Validation of a detailed human body model in rear impact conditions

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Validation of a Detailed Human Body Model in Rear Impact Conditions

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WFW-report Nr. 98.018

Practical Training carried out at TNO Crash Safety Research Centre, Delft from January 1998 to April 1998.

Under supervision of ir. M.J. van der Horst (TUE/UM) and dr.ir. A.J. van den Kroonenberg (TNO)
Abstract

Neck injuries occur frequently in car crashes, especially in rear-end collisions. The implications for society are serious, as the social costs are high and the complaints are long-lasting. Knowledge of injury mechanisms through which loads cause injuries to the neck is incomplete, especially for minor injuries. In an attempt to minimize the severity and the number of the neck injuries, numerical and experimental study is done to investigate the dynamic behaviour of the head neck system in rear-end collisions and to design safer vehicles.

In this study the head-neck system in a global human body model was replaced by a detailed head-neck model. The global model, the detailed head-neck model and the detailed human body model are described and evaluated by comparison of the model responses to post mortem human subjects (PMHS) responses to a 7g rear impact. Responses that were compared are: linear and angular accelerations of the head, horizontal and vertical displacements of the head, the neck length, and rotations of the head and the neck. Finally the various models are compared to each other.

The main conclusions are that the rotations and displacements of the head-neck system can be well predicted by the global model, as opposed to the head accelerations. The CMN model is not capable of predicting a 7g rear impact correctly and large head and neck rotations and displacements occur. However, this model is suited for predicting frontal and lateral impact. The detailed model is not able to simulate the PMHS experiments correctly, either, but the head accelerations of the detailed model are closer to the PMHS corridors than those of the global model.

Finally it can be stated that the differences between the responses of the CMN model and the detailed model are small and that considering the calculation times, it can be recommended to use the global model for design applications; the CMN model for injury mechanism studies and the detailed model for refinement of designs and injury studies.
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Chapter 1

Introduction

1.1 Introduction

This research is related to neck injuries due to automotive accidents. Neck injuries occur frequently in car crashes, especially in rear-end collisions, where the neck is more easily injured than in other collisions and where injuries occur already at low speeds. These minor injuries are often referred to as whiplash injuries.

Although severe neck injuries can result in serious damage and lead to permanent disability or even death, most of the social costs of neck injuries are caused by minor injuries, due to the resulting long-lasting complaints.

As the human head-neck system is an anatomically and mechanically complex structure, it is not well understood how car-accidents cause low severity neck injuries. Experimental and numerical research can aid to improve this understanding and lead to better models to be used in injury prevention research.

Although many complex biomechanical neck models are presented in literature, only a few models are validated for rear impacts. Van der Horst described a detailed Head-Neck model: the Curved Muscle Neck (CMN) model [4]. In this model the detailed Head-Neck model of De Jager [5] was adapted by adding muscles [3] and improving the muscle geometry, by applying multisegment muscle description, resulting in muscles curving around the vertebrae during neck bending. This CMN model was validated only for frontal and lateral impact volunteer experiments.

Van den Kroonenberg [8] described a global model of the complete human body which was validated for rear-end sled tests with volunteers and post mortem human subjects (PMHS) at different impact levels.

1.2 Existing models

1.2.1 Global Human Body Model

The global human body model described by Van den Kroonenberg [8] is based on the MADYMO model of a 50th percentile sitting adult male Hybrid III dummy. The human
model consists of 3 components: a thoracic and lumbar model representing the human spine up to T2; a head-neck model, starting with T1; and the remaining body parts, such as arms and legs. In figure 1.1 a lateral view of the global human body model is shown in which it is placed on a simple rigid seat and restrained with a 3-point belt.

![Figure 1.1: Lateral view of the global human body model.](image)

**Lumbar and Thoracic Spine Model** The spine model consists of 16 bodies representing the lumbar and thoracic vertebrae (except T1), in which the intervertebral discs are incorporated. In this spine model only two degrees of motion are allowed: flexion/extension in the plane of impact and axial elongation/compression. Regarding the flexion/extension motion, linear stiffnesses are defined for each of the joints to represent the soft tissue and muscles acting at the joints. The stiffness increases non-linearly. The location and orientation of the spine joints are chosen according to the antropometry of a 50th percentile seated adult male.

**Head-Neck Model** The head and cervical spine are represented by the global neck model developed by De Jager [5, 6]. This model consists of nine rigid bodies for the head, the seven cervical vertebrae and the first thoracic vertebra (T1). The bodies are connected by three dimensional non-linear viscoelastic elements and the muscle behaviour is lumped into the intervertebral joint stiffness. This model was validated for frontal impacts.

Van den Kroonenberg validated the global human body model for rear impacts and changed the stiffness characteristics for flexion/extension of the neck joints slightly, as the total head rotation was too great.

For a detailed description of the global human body model, the reader is referred to Van den Kroonenberg [8].

### 1.2.2 Curved Muscle Neck Model

The Curved Muscle Neck Model by Van der Horst [4], comprises nine rigid bodies, representing the first thoracic vertebra (T1), the cervical vertebrae (C1-C7) and the head (C0). The skull and the vertebrae with spinous and transverse processes and
Articular facets are represented by ellipsoids. The bodies are connected through three-dimensional linear viscoelastic discs, two-dimensional nonlinear viscoelastic ligaments, frictionless facet-joints (ellipsoid contacts) and curved contractile Hill-type muscles. In figure 1.2 a frontal and a lateral view of the CMN model is shown. In figure 3.1 a lateral view of the CMN model is shown in which the muscles are made invisible, in order to show the vertebrae, the facets and the ligaments more clearly.

Figure 1.2: frontal and lateral view of the CMN model

For this study some adaptations have been made to the CMN model. The insertions of one muscle (longissimus cervicis) have been slightly moved (see Appendix A, table A.2) and contact is defined between the spinous processes of the vertebrae, in order to make the model more anatomically correct.

For a detailed description of the CMN model, the reader is referred to Van der Horst [4]. A description of the muscles is given in Appendix A.

As the CMN model was not validated for rear-end impact and the global model was only validated limited, these models are evaluated in this study. It is not proved whether it is allowed to study the dynamic behaviour of the head-neck system with merely a head-neck model. Because of that, the influence of the mass of the body on the dynamic behaviour of the head-neck system is investigated. In this study a detailed human body model is created by replacing the head-neck system of the global human body model by the CMN model. This model will be tested for rear impacts in order to study the dynamic behaviour of the human head-neck system in rear-end collisions. In the future, an improved version of this model might be used to study injury mechanisms.
1.3 Objectives

As the CMN model was not validated for rear-end impact and the global model was only validated limited, these models are evaluated in this study. It is not proved whether it is allowed to study the dynamic behaviour of the head-neck system with merely a head-neck model. Because of that, the influence of the mass of the body on the dynamic behaviour of the head-neck system is investigated. In this study a detailed human body model is created by replacing the head-neck system of the global human body model by the CMN model. This model will be tested for rear impacts in order to study the dynamic behaviour of the human head-neck system in rear-end collisions. In the future, an improved version of this model might be used to study injury mechanisms.

The objectives of this study are:

- to evaluate the existing models for a 7g rear impact in which no head contact occurs,
- to create a detailed model by adding the CMN model by Van der Horst to the global human body model by Van den Kroonenberg,
- to validate this detailed human body model with PMHS responses in a 7g rear sled test in which no head contact occurs and
- to compare the various models.

1.4 Overview

In chapter 2 the detailed human body model will be described. Further a description will be given of the PMHS experiments and the simulations that are carried out with MADYMO. In chapter 3 results of the simulations with various models will be shown. In chapter 4 the results of the experiments and the simulations will be discussed. Finally, conclusions will be drawn in chapter 5 and recommendations for future research will be suggested.
Chapter 2

Method

The original human body model is adapted by replacing the head-neck system by the improved version of the CMN model of Van der Horst. This detailed human body model is tested for PMHS responses to a 7g rear impact. Responses that will be compared are: linear horizontal acceleration of T1, linear and angular accelerations of the head, horizontal and vertical displacements of the head, the neck length, and rotations of the head and the neck.

Both active and passive muscle behaviour will be validated to simulate the influence of muscle activation. The responses of this new detailed human body model will be compared with the response of the CMN model and the global human body model. The validation will be carried out with the software package MADYMO (MAthematical DYnamical MOdels), version 5.3, developed by TNO Crash Safety Research Centre. The models are described by using the multibody module [14, 15].

2.1 Detailed Human Body Model

In the detailed human body model the global head-neck model is replaced by the CMN model. The model consists of 3 components: a thoracic and lumbar model representing the human spine up to T2; a head-neck model, starting with T1 (this is the modified CMN model); and the remaining body parts, such as arms and legs.

The head-neck model comprises nine rigid bodies, representing the first thoracic vertebra (T1), the cervical vertebrae (C1-C7) and the head (C0). The skull and the vertebrae with spinous and transverse processes and articular facets are represented by ellipsoids. The bodies are connected through three-dimensional linear viscoelastic discs, two-dimensional nonlinear viscoelastic ligaments, frictionless facet-joints (ellipsoid contacts) and curved contractile Hill-type muscles.

All muscles which were attached to T1 in the CMN model are inserted to their anatomically correct body of origin in the detailed model, except the muscles which are in reality inserted to the scapulae, the ribs, the sternum and the clavicles. The reason for this is that these parts of the body are not modelled anatomically correct in the global model. So, before inserting muscles to these bodyparts, those parts should be remodelled first. Thus, visually the insertions of the muscles are not changed (except for the muscles that were slightly moved compared to the original CMN model); merely the bodies to which they are inserted have been changed.
Table A.1 and A.2 in Appendix A give an overview of the modelled muscles. They also show which muscles are modified, of which muscles the insertions have been moved and which muscles should be inserted to different bodies in future versions of the model.

In figure 2.1 a lateral view of the detailed human body model, placed on a rigid seat is shown.

![Figure 2.1: lateral view of the detailed human body model](image)

### 2.2 Experiments

Two identical 7g rear impact PMHS experiments were conducted at the University of Heidelberg in 1993 [13]. In these experiments the PMHS’s were seated in an upright position on a 90 degrees rigid seat which was mounted on a sled and restrained by diagonal shoulder straps and a lap strap. The arms were restrained by an additional belt.

The human body models have been validated for these PMHS experiments.

Corridors are available for:
- the linear and angular acceleration of the head’s centre of gravity relative to the inertial space, corrected for the prescribed acceleration (+x is forward, +y is left, +z is up);
- the trajectories of the occipital condyles (OC) and the head’s centre of gravity (CG) relative to the T1-vertebral body;
- the neck link length, which is defined as the length of the straight line between T1 and the occipital condyles;
- the neck rotation, i.e. the neck link rotation relative to T1;
- the head rotation, i.e. the rotation of the head’s centre of gravity relative to T1 and
- the head lag, which is the neck rotation as a function of the head rotation.
In figure B.1 the responses of those experiments are shown. Each figure shows the positive and negative standard deviation of the responses of two human cadaver subjects.

2.3 Simulations

The average horizontal acceleration in impact direction of the sled is used as input to the human body model to simulate the impact; as input for the neck model the average horizontal acceleration of vertebra T1 in the experiment is used [4, 13]. These accelerations are shown in figure 2.2. Simulations are run for 200 ms.

![Figure 2.2](image)

Figure 2.2: Acceleration used as input to the models to simulate the impact.

The effect of muscle activation on the head-neck response is evaluated by simulations with (active) and without (passive) muscle activation, as the behaviour of the PMHS's lies in between active and passive muscle behaviour: in cadavers no muscle activation occurs, but due to death changes in the material properties with respect to living tissue have occurred resulting in stiffening of the muscles.

In the simulations with active muscle behaviour, the flexor muscles are 100% activated to oppose the extension motion of the head and neck and a reflex time of 25 ms is used [4].

In reality, the neck muscles are slightly activated to maintain the initial position of the head in the presence of gravitational forces. To simulate this behaviour, a complex feedback mechanism is needed. As this mechanism is not included in the model, gravity is neglected in all simulations.
Chapter 3

Results

3.1 Global Model

Van den Kroonenberg [8] reported that the global model fits well within the corridors. However, this model was validated in a limited way. The dynamic behaviour of the model is tested by comparison with rear-end sled tests with human volunteers and human cadavers. Of the head-neck system merely the overall kinematics, the head angle and the vertical displacement of T1 are considered. Because of that, the model is tested again in this study and head accelerations are considered, too.

In figure C.1 the response of the global human body model to a 7g rear-end sled test is compared with the PMHS corridors. From that figure it can be seen that a large peak occurs in the head accelerations at 150 ms. The OC and CG trajectories show a shift in the initial position of head, but the shape of the curves agrees with the corridors. The neck length and the neck rotation agree reasonably with the corridors, whereas the head rotation is almost twice as large as the PMHS respons.

3.2 CMN Model

Including contact between the spinous processi and modifying four muscle insertions alter the responses only slightly. Comparison of the overall dynamics of the original and the modified CMN model learns that the neck bends in all joints after the modification.

In figure 3.1 the overall dynamics of the CMN model with active muscle behaviour are shown. For clarity, the muscles are not shown in this figure.
Figure 3.1: Initial position and extreme extension of the CMN model for 7g rear impact. For clarity, muscles are not shown.

From this figure it can be seen that the curvature of the neck is very large and that the articular facets loose contact. In reality this can only occur if the ligaments are torn. However, no rupture occurred in the PMHS experiments that are simulated in this study.

Figure C.2 shows the response of this model, both active and passive. The head accelerations show a peak up to three times as large as the accelerations of the PMHS's. The displacements of the occipital condyles and the head's centre of gravity are a factor of two as large as the PMHS response and the head and neck rotation are a factor of six and a factor of two too large respectively, compared to the PMHS corridors. However, the neck length is close to the corridors for active muscle behaviour. The initial position of the occipital condyles and the head's centre of gravity agree with the PMHS corridors.

Muscle activation influences the responses: the peaks in the acceleration decrease and the neck length decreases significantly. Head trajectories and head and neck rotations are closer to the corridors, too.

3.3 Detailed Model

In figure 3.2 the T1 acceleration of the CMN model, which was measured in PMHS experiments, is compared to the T1 acceleration which is generated by the simulation of the sled test with the detailed human body model.
Figure 3.2: X-component of linear T1-cg accelerations in the human body model and in the experiment.

From this figure it can be seen that the T1 acceleration generated by the simulation shows noise at 150 ms. This might be caused by numerical effects. It can also be seen that the T1 accelerations for the simulation with passive and active muscle behaviour do not differ considerably. Furthermore the figure shows that the pulses in the experiment and the simulations lie close during the first 100 ms, but differ after the first 100 ms.

**Overall Dynamics** Figure 3.3 illustrates the overall dynamic behaviour of the human model with active muscle behaviour during the impact. The time interval between the images is 40 ms.

Figure 3.3: Overall kinematics of detailed human body model with muscle activation. The time interval between the images is 40 ms, muscles are not shown for clarity.

From this figure it can be seen that the neck joint rotations are large. It is also clear that the pelvis is lifted from the seat. It can also be noted from this figure and from
the head lag in figure C.3 that the head extension is preceded by a rearward translation of the head.

Figure C.3 shows the results of the detailed human body model compared to the PMHS corridors. The head accelerations are up to a factor of two too large, and the initial position of the head is different than in the PMHS experiments. The x and z-displacements of the head are a factor of two and eight too large respectively. The neck length lies between the corridors and the neck rotation is close to the corridors. The head rotation is a factor of five larger than the PMHS response.

Figure C.4 shows the results of the detailed model compared to the CMN model. For this figure a simulation is done for the CMN model in which as input the T1 pulse is used which was generated with the detailed human body model. That means that exactly the same T1 pulses are working on the head-neck system of both models. From this figure it can be seen that the difference between the models is small. However, there is a difference although the accelerations on both models are equal. The figure with the trajectories shows that the initial position of the CMN model is much closer to the corridors than the initial position of the detailed model.

Figure C.5 shows the results of the detailed human body model compared to the global model. The accelerations of the detailed model are slightly closer to the PMHS corridors than the accelerations of the global model, as is the neck length. However, the head and neck rotations and the trajectories of the global model are much closer to the PMHS corridors than those of the detailed model.

The calculation times of the global, the CMN and the detailed model are respectively 3, 13 and 18 minutes.
In this study, the CMN model is placed on the global human body model. The model consists of a lumbar and thoracic spine model, a detailed head-neck model and remaining body parts. The CMN model is used to represent the head-neck system. This model consists of rigid head and vertebrae, linear viscoelastic discs, frictionless facet joints, nonlinear viscoelastic ligaments and segmented contractile muscles. PMHS responses to 7g rear impact experiments are used to evaluate the global, CMN and detailed model.

**Global Model**  As this model was validated in a limited way and was tuned for head angles, the head angles agree reasonably well with the corridors, but the accelerations are too large. The shift in the trajectories may be explained by the difference in the initial position of the seats that are used in the experiments and the simulations.

**CMN Model**  Although the muscles are activated and contact is defined between the spinous processes, extreme joint rotations occur during rear impact, causing unrealistic large head and neck rotation, especially in case of no muscle activity. However, the responses of the CMN model for frontal and lateral impact agree well with the corridors [4].

**Detailed Model**  Like the CMN model, the detailed model shows extreme joint rotations, resulting in too large head and neck rotations. However, active muscle behaviour slightly improves the response of the model. Due to the difference in the initial position of the seats a shift occurs in the OC and CG trajectories.

The difference between the T1 pulse that is generated by the detailed model and the T1 pulse that was measured in the experiments that occurs after 100 ms, show that the model is not able to describe the behaviour of the body under the head-neck system correctly. Part of the difference may be explained by the different seats and different restraints that are used in the experiments and simulations.

The response of the global model is significantly influenced by replacing the head-neck system with the CMN model. The accelerations and the neck length are improved significantly, especially the angular acceleration, which is reduced by a factor of 2. However, the head and neck rotation of the global model are much closer to the corridors.
than the detailed model. This can be explained by the fact that the global model was
tuned for the head rotation and accelerations were not considered.
In both simulations the initial position of the head is poor. This can be explained by
the different seats in the simulation and the PMHS experiments.

The responses that are shown in figure C.4 are obtained by putting the same T1 pulses
on the head-system in both models. Therefore it can be stated that any difference in
the responses is caused by a difference in the models (such as the mass of the remaining
body and the different initial positions).
As the results only differ slightly, it can be concluded that the influence of the mass
of the remaining body under the head-neck system is minor. However, the influence of
the seat on the responses of the models should be investigated.

In both the detailed and CMN model extreme joint rotations occur causing too large
head and neck rotation. Therefore the neck response at the segmental level needs to be
improved, which may be achieved by improving the characteristics of the intervertebral
disks and ligamental structure, preventing the facet joints to loose contact.

Experiments
Only two PMHS experiments are used for the corridors. Sometimes
the graphs of figure B.1 cross or coincide. Because of that the results of the experiment
should not be called corridors.
Besides, the PMHS's are seated upright, which causes a deviation of the initial position
of the head. Also, the PMHS's were restrained differently from the models in the
simulations and the arms were also restrained. An extra disadvantage of the PMHS
experiments is the absence of muscle activation and the change in material properties
with respect to living tissue.
For those reasons the corridors should be regarded with caution.

In all simulations gravity was neglected, although gravitational forces play an impor-
tant role in the PMHS experiments. Adding gravitational forces in the model will lead
to even larger head displacements due to inertial properties. Therefore a new adapta-
tion of the model will be needed in which gravitational forces can be applied requiring
an equilibrium in initial position of the head-neck system.

Calculation Times
From the calculation times as stated in the previous chapter, it is
clear that the detailed model needs most calculation time, although the difference
with the CMN model is small. Therefore it can be recommended to use the global
model for design applications such as seats and airbags. In the future, the CMN model
might be used to study injury mechanisms in rear impact and the detailed human body
model might be used to refine the designs that are made by using the global model.
Chapter 5

Conclusions and Recommendations

5.1 Conclusions

- The CMN model is placed on the global human body model and muscle insertions are changed. The model consists of a lumbar and thoracic spine model, a detailed head-neck model and remaining body parts. The CMN model is used to represent the head-neck system. This model comprises head and vertebrae connected by intervertebral discs, facet joints, ligaments and segmented Hill-type muscles.

- The global human body model, the CMN model and the detailed human body model are evaluated for 7g rear impact PMHS experiments without head contact. The CMN model and the detailed model are evaluated with passive and active muscle behaviour and a reflex time (in active muscle behaviour) of 25 ms.

- The rotation and displacements of the head-neck system can be well predicted by the global model. The head accelerations can not be predicted correctly by this model and are a factor of two to large compared to the PMHS response.

- The CMN model is not capable of predicting a 7g rear impact correctly. Due to large joint rotations unrealistic large head and neck rotations and displacements occur. However, the model is suited for predicting frontal and lateral impact [4].

- The detailed model is not able to simulate the PMHS experiments correctly. The head accelerations, rotations and displacements are too large. However, the head accelerations of the detailed model are closer to the PMHS corridors than those of the global model, in contradistinction to the head rotations and displacements, which are closer to the corridors for the simulations with the global model.

- The differences between the responses of the CMN model and the detailed model are small. So the influence of the mass of the remaining body under the head-neck system is small and merely the head-neck model should be sufficient to study the behaviour of the head-neck system during impact.
• Considering the calculation times, it can be recommended to use the global model for design applications; the CMN model can be used to study injury mechanisms and the detailed model might be used to refine designs and injury studies.

5.2 Recommendations

• The simulations should be carried out with the same seat position and restraint as the experiments. Furthermore the initial position should be varied to investigate the influence of the initial position of the model.

• As the calculation times are long, it is recommended to do a sensitivity analysis on the muscles in order to investigate whether the model comprises muscles which are less relevant for rear impact than for frontal and lateral impact. In order to decrease the calculation times, these muscles might be removed from the model for rear impact.

• A new adaptation of the model will be needed in which gravitational forces can be applied requiring an equilibrium in initial position of the head-neck system.

• More experimental data on rear-end sled tests with human volunteers and PMHS's are needed to validate the model thoroughly.

• The neck response at the segmental level needs to be improved, by improving the geometry of the atlanto-occipital joint and the atlanto-axial joint, the ligamental structure and the characteristics of the intervertebral discs, see [5]. This might be reached by defining a new center of rotation for the intervertebral discs. De Jager used different positions for these centers than Van Mameren and Dvorak found [2, 9, 10]. Furthermore more experimental data are needed to improve the modelling of the ligaments and the intervertebral disc. No information is found by the author on measuring of damping characteristics of the intervertebral discs and stiffness of the discs is measured with disc segments that comprised anterior and posterior longitudinal ligaments [5].

5.3 Acknowledgements

I would like to thank Dr. H. van Mameren of the University of Maastricht and Dr. J. Patijn of SMG Eindhoven, who assisted me with the anatomical structure of the head-neck system and who gave suggestions for improving the model.
Bibliography


20
Appendix A

Modelled Muscles in the Detailed Human Body Model

In table A.1 and A.2 an overview is given of the muscles that are used in the model. In table A.1 all modelled flexor muscles are shown and in table A.2 all extensor muscles are shown. For a detailed description of the human muscle anatomy, the reader is referred to [1, 7, 11, 12].

Table A.1: Flexor muscles

<table>
<thead>
<tr>
<th>Flexor muscle</th>
<th>Origin</th>
<th>Insertion</th>
</tr>
</thead>
<tbody>
<tr>
<td>longus colli</td>
<td>T1</td>
<td>C6</td>
</tr>
<tr>
<td>longus colli</td>
<td>T1</td>
<td>C5</td>
</tr>
<tr>
<td>longus colli</td>
<td>T1</td>
<td>C4</td>
</tr>
<tr>
<td>longus colli</td>
<td>T1</td>
<td>C3</td>
</tr>
<tr>
<td>longus colli</td>
<td>T1</td>
<td>C2</td>
</tr>
<tr>
<td>longus colli</td>
<td>T1</td>
<td>C1</td>
</tr>
<tr>
<td>longus colli</td>
<td>T1</td>
<td>Skull</td>
</tr>
<tr>
<td>longus capitis</td>
<td>C3</td>
<td>Skull</td>
</tr>
<tr>
<td>longus capitis</td>
<td>C4</td>
<td>Skull</td>
</tr>
<tr>
<td>longus capitis</td>
<td>C5</td>
<td>Skull</td>
</tr>
<tr>
<td>longus capitis</td>
<td>C6</td>
<td>Skull</td>
</tr>
<tr>
<td>scalenus anterior</td>
<td>T1</td>
<td>C4</td>
</tr>
<tr>
<td>scalenus medius</td>
<td>T1</td>
<td>C3</td>
</tr>
<tr>
<td>scalenus anterior</td>
<td>T2</td>
<td>C5</td>
</tr>
<tr>
<td>lumped hyoids</td>
<td>T1</td>
<td>Skull</td>
</tr>
</tbody>
</table>

\[b\] inserted to other body compared to Van der Horst model
\[c\] should be inserted to other body in future versions

The tables also show of which muscles the insertions are moved compared to the original CMN model (\[a\]), which muscles are inserted to different bodies compared to the the original CMN model (\[b\]) and which muscles are in reality inserted to another body.
Appendix A: Modelled Muscles in the Detailed Human Body Model

than in the current detailed model (\(^\circ\)).
The following muscles are inserted to different bodies than in reality:
- the scaleni; originate from T1 and T2 in stead of 1\(^{st}\) and 2\(^{nd}\) rib,
- the lumped hyoids; originate from T1 in stead of sternum and scapulae,
- the trapezius; originates from T1 in stead of clavicles and scapulae,
- the sternocleidomastoid; originates from T1 in stead of sternum and clavicle, and
- the levator scapulae; originate from T1 in stead of scapulae.

As stated before, visually the insertions of the muscles are not changed (except for
the muscles marked with \(^a\)); merely the bodies to which they are inserted have been
changed.

Table A.2: Extensor muscles

<table>
<thead>
<tr>
<th>Extensor muscle</th>
<th>Origin</th>
<th>Insertion</th>
<th>Extensor muscle</th>
<th>Origin</th>
<th>Insertion</th>
</tr>
</thead>
<tbody>
<tr>
<td>trapezius (^c)</td>
<td>T1</td>
<td>Skull</td>
<td>longissimus cervicis (^b)</td>
<td>T2</td>
<td>C2</td>
</tr>
<tr>
<td>sternocleidomastoid (^c)</td>
<td>T1</td>
<td>Skull</td>
<td>longissimus cervicis (^b)</td>
<td>T2</td>
<td>C3</td>
</tr>
<tr>
<td>splenius capitis (^b)</td>
<td>T2</td>
<td>Skull</td>
<td>longissimus cervicis (^b)</td>
<td>T2</td>
<td>C5</td>
</tr>
<tr>
<td>splenius cervicis (^b)</td>
<td>T3</td>
<td>C3</td>
<td>longissimus cervicis (^a,b)</td>
<td>T2</td>
<td>C6</td>
</tr>
<tr>
<td>splenius cervicis (^b)</td>
<td>T3</td>
<td>C2</td>
<td>longissimus cervicis (^a,b)</td>
<td>T2</td>
<td>C7</td>
</tr>
<tr>
<td>splenius cervicis (^b)</td>
<td>T3</td>
<td>C1</td>
<td>levator scapulae (^c)</td>
<td>T1</td>
<td>C1</td>
</tr>
<tr>
<td>semispinalis capitis</td>
<td>C4</td>
<td>Skull</td>
<td>levator scapulae (^c)</td>
<td>T1</td>
<td>C2</td>
</tr>
<tr>
<td>semispinalis capitis</td>
<td>C5</td>
<td>Skull</td>
<td>levator scapulae (^c)</td>
<td>T1</td>
<td>C3</td>
</tr>
<tr>
<td>semispinalis capitis</td>
<td>C6</td>
<td>Skull</td>
<td>levator scapulae (^c)</td>
<td>T1</td>
<td>C4</td>
</tr>
<tr>
<td>semispinalis capitis</td>
<td>C7</td>
<td>Skull</td>
<td>multifidus cervicis</td>
<td>C5</td>
<td>C2</td>
</tr>
<tr>
<td>semispinalis capitis (^b)</td>
<td>T3</td>
<td>Skull</td>
<td>multifidus cervicis</td>
<td>C6</td>
<td>C2</td>
</tr>
<tr>
<td>semispinalis cervicis (^b)</td>
<td>T1</td>
<td>C2</td>
<td>multifidus cervicis</td>
<td>C6</td>
<td>C3</td>
</tr>
<tr>
<td>semispinalis cervicis (^b)</td>
<td>T2</td>
<td>C3</td>
<td>multifidus cervicis</td>
<td>C7</td>
<td>C3</td>
</tr>
<tr>
<td>semispinalis cervicis (^b)</td>
<td>T3</td>
<td>C4</td>
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<td>C7</td>
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<td>semispinalis cervicis (^b)</td>
<td>T4</td>
<td>C5</td>
<td>multifidus cervicis</td>
<td>T1</td>
<td>C4</td>
</tr>
<tr>
<td>semispinalis cervicis (^b)</td>
<td>T5</td>
<td>C6</td>
<td>multifidus cervicis</td>
<td>T1</td>
<td>C5</td>
</tr>
<tr>
<td>semispinalis cervicis (^b)</td>
<td>T6</td>
<td>C7</td>
<td>multifidus cervicis (^b)</td>
<td>T2</td>
<td>C5</td>
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<td>longissimus capitis</td>
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<td>T2</td>
<td>C6</td>
</tr>
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<td>longissimus capitis</td>
<td>C4</td>
<td>Skull</td>
<td>multifidus cervicis (^b)</td>
<td>T3</td>
<td>C6</td>
</tr>
<tr>
<td>longissimus capitis</td>
<td>C5</td>
<td>Skull</td>
<td>multifidus cervicis (^b)</td>
<td>T3</td>
<td>C7</td>
</tr>
<tr>
<td>longissimus capitis</td>
<td>C6</td>
<td>Skull</td>
<td>multifidus cervicis (^b)</td>
<td>T4</td>
<td>C7</td>
</tr>
<tr>
<td>longissimus capitis (^b)</td>
<td>T2</td>
<td>Skull</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

\(^a\) origin moved compared to Van der Horst model
\(^b\) inserted to other body compared to Van der Horst model
\(^c\) should be inserted to other body in future versions

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Appendix B

Responses of the PMHS Experiments
Appendix B: Responses of the PMHS Experiments

PMHS corridor (2 experiments)

7g rear end impact

resultant linear acceleration

linear x-acceleration

linear z-acceleration

linear 14-acccleration

OC and CG trajectory

head lag

head y-rotation

neck y-rotation

Figure B.1: Positive and negative standard deviation of the PMHS responses to 7g rear impact. Shown are: the linear and angular acceleration of the head's centre of gravity relative to the inertial space, corrected for the prescribed acceleration (+x is forward, +y is left, +z is up); the trajectories of the occipital condyles (OC) and the head's centre of gravity (CG) relative to the T1-vertebral body; the neck link length, which is defined as the length of the straight line between T1 and the occipital condyles; the neck rotation, i.e. the neck link rotation relative to T1; the head rotation, i.e. the rotation of the head's centre of gravity relative to T1 and the head lag, which is the neck rotation as a function of the head rotation. In the figure of the OC and CG trajectory, the upper graph is the CG trajectory and the lower graph is the OC trajectory.
Appendix C

Responses of the Models
Appendix C: Responses of the Models

- global human body model
- PMHS corridor (2 experiments)

---

global human body model

resultant linear acceleration

linear x–acceleration

linear z–acceleration

OC and CG trajectory

angular y–acceleration

neck length

head lag

head y–rotation

neck y–rotation

---

Figure C.1: Response to 7g rear impact of the global human body model compared with PMHS corridors.
Appendix C: Responses of the Models

- active CMN model
- PMHS corridor (2 experiments)
- passive CMN model

CMN model

Figure C.2: Response to 7g rear impact of the CMN model with passive and active muscle behaviour compared with PMHS corridors.
Appendix C: Responses of the Models

- active detailed human body model
- PMHS corridor (2 experiments)
- passive detailed human body model

**detailed human body model**

![Graphs showing responses](image)

**Figure C.3:** Response to 7g rear impact of the detailed human body model model with passive and active muscle behaviour compared with PMHS corridors.
Appendix C: Responses of the Models

PMHS corridor (2 experiments)
•- active CMN model with generated T1 pulse
•-- active detailed body model

CMN and detailed model

resultant linear acceleration

linear x-acceleration

linear z-acceleration

OC and CG trajectory

angular y-acceleration

neck length

head lag

head y-rotation

neck y-rotation

Figure C.4: Responses to 7g rear impact of the detailed human body model and CMN model compared with PMHS corridors. For the CMN model the T1 pulse is used which is generated by the detailed model. Thus, the same T1 acceleration is applied to both models.
Appendix C: Responses of the Models

- active detailed human body model
- PMHS corridor (2 experiments)
- global human body model

global and detailed human body model

resultant linear acceleration
linear x-acceleration
linear z-acceleration

OC and CG trajectory
angular y-acceleration
neck length

head lag
head y-rotation
neck y-rotation

Figure C.5: Response to 7g rear impact of the global and detailed human body model compared with PMHS corridors.