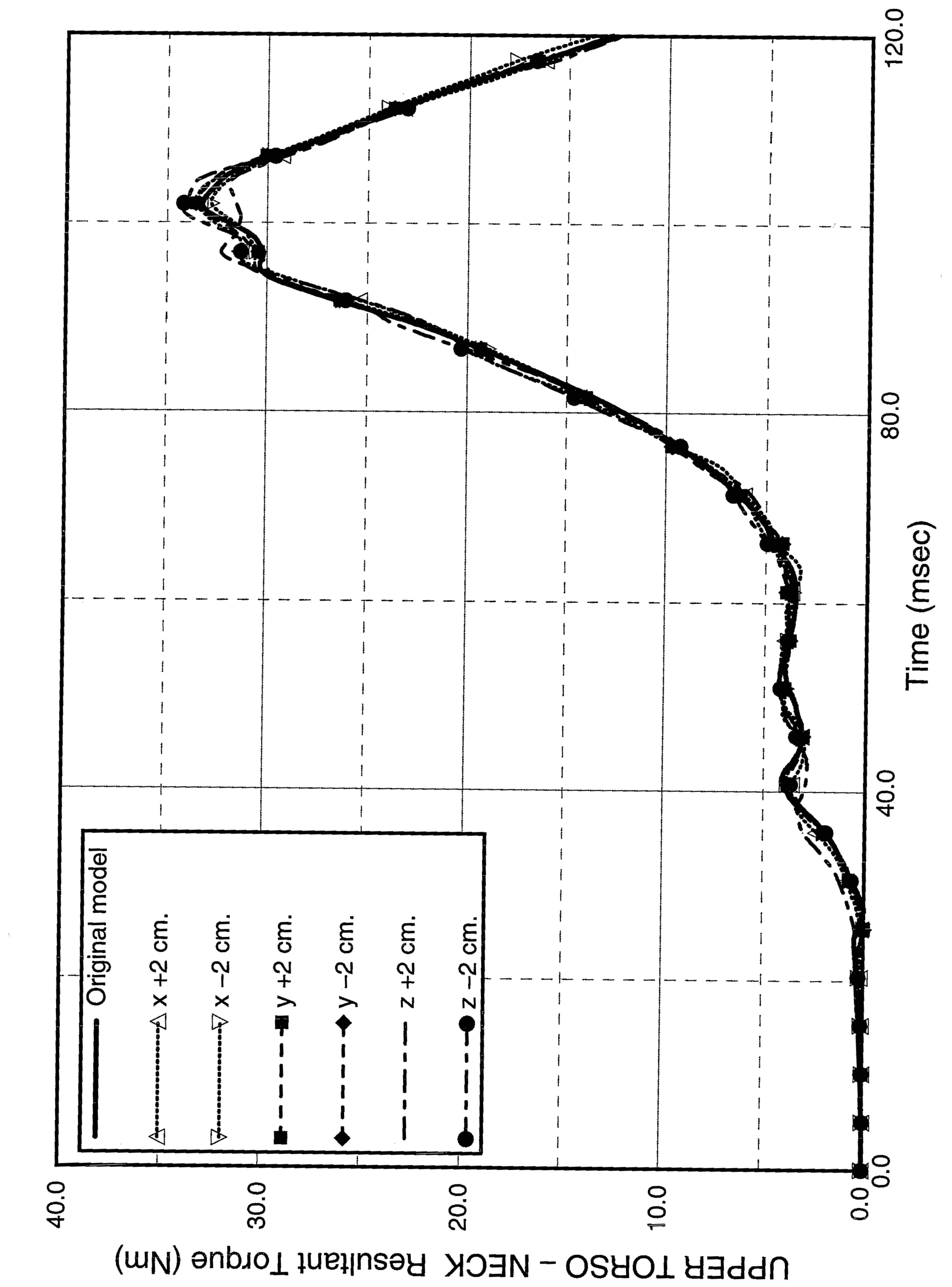
The following results are presented :

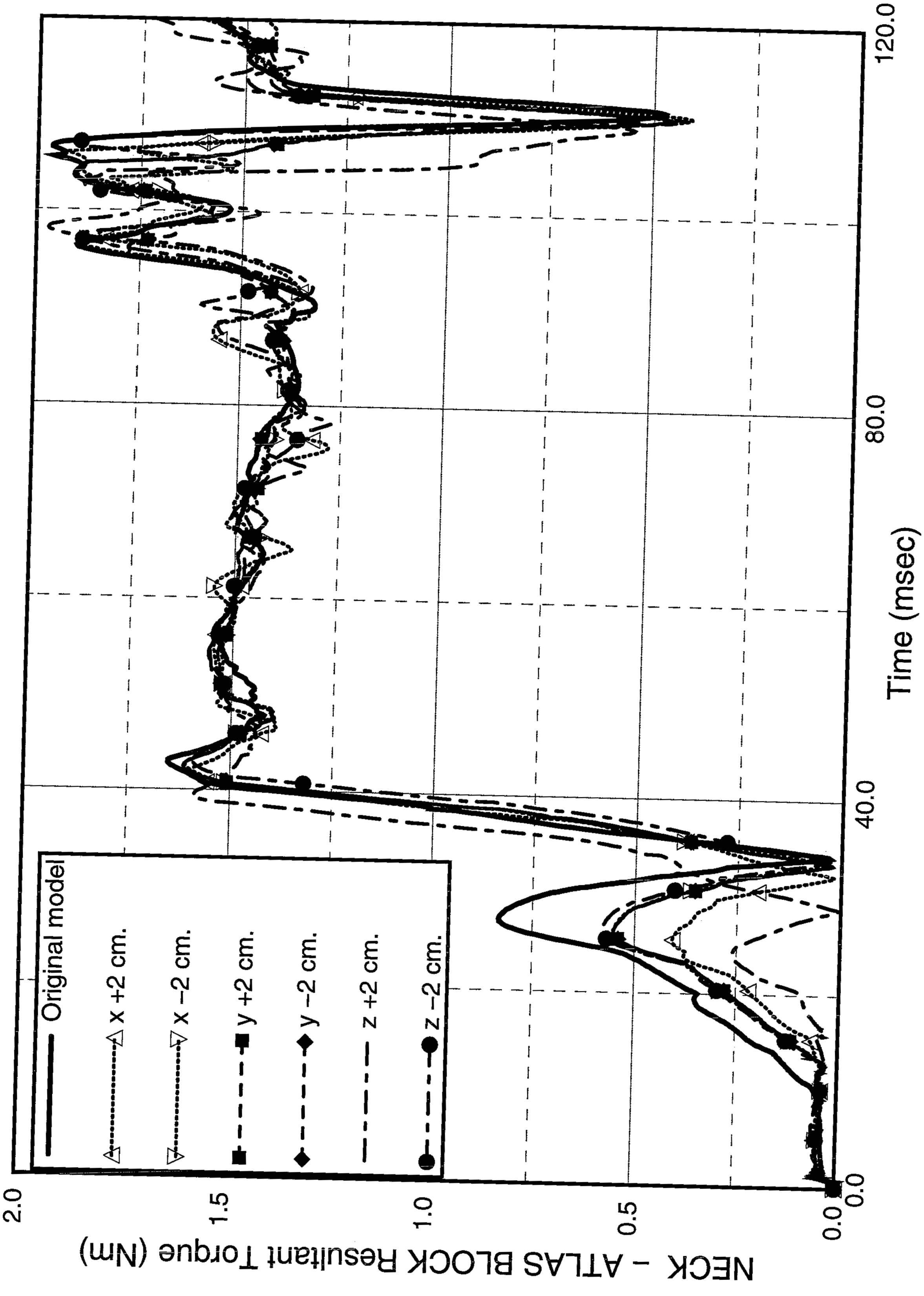

Original model
x +2 cm.
x −2 cm.
y +2 cm.
y −2 cm.
z +2 cm.
z −2 cm.
LOWER TORSO Res. acceleration (m/s**2)
Time (msec)
0
100
200
300
400
0
40
80
120

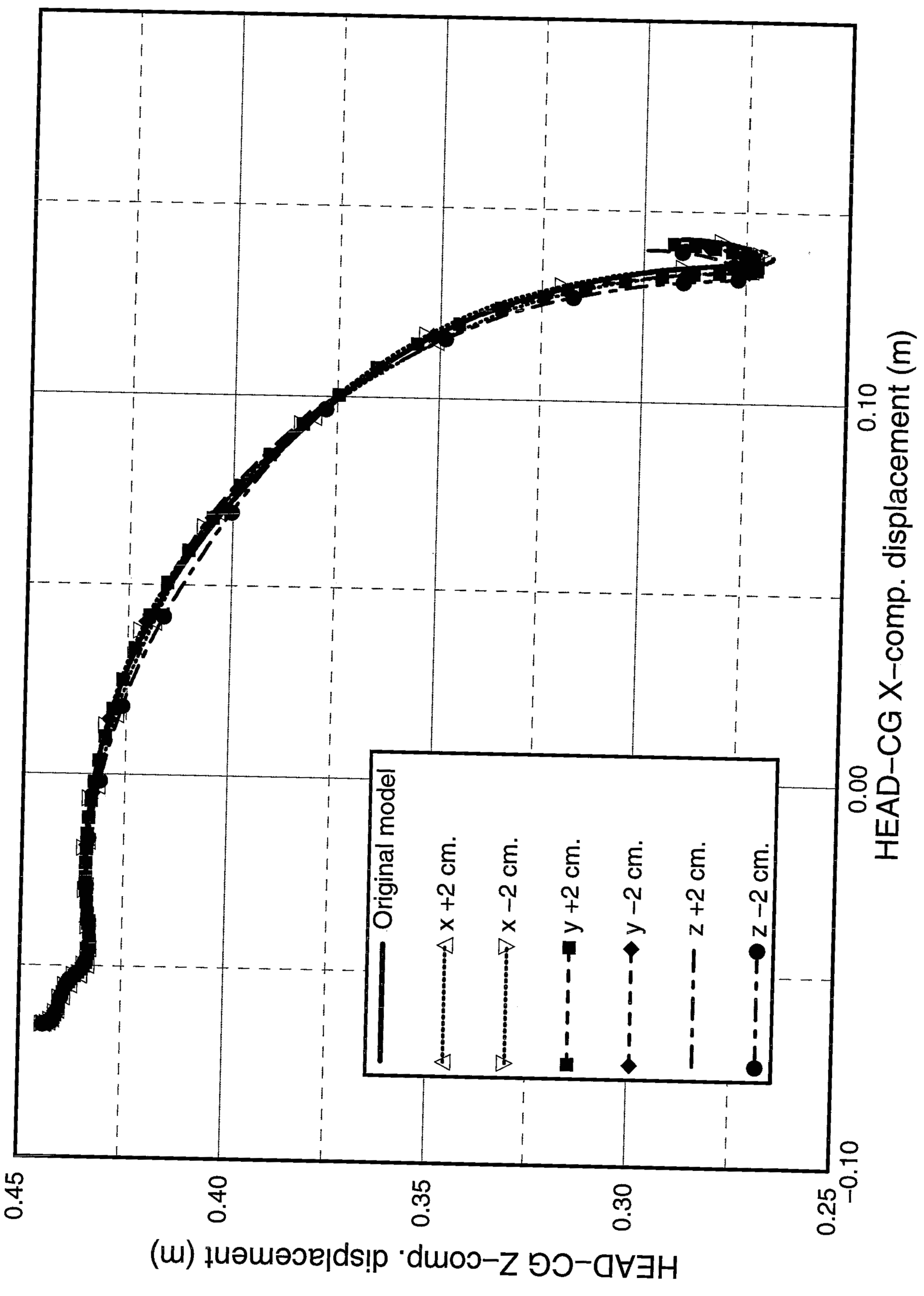

Original model
x +2 cm.
x −2 cm.
y +2 cm.
y −2 cm.
z +2 cm.
z −2 cm.
HEAD Res. acceleration (m/s**2)
800
600
400
200
0
Time (msec)
0
40
80
120


Original model
x +2 cm.
x −2 cm.
y +2 cm.
y −2 cm.
z +2 cm.
z −2 cm.
300.0
200.0
100.0
0.0
0.0
40.0
80.0
120.0
Time (msec)
UPPER TORSO Res. acceleration (m/s**2)


Original model
x +2 cm.
x −2 cm.
y +2 cm.
y −2 cm.
z +2 cm.
z −2 cm.
LOWER TORSO – SPINE Resultant Torque (Nm)
Time (msec)
0
20
40
60
80
100
0
40
80
120

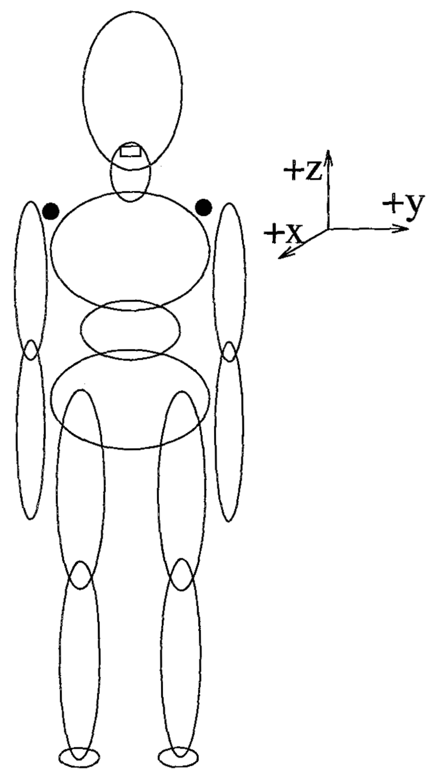

UPPER TORSO – NECK Resultant Torque (Nm)
Time (msec)
0.0
10.0
20.0
30.0
40.0
0.0
40.0
80.0
120.0
Original model
x +2 cm.
x –2 cm.
y +2 cm.
y –2 cm.
z +2 cm.
z –2 cm.


Original model
x +2 cm.
x −2 cm.
y +2 cm.
y −2 cm.
z +2 cm.
z −2 cm.
NECK - ATLAS BLOCK Resultant Torque (Nm)
Time (msec)
0.0
0.5
1.0
1.5
2.0
0.0
40.0
80.0
120.0

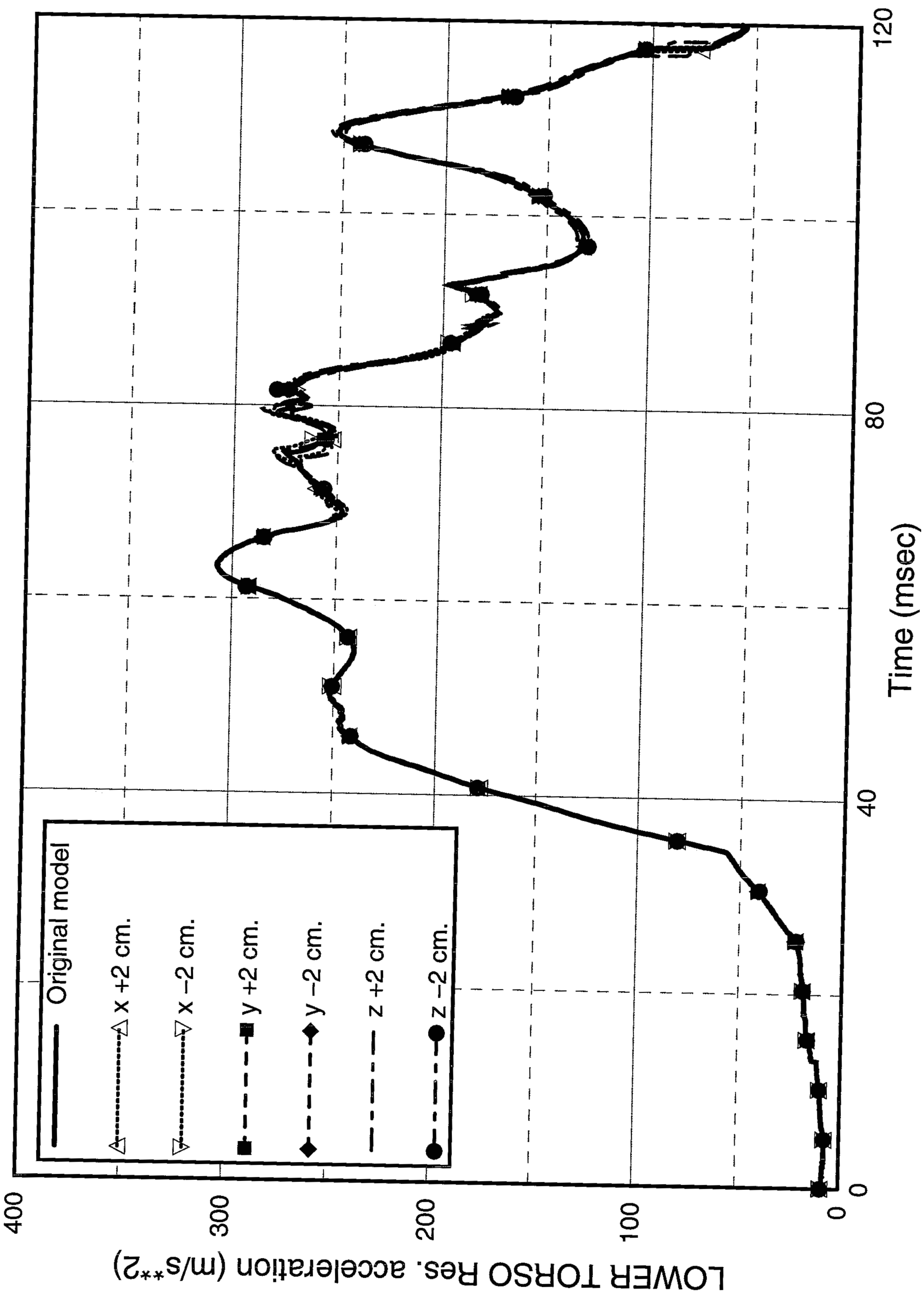

HEAD–CG X–comp. displacement (m)
HEAD–CG Z–comp. displacement (m)
−0.10
0.00
0.10
0.25
0.30
0.35
0.40
0.45
Original model
x +2 cm.
x −2 cm.
y +2 cm.
y −2 cm.
z +2 cm.
z −2 cm.

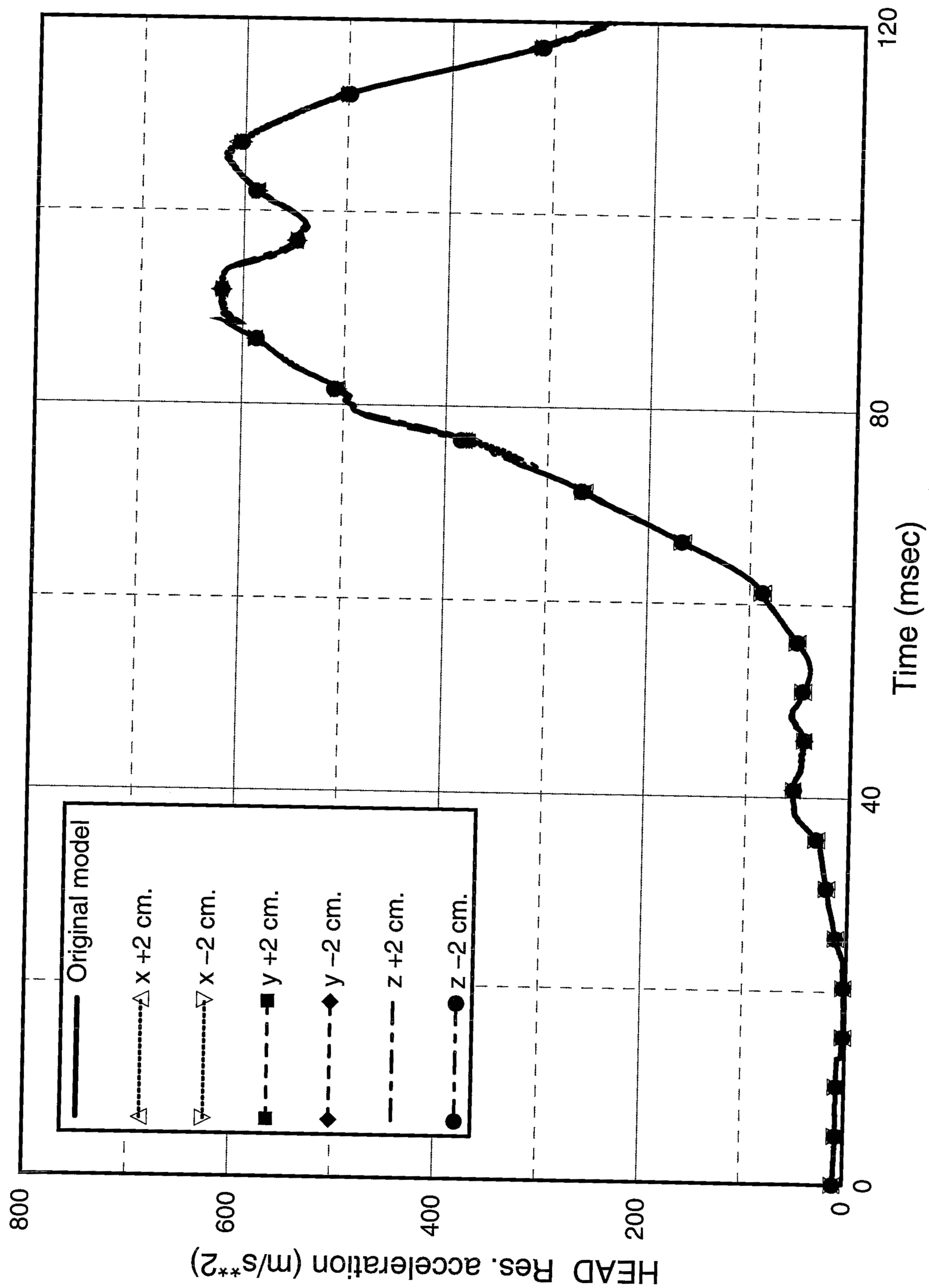
Appendix I

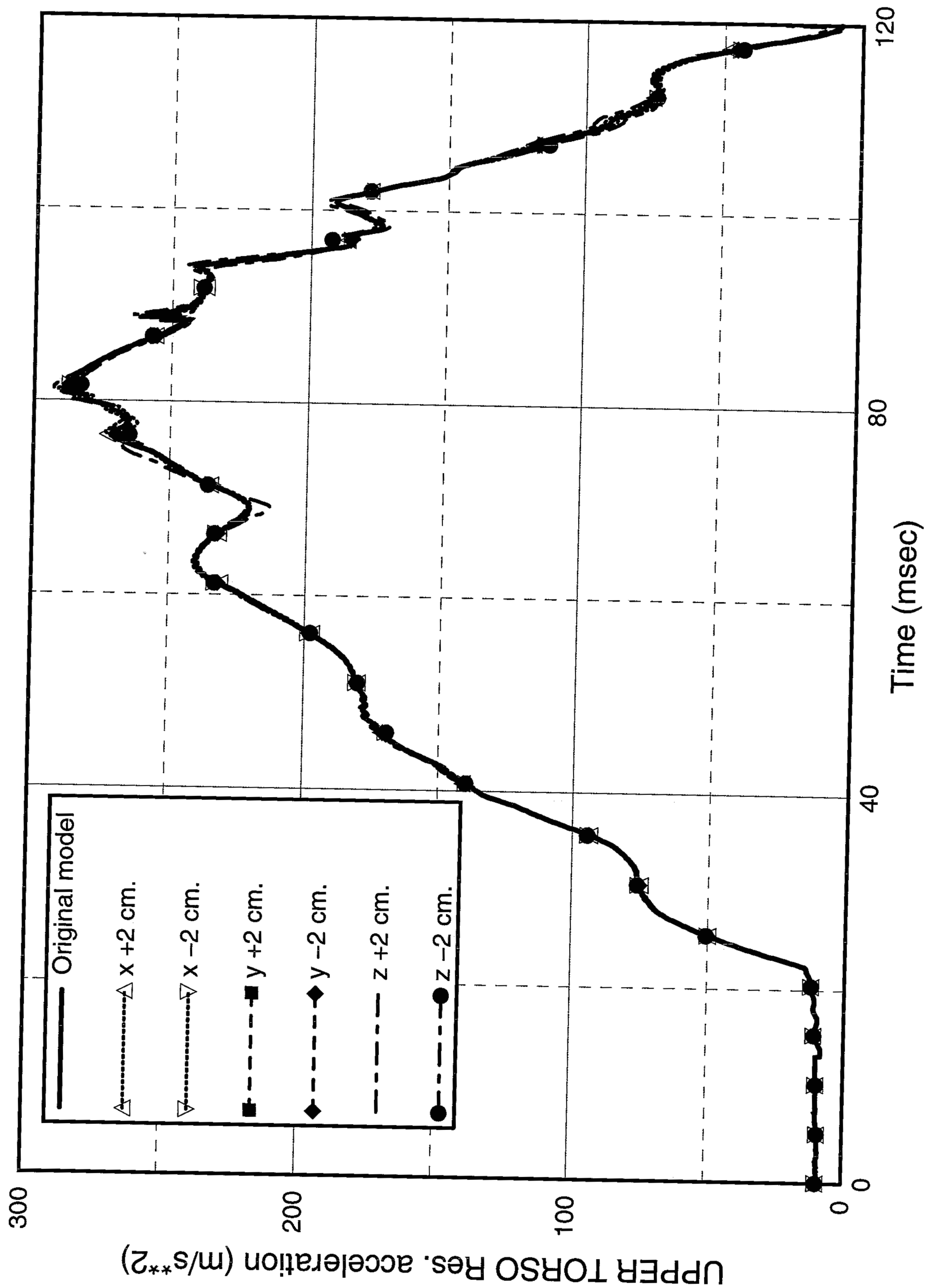
On the following pages, the results of 7 simulations of a sled test involving a restrained 3 year old child multibody model, generated by the combination GEBOD/CANDAT are included. The simulations consist of the original model and 6 variations in the location of the shoulder joints. The + x-direction, + y-direction and the + z-direction are shown in the figure below.

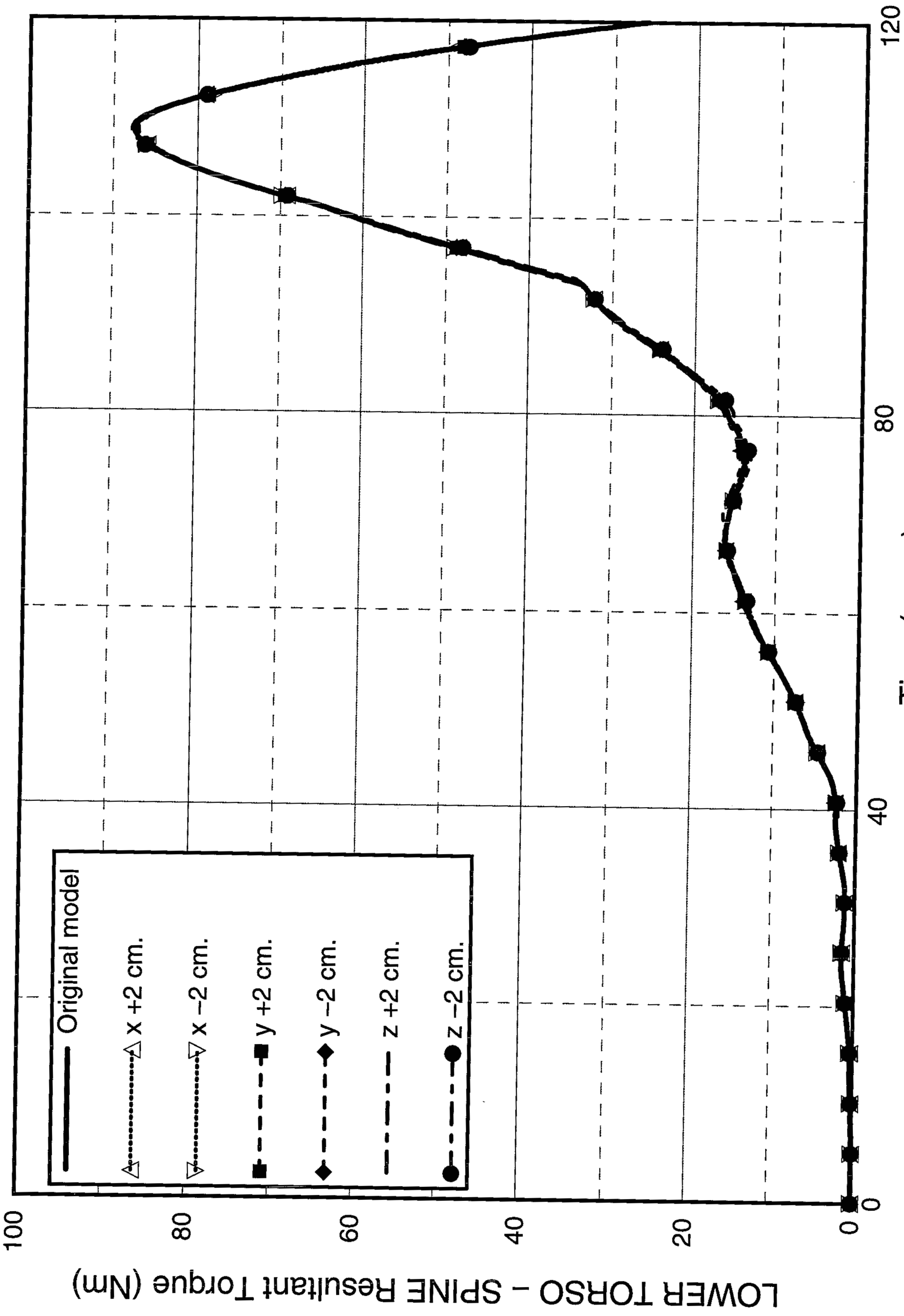


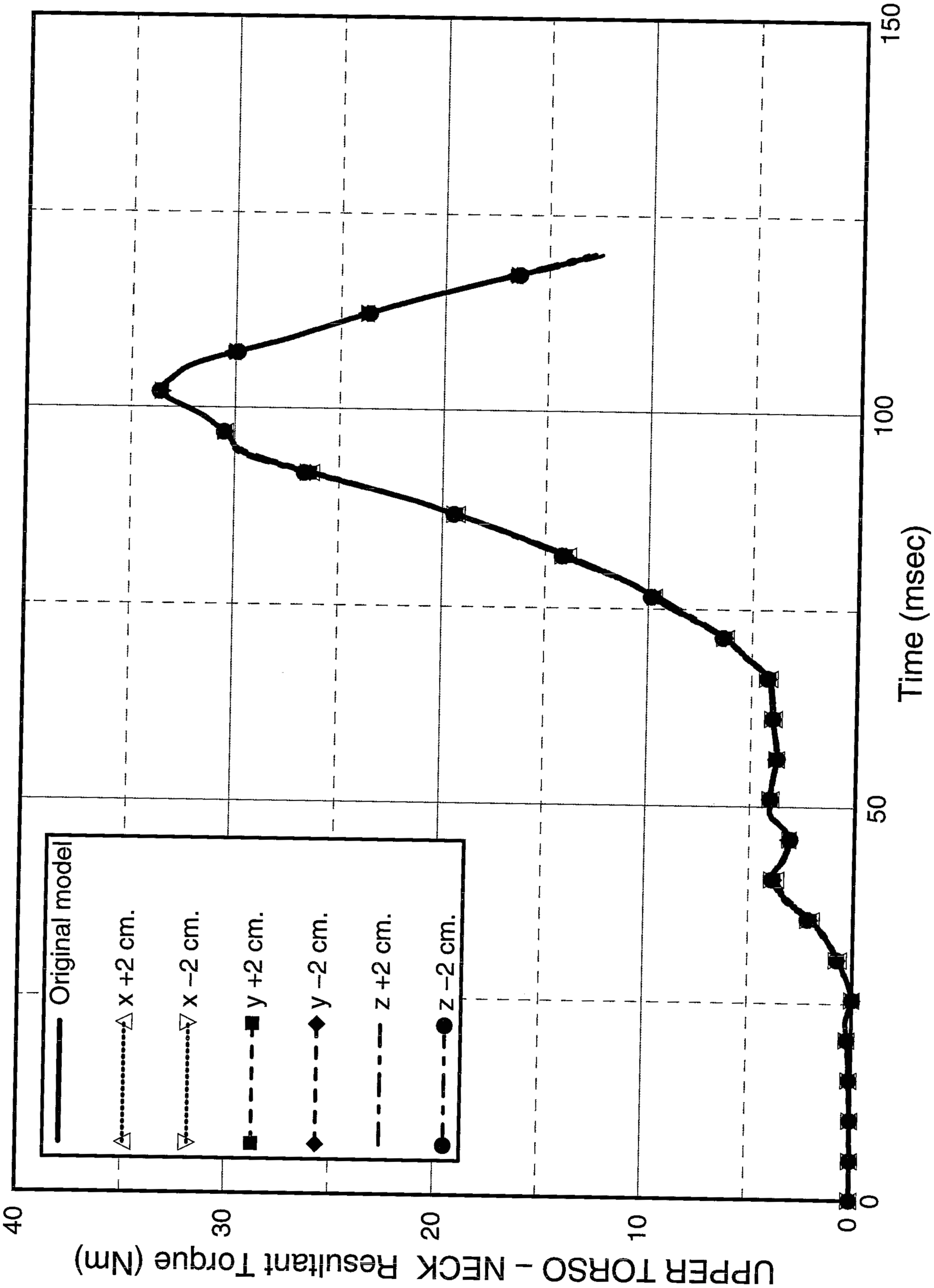
The following results are presented :

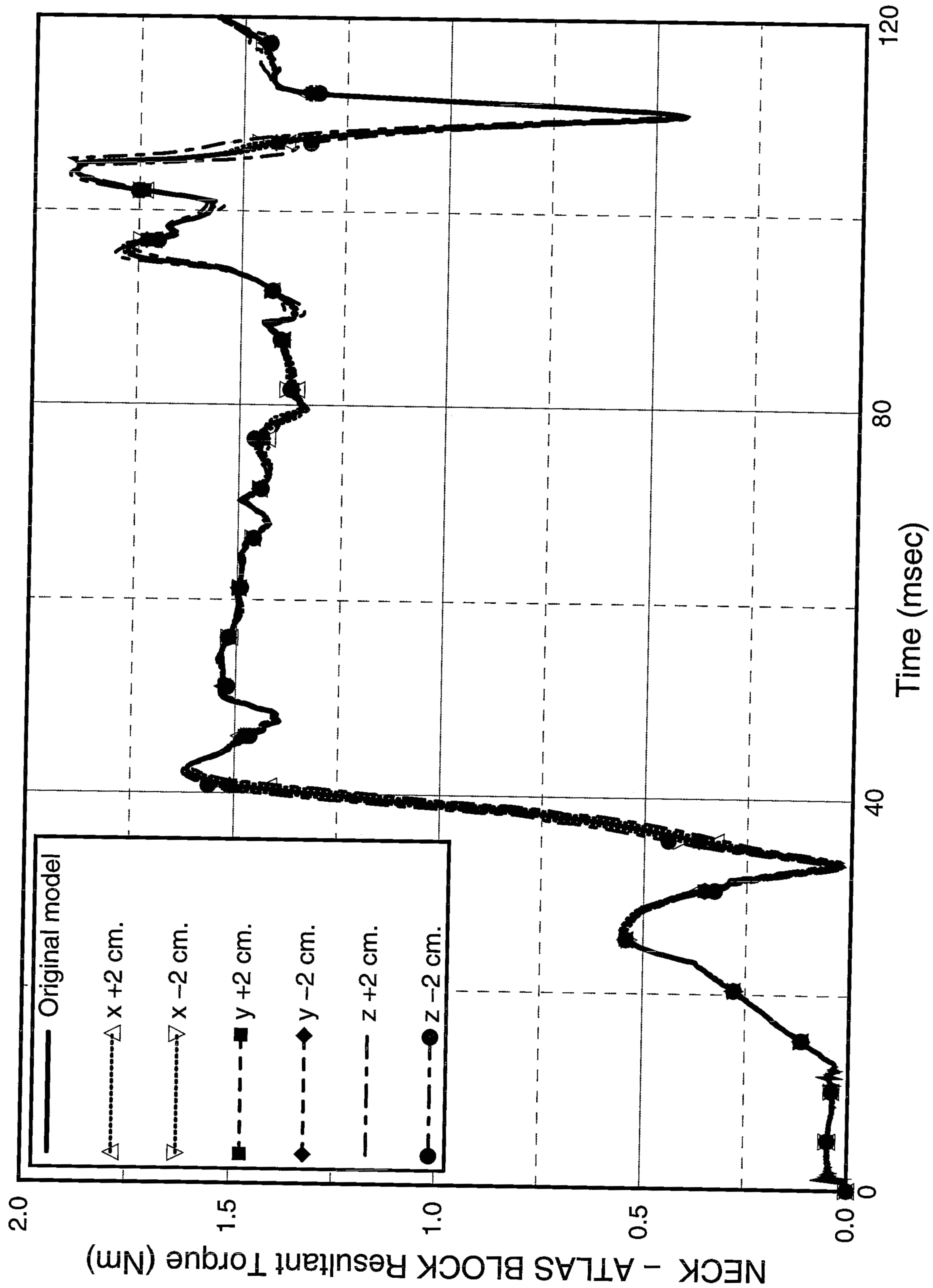

LOWER TORSO Res. acceleration (m/s**2)
0
100
200
300
400
Time (msec)
0
40
80
120
Original model
x +2 cm.
x −2 cm.
y +2 cm.
y −2 cm.
z +2 cm.
z −2 cm.


HEAD Res. acceleration (m/s**2)
0
200
400
600
800
Time (msec)
0
40
80
120
Original model
x +2 cm.
x −2 cm.
y +2 cm.
y −2 cm.
z +2 cm.
z −2 cm.

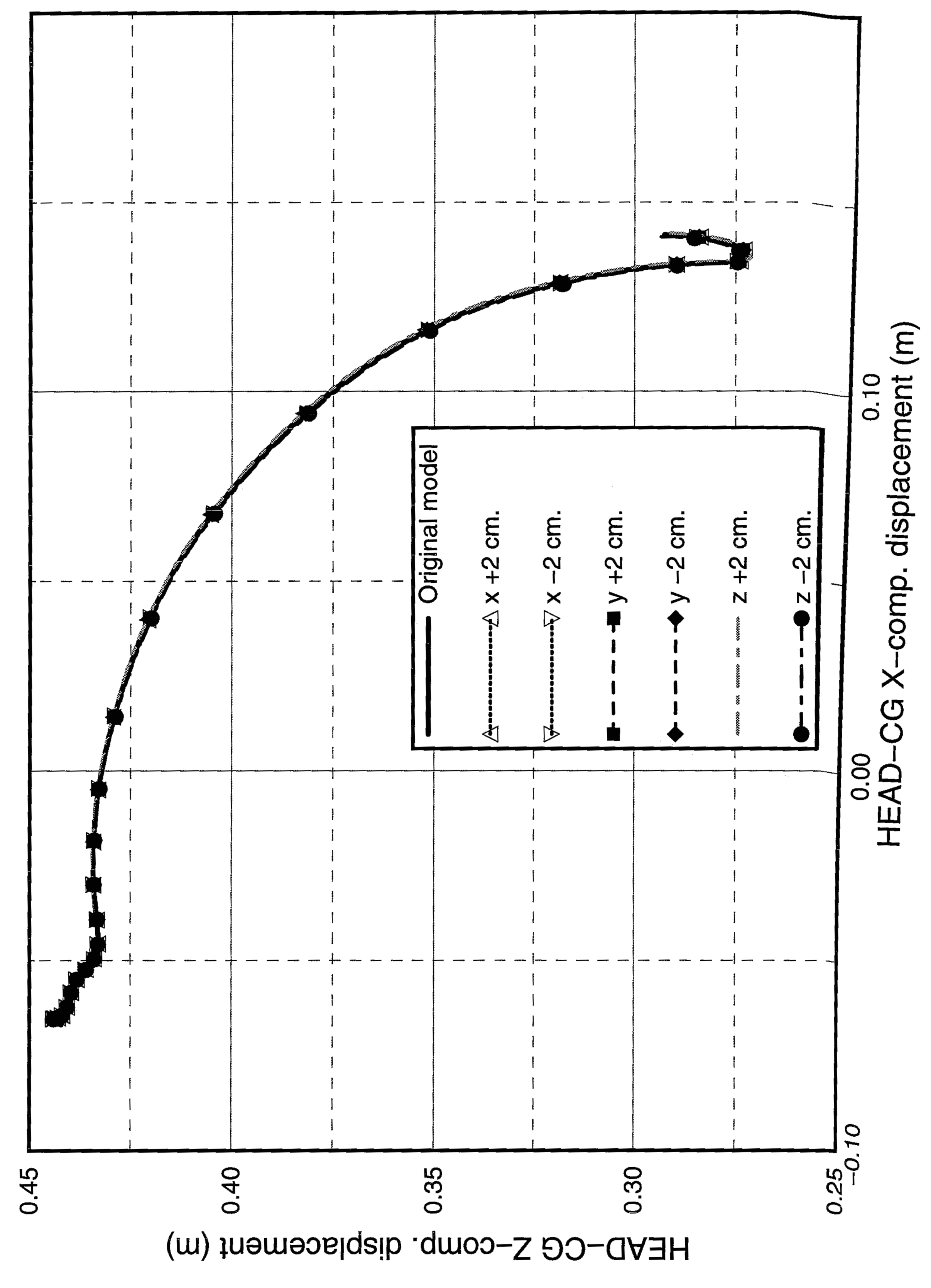

Original model
x +2 cm.
x −2 cm.
y +2 cm.
y −2 cm.
z +2 cm.
z −2 cm.
0
40
80
120
Time (msec)
0
100
200
300
UPPER TORSO Res. acceleration (m/s**2)


LOWER TORSO - SPINE Resultant Torque (Nm)
Time (msec)
0
20
40
60
80
100
0
40
80
120
Original model
x +2 cm.
x -2 cm.
y +2 cm.
y -2 cm.
z +2 cm.
z -2 cm.


Original model
x +2 cm.
x −2 cm.
y +2 cm.
y −2 cm.
z +2 cm.
z −2 cm.
0
10
20
30
40
0
50
100
150
UPPER TORSO − NECK Resultant Torque (Nm)
Time (msec)

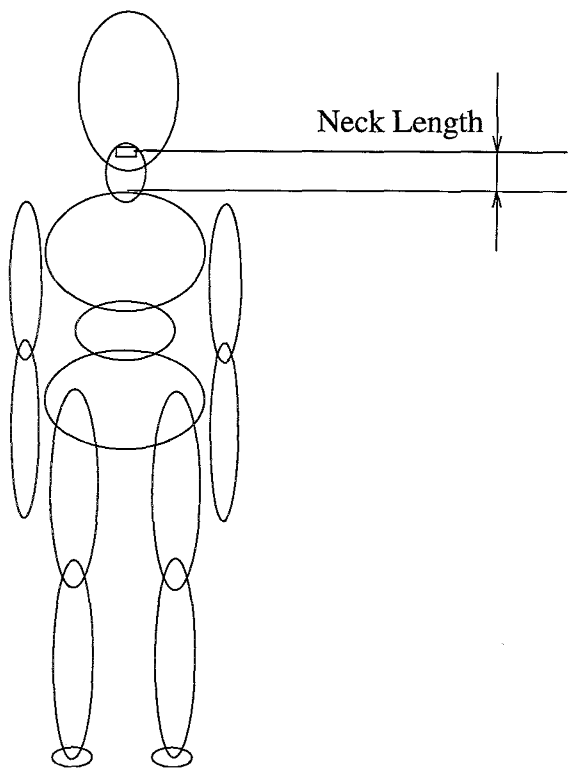


Original model
x +2 cm.
x –2 cm.
y +2 cm.
y –2 cm.
z +2 cm.
z –2 cm.
NECK – ATLAS BLOCK Resultant Torque (Nm)
0.0
0.5
1.0
1.5
2.0
Time (msec)
0
40
80
120

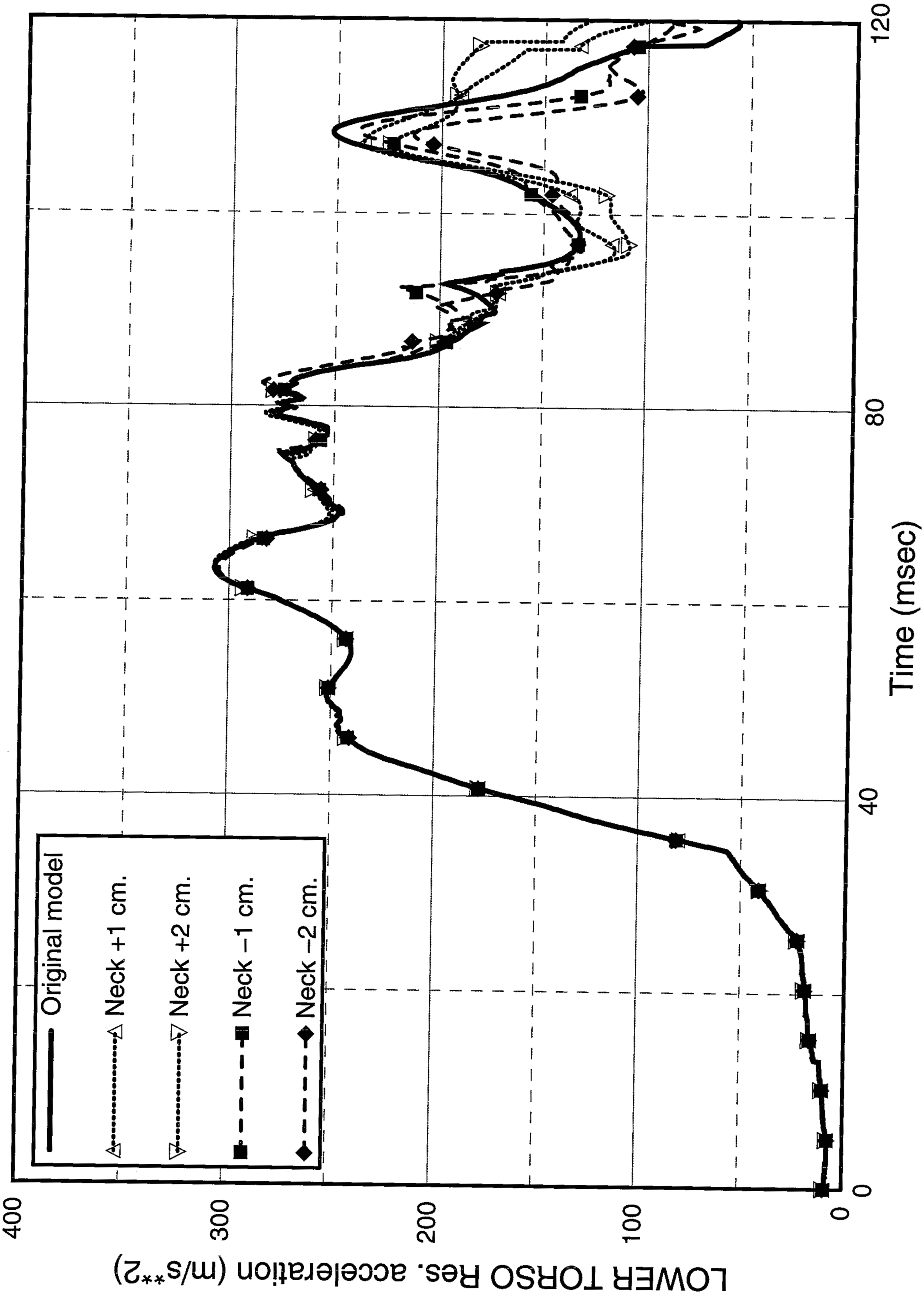

HEAD−CG Z−comp. displacement (m)
0.25
0.30
0.35
0.40
0.45
HEAD−CG X−comp. displacement (m)
−0.10
0.00
0.10
Original model
x +2 cm.
x −2 cm.
y +2 cm.
y −2 cm.
z +2 cm.
z −2 cm.

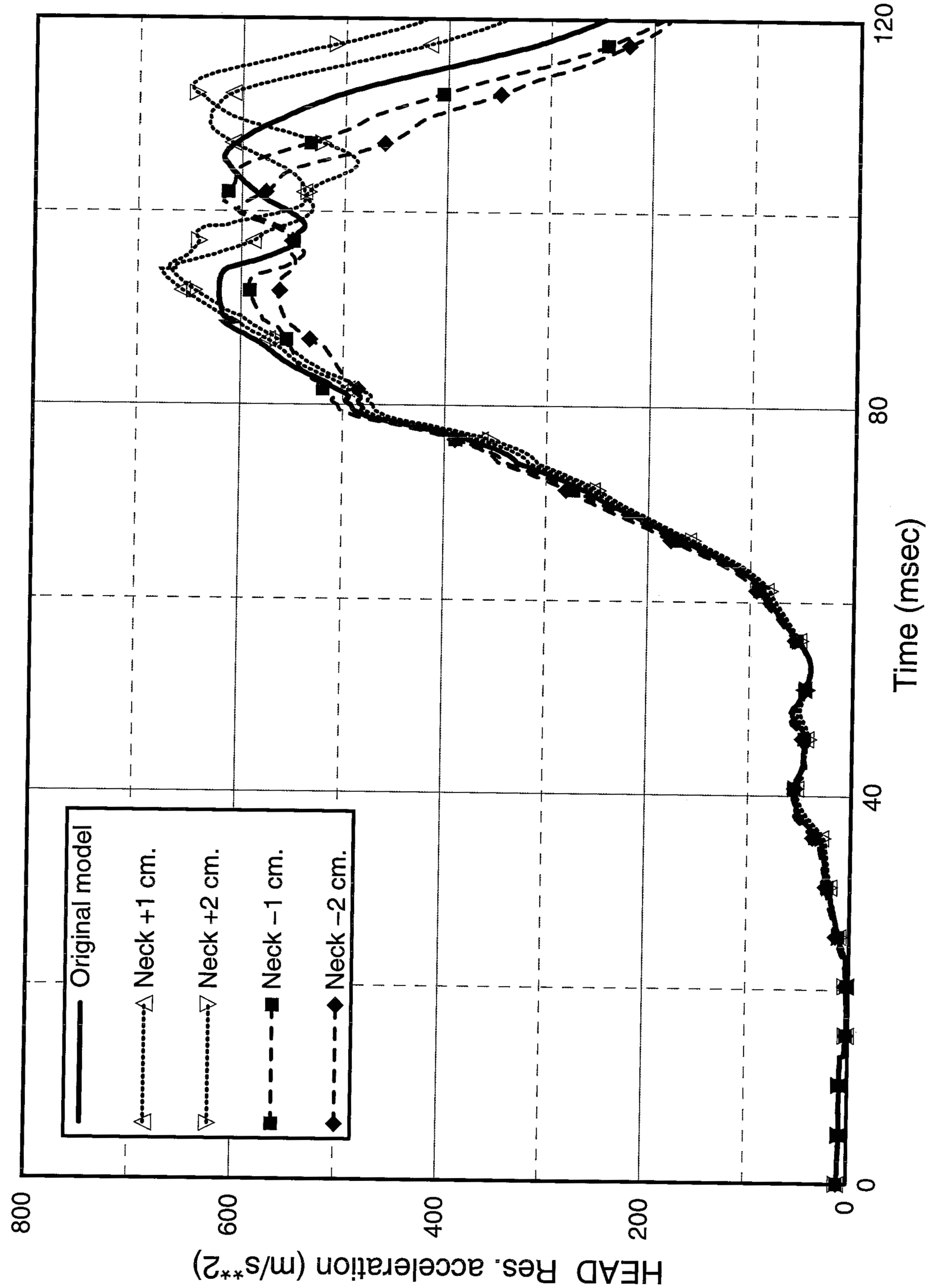
Appendix J

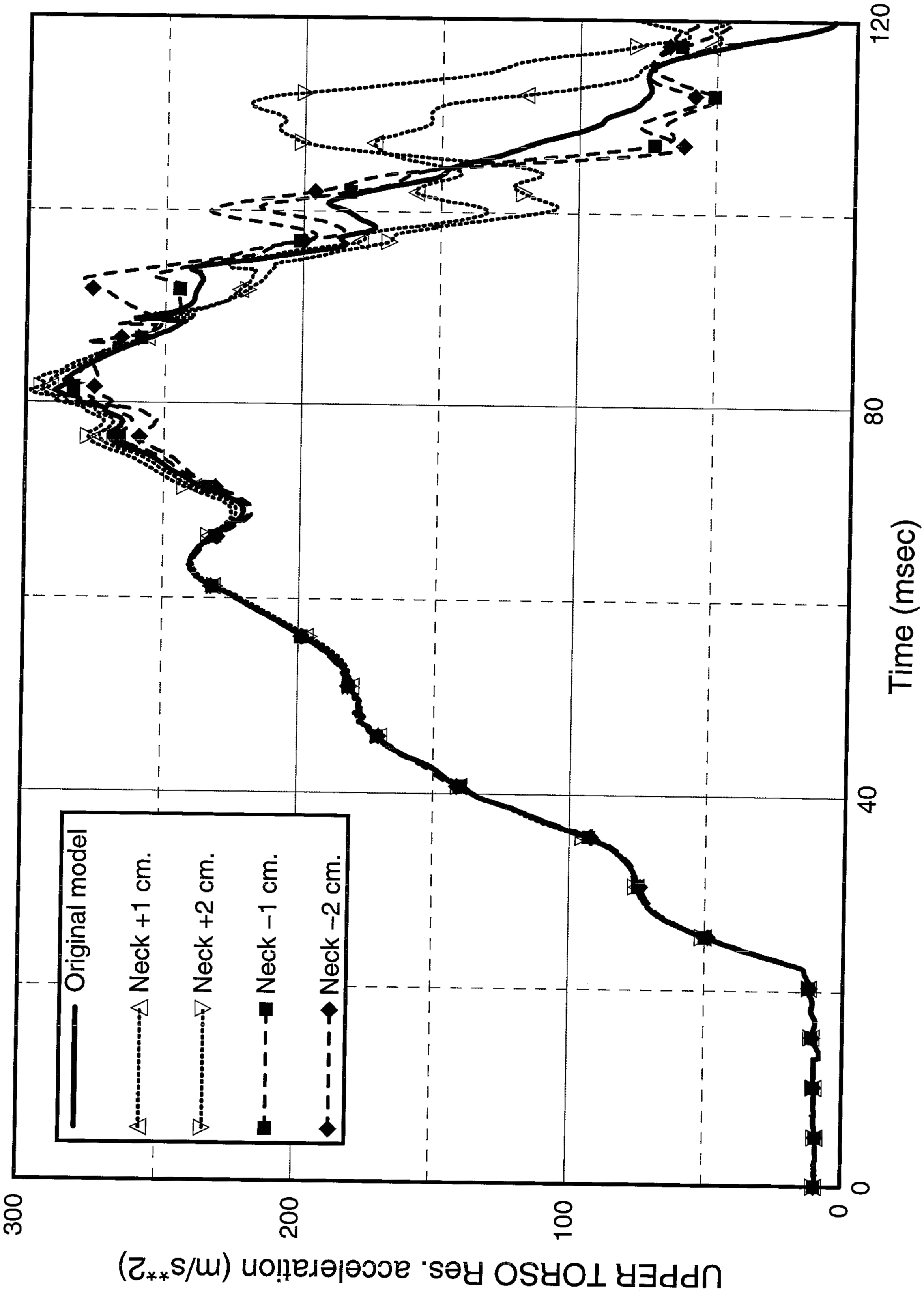
On the following pages, the results of 5 simulations of a sled test involving a restrained 3 year old child multibody model, generated by the combination GEBOD/CANDAT are included. The simulations consist of the original model and 4 variations in the length of the neck.

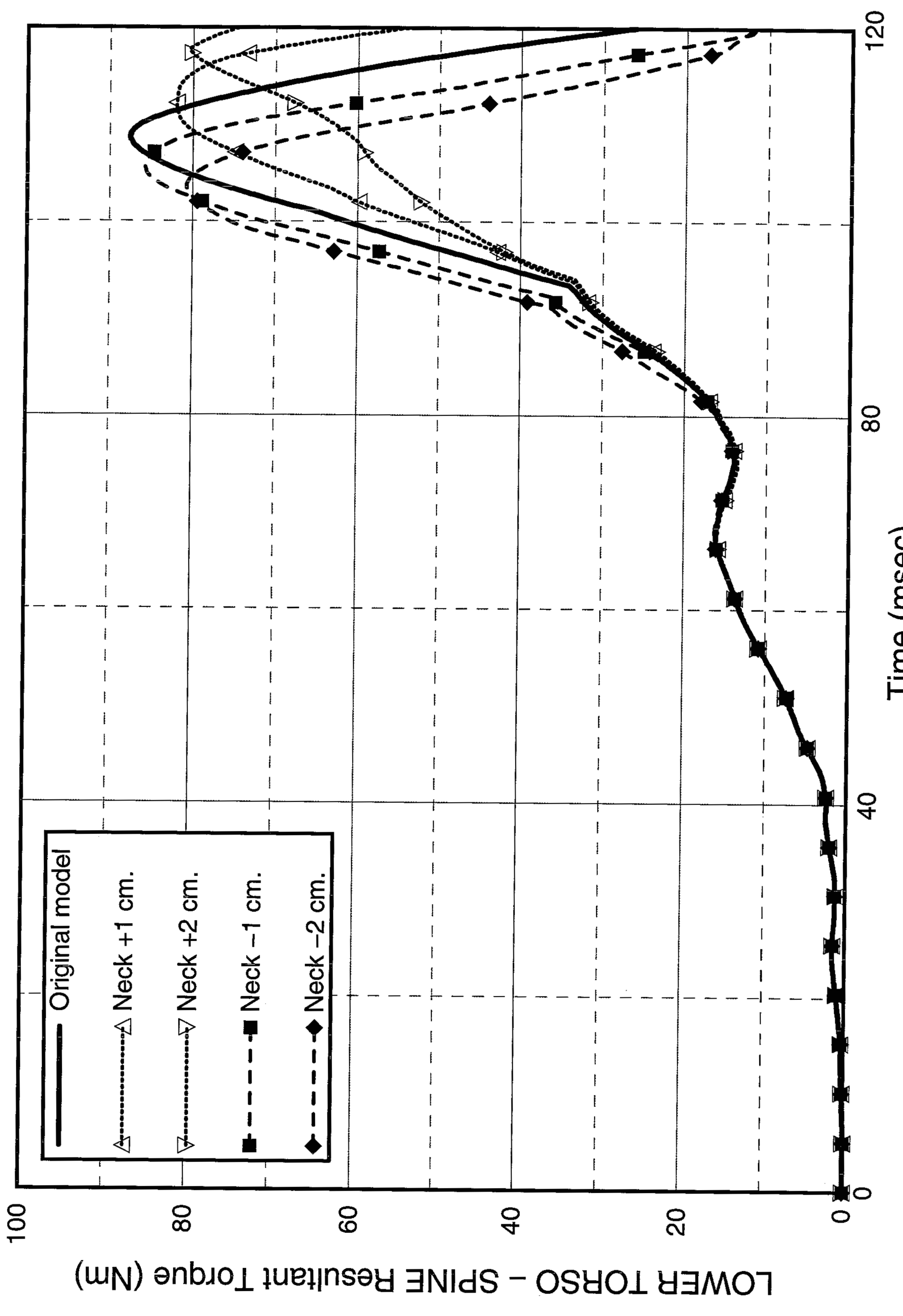


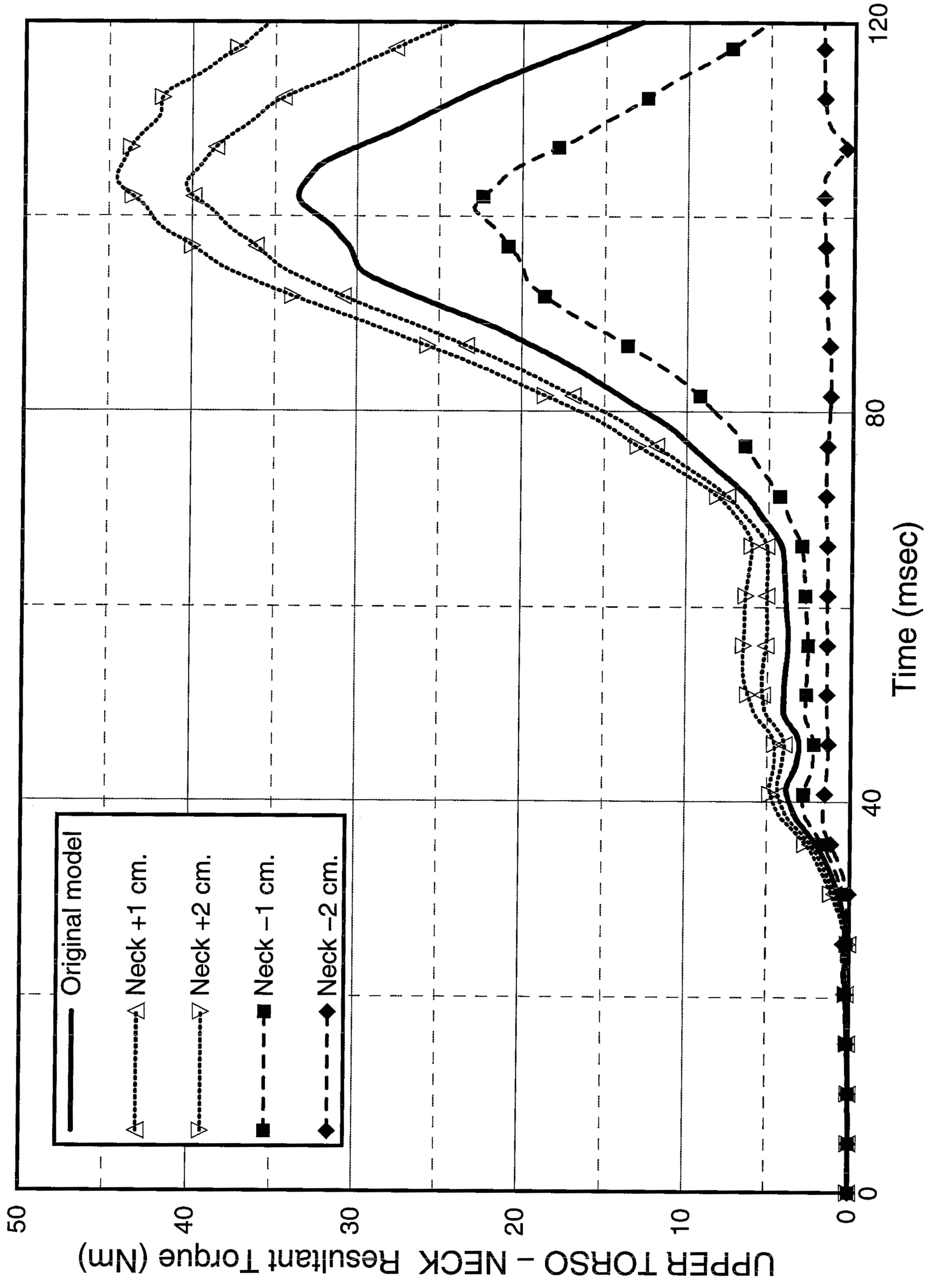
The following results are presented :

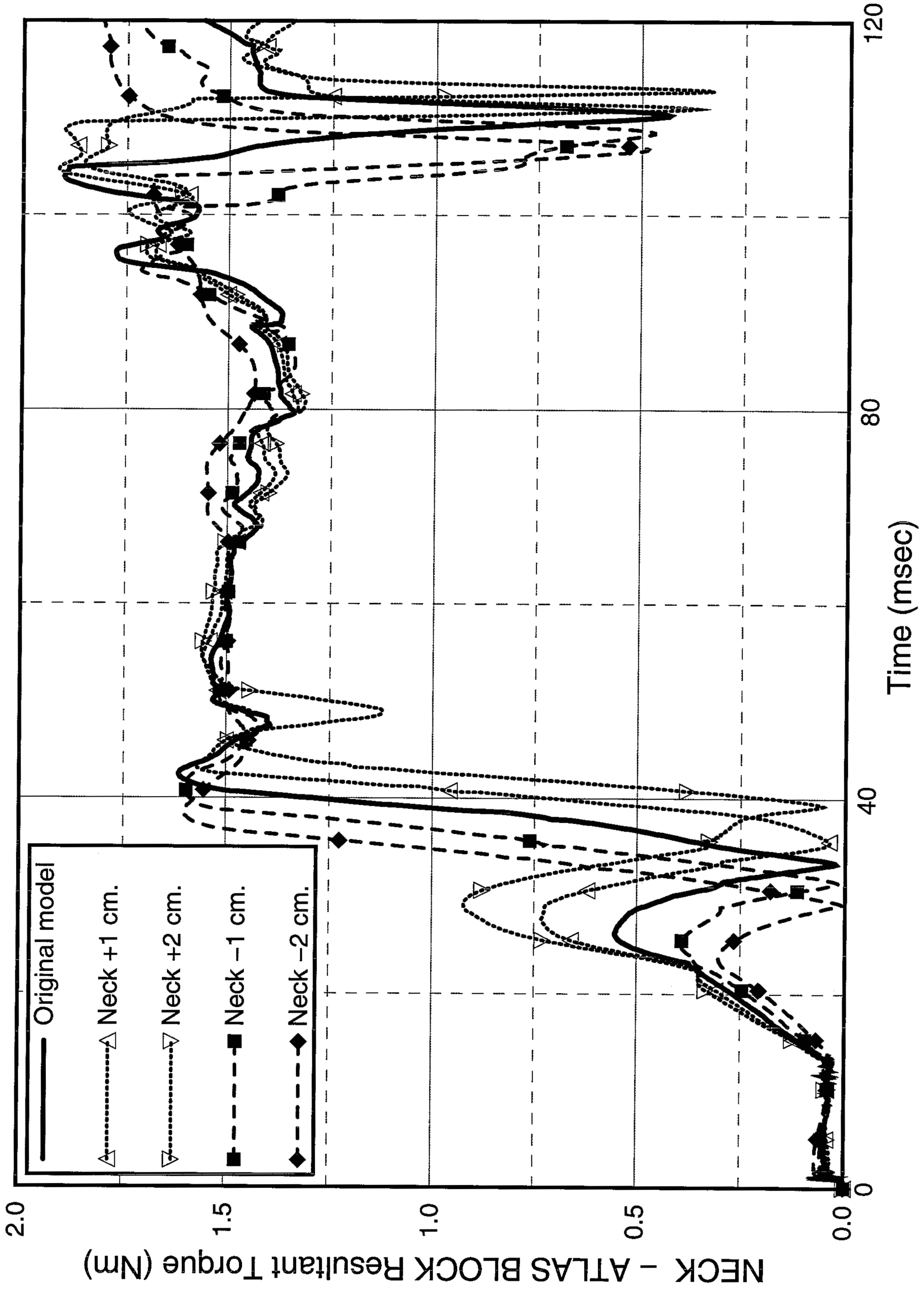

Original model
Neck +1 cm.
Neck +2 cm.
Neck −1 cm.
Neck −2 cm.
LOWER TORSO Res. acceleration (m/s**2)
0
100
200
300
400
Time (msec)
0
40
80
120

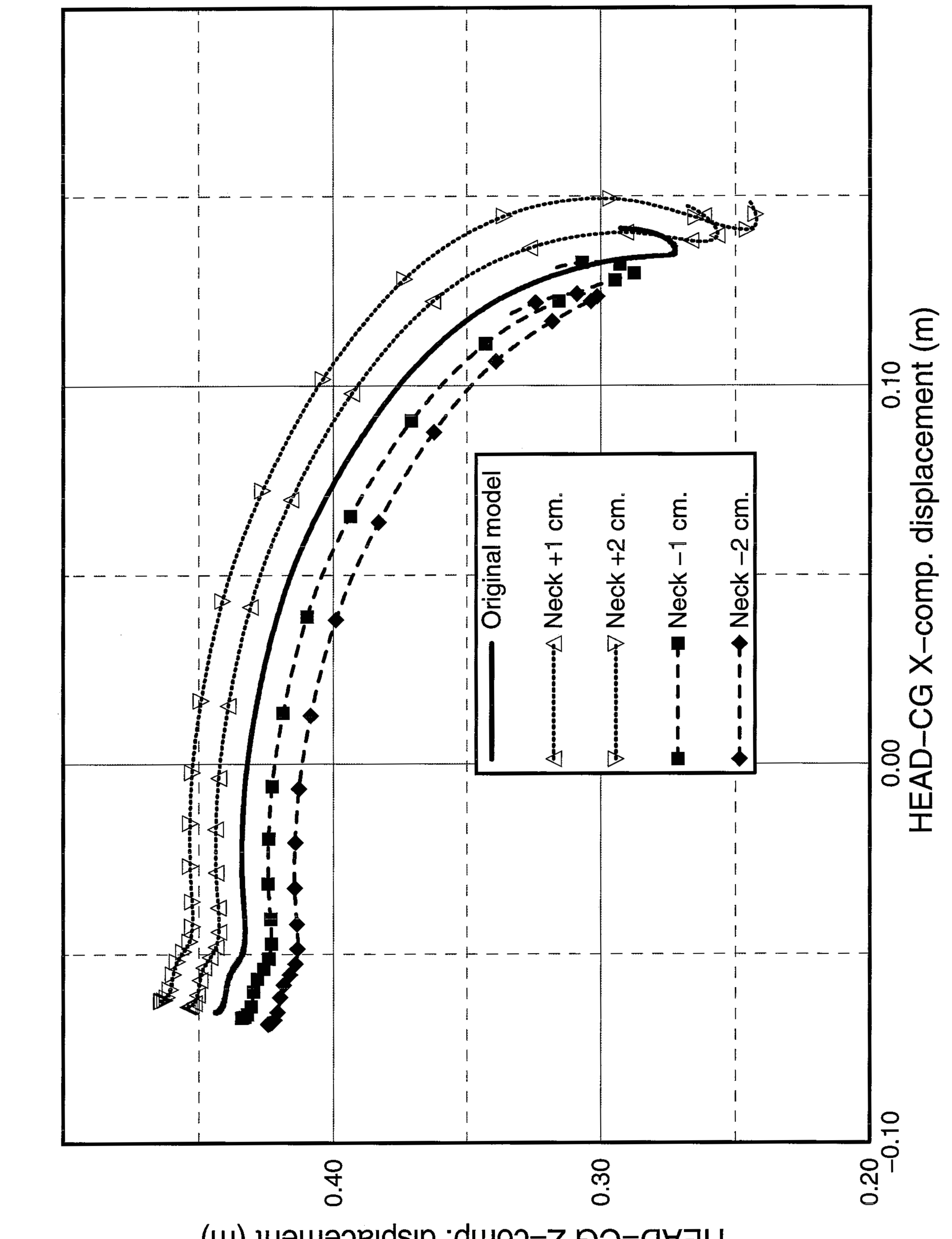

Original model
Neck +1 cm.
Neck +2 cm.
Neck –1 cm.
Neck –2 cm.
HEAD Res. acceleration (m/s**2)
Time (msec)
0
200
400
600
800
0
40
80
120


Original model
Neck +1 cm.
Neck +2 cm.
Neck −1 cm.
Neck −2 cm.
UPPER TORSO Res. acceleration (m/s**2)
Time (msec)
0
100
200
300
0
40
80
120


Original model
Neck +1 cm.
Neck +2 cm.
Neck –1 cm.
Neck –2 cm.
0
40
80
120
Time (msec)
0
20
40
60
80
100
LOWER TORSO – SPINE Resultant Torque (Nm)


Original model
Neck +1 cm.
Neck +2 cm.
Neck −1 cm.
Neck −2 cm.
UPPER TORSO − NECK Resultant Torque (Nm)
Time (msec)
0
10
20
30
40
50
0
40
80
120


Original model
Neck +1 cm.
Neck +2 cm.
Neck −1 cm.
Neck −2 cm.
NECK − ATLAS BLOCK Resultant Torque (Nm)
0.0
0.5
1.0
1.5
2.0
Time (msec)
0
40
80
120


Original model
Neck +1 cm.
Neck +2 cm.
Neck −1 cm.
Neck −2 cm.
HEAD−CG X−comp. displacement (m)
−0.10
0.00
0.10
HEAD−CG Z−comp. displacement (m)
0.20
0.30
0.40