EVALUATION OF THE DYNAMIC AND KINEMATIC PERFORMANCE OF THE THOR DUMMY: NECK PERFORMANCE

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ABSTRACT

The objective of this study is to evaluate the frontal head-neck performance of the THOR neck with respect to the human frontal head-neck performance and the Hybrid-III frontal head-neck performance. For this purpose, tests were carried out with an isolated THOR and Hybrid-III head-neck system on a HyGe sled. The acceleration applied to the dummy head-neck system is comparable to the T1 acceleration experienced by volunteers during testing at the Naval Biodynamics Laboratory in the eighties. The Hybrid-III and THOR neck response is compared with human neck response corridors. The study revealed that, although the THOR neck needs some further improvement, its response during frontal flexion is much more biofidelic than the Hybrid-III neck response.

IN OCTOBER 1998, EUROPEAN regulation 96/79/EC for protection of car occupants in frontal collisions will become effective. In this regulation, a full scale crash test is proposed in which the vehicle impacts a deformable structure at a velocity of 56 km/hr (Lowne, 1996; Directive 96/79/EC). The 50th percentile Hybrid-III crash dummy will be used to measure biomechanical criteria. Several studies (Cesari, 1990; Thunnissen, 1995; Lowne, 1996; Beusenberg, 1996) have indicated that the Hybrid-III design is only partly suitable to assess injury risk in European restraint conditions. Therefore, the European Community decided to sponsor the ADRIA Consortium[1]. This consortium will evaluate new promising dummy parts for frontal impact tests. The work of the consortium also includes review of existing biomechanical knowledge and accident reconstructions.

[1] ADRIA is the acronym for Advanced Crash Dummy Research for Injury Assessment in Frontal Test Conditions. The ADRIA consortium has started its work in February 1997 and involves INRETS, Transport Research Laboratory, TNO Crash Safety Research Centre, University of Heidelberg, University of Madrid, University of Eindhoven (Technical Annex Contract PL96-1074, 1997).

THOR

Part of the work in the ADRIA project involves evaluation of the THOR[2] dummy, a new frontal crash test dummy which has been developed in the US. This dummy is the successor of the TAD-50m (Melvin, 1988; Schneider, 1992) and has been developed under contract of NHTSA (US National Highway Traffic Safety Administration) by GESAC.

The THOR (shown in Figure 1) incorporates several specific features which are different from other (frontal) dummies: a new shoulder design and a new upper torso design with articulation point which allow the THOR to interact realistically with the restraint systems, an instrumented abdomen to detect dynamic interaction with belt and airbag, a multi-directional neck to accurately simulate head motion, and a face which allows facial fracture measurements.

One of the important criticised Hybrid-III parts is the neck (Saul, 1984, Hoen, 1986, Seemann, 1986, Thunnissen, 1995, Beusenberg, 1996). This paper will focus on the THOR frontal neck performance, in comparison with Hybrid-III and volunteers.

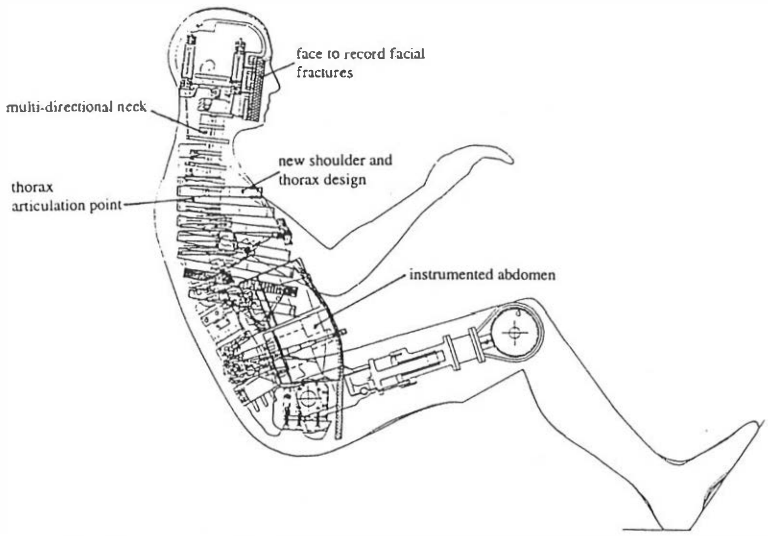

Figure 1 - THOR Dummy

The THOR head and neck (Figure 5) are assembled at the condyles pin and by means of two cables: one at the front and one at the back of the neck. These cables are connected to springs assembled in the THOR head. Before every test, the springs are hand-tightened to keep the head upright before a test, however no large pretension is applied to the cables. The upper neck load cell records forces and torques at the top of the neck. The tension forces in the front and aft cables are recorded with a front spring load cell and an aft spring load cell respectively. A lower neck load cell records loads at the neck base.

The THOR neck construction influences the load transmission from head to neck (and visa versa): as long as the head translates and the neck rotates with respect to the inertial space, no torque will be generated at the occipital condyles joint. The relative rotation between head and neck takes place without significant friction at the condyles pin.

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[2] THOR is the acronym for Test Device for Human Occupant Restraint

As soon as the head position is 'locked' with respect to the neck (i.e. the aft soft stop hits the upper neck load cell surface), a moment is build at the condyles pin.

AIMS

The aim of this study is twofold:

1. establish THOR frontal neck performance and compare the performance with the Hybrid-III response and volunteer response.
2. test the durability and repeatability of the THOR dummy neck.

MATERIAL AND METHODS

PERFORMANCE REQUIREMENTS - A minimum set of frontal neck performance requirements were described by Thunnissen et al (1995), based on nine volunteer tests conducted by the Naval Biodynamics Laboratory (NBDL) in New Orleans (Ewing, 1973). This set consists of:

1. head centre of gravity trajectory or, as an alternative, the occipital condyles trajectory relative to T1
2. head rotation (flexion) as a function of time relative to T1
3. resultant head centre of gravity acceleration as a function of time
4. mid-sagittal head rotational acceleration as a function of time or, as an alternative, the mid-sagittal moment of force around the occipital condyles joint.

The NBDL volunteers were strapped tightly into their seat, allowing just the head, neck and a small part of the upper thoracic spine to deform during the impact. Translations and rotations of T1 relative to the sled were observed. In analyses used by NHTSA to define the requirements for the THOR dummy neck (Klinich, 1992; Beusenberg, 1994) T1 rotations has been neglected. In other words, T1 was assumed to stay aligned with the sled co-ordinate system. Such requirements are valid if indeed the rotation at the dummy's T1 level (i.e. neck base) with respect to the laboratory co-ordinate system, due to rotation in the upper thoracic spine, is minimal. In order to make proper judgement of the THOR neck response possible, the proposed requirements by Thunnissen (1995) have been updated and expressed with respect to a non-rotating T1 co-ordinate system.

A trajectory does not include any indication for timing of the kinematics, therefore the X and Z displacement of either occipital condyles or head centre of gravity versus time are added to the performance requirement set. 'Head lag' of the head-neck system has also been added as an additional requirement to the proposed criteria of Thunnissen et al (1995). Head lag occurs during the first part of a frontal impact: the head translates and shows negligible rotation while the neck is already deforming (see further Appendix A). It is interesting to compare the response of THOR and Hybrid-III with the volunteer response as the THOR construction is specifically designed to simulate 'head lag'.

The resulting frontal neck performance requirement corridors are presented in Figure 2. The corridors are the mean value minus and plus the standard deviation.

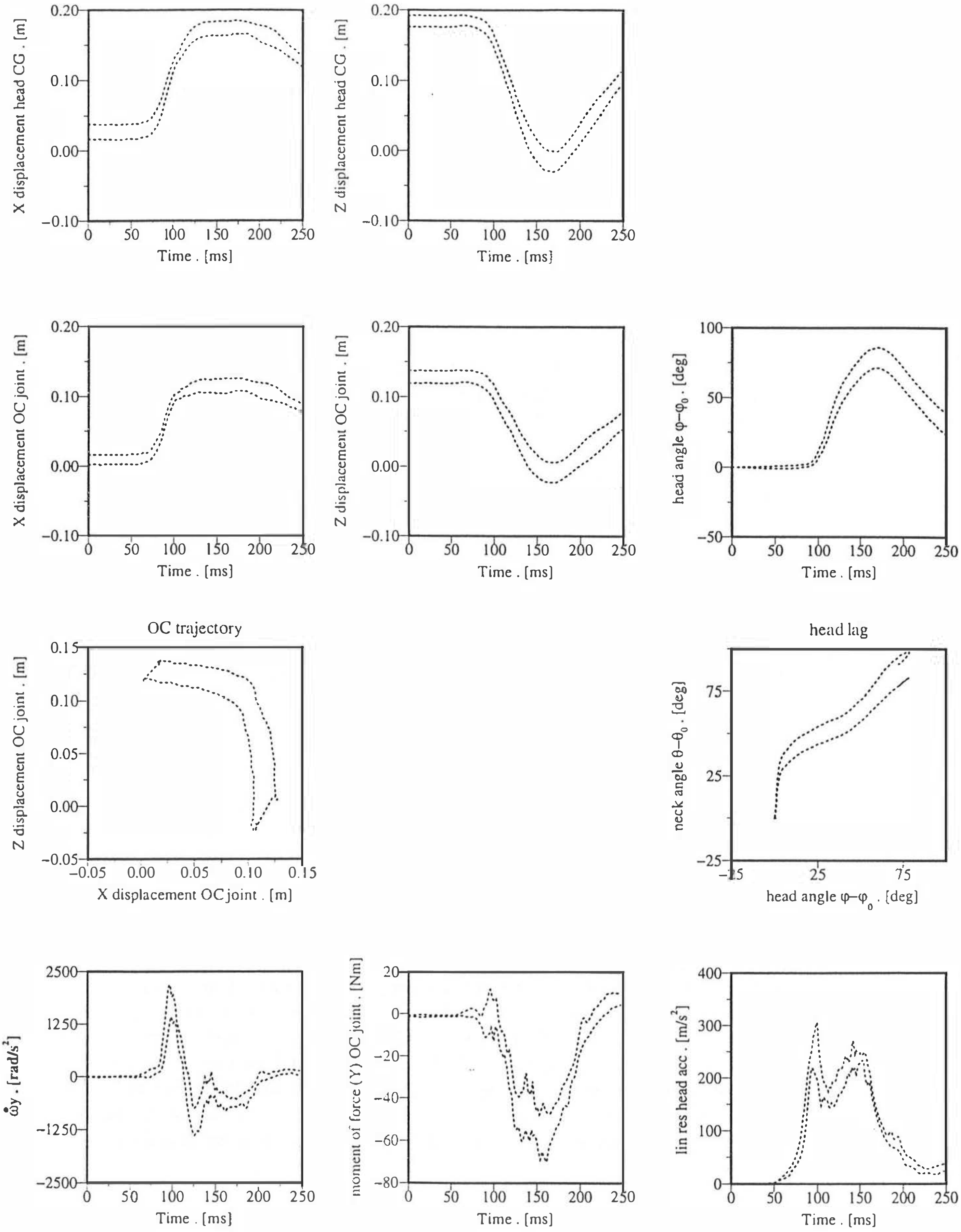

Figure 2 - Frontal Neck Performance Requirement Corridors ($\Delta V \sim 65$ km.h^{-1}, $a_{peak} \sim 15$ G, $a_{average} \sim 11.2$ G, tensed volunteers)

TEST SET-UP - The test set-up is shown in Figure 3. An isolated THOR head-neck system and a Hybrid-III head-neck system are placed directly on a HyGe sled. Thunnissen et al (1995) concluded that the linear T1 acceleration in X direction is the most relevant T1 motion parameter for the head-neck response. Therefore, the two dummy head-neck systems are accelerated with a sled pulse equivalent to the average X-acceleration measured at the first thoracic vertebra of the NBDL volunteers (Figure 4). The initial angular orientation of the dummy neck was 5.6 degrees forward, in order to align the Frankfort plane with the sled surface, similar to the average initial angular head orientation of the volunteers.

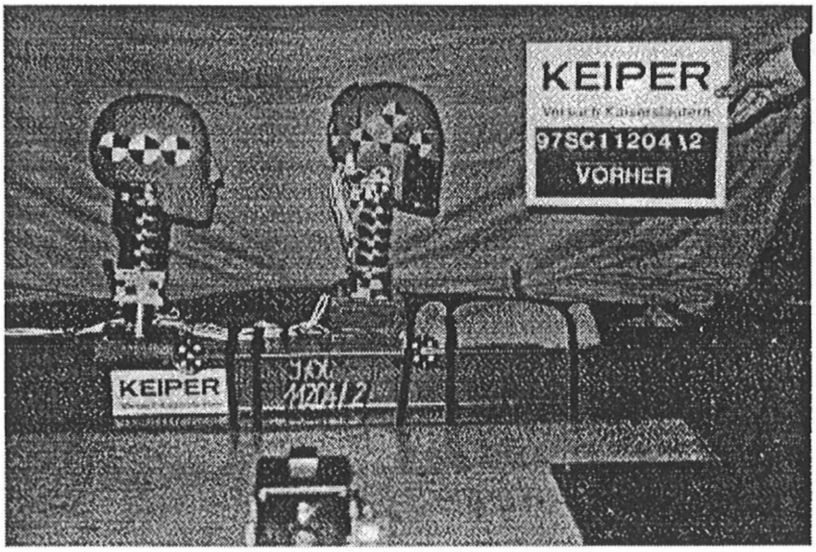

Figure 3 - Test Set-Up HyGe Sled Tests, Hybrid-III Head-Neck System (left) and THOR Head-Neck System (right)

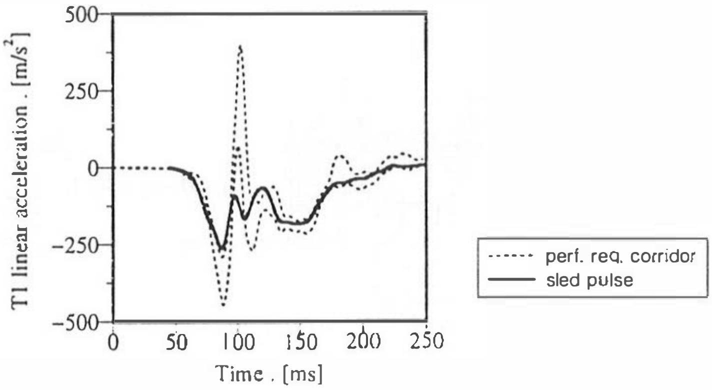

Figure 4 - Sled Acceleration Pulse

MEASUREMENTS - For both dummy head-neck systems, the linear accelerations at the head center of gravity, the upper neck loads and lower neck loads were recorded during the impact. The THOR head is equipped with a nine accelerometer array. The output of this array was used during testing to be able to calculate the angular acceleration of the head about the axis perpendicular to the plane of impact. The THOR has a rotary potentiometer at the occipital condyles joint, however, this was not ready to be plugged into the data acquisition system without rebuilding and re-calibrating it first. Due to lack of time, this potentiometer was not used. High Speed video recordings were made as well.

REPEATABILITY AND DURABILITY- After a HyGe sled test series of 9 tests, the THOR head-neck system was tested on a pendulum to be able to obtain information on the neck's repeatability. The test set-up was almost identical to the test set-up that is used for calibration of the Hybrid-III neck.

RESULTS

THOR AND HYBRID-III PERFORMANCE - For the analysis of the THOR and Hybrid-III neck kinematics (i.e. X and Z displacement of the occipital condyles joint and neck angle), the average measured initial T1 location of the NBDL volunteers was used as a reference in the dummy tests (Figure 5). For the THOR neck, T1 is located about 65 mm above the center of the lower neck load cell. For the Hybrid-III, T1 is located in the base plate of the neck. The location of T1 in the THOR neck relative to the THOR thorax will alter during an impact, as T1 is located in the deformable rubber column part of the neck. The location of T1 in the Hybrid-III neck will not change during an impact.

The relation between the THOR occipital condyles joint location and the THOR T1 location with respect to the thorax has been determined from High Speed Video recordings.

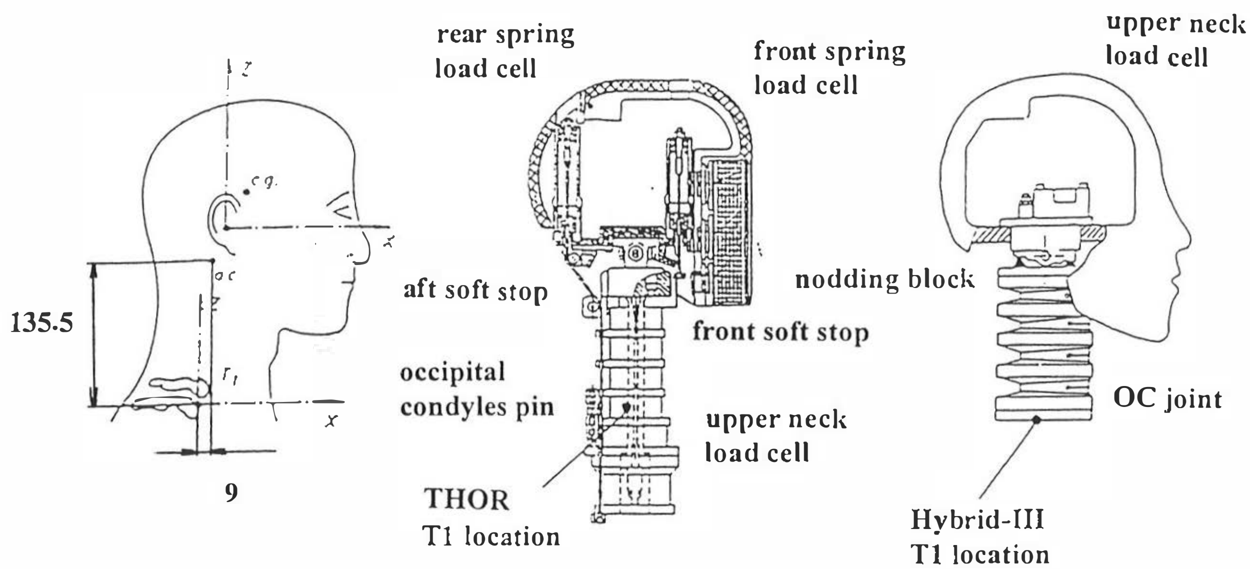

Figure 5: Average T1 position for NBDL volunteer, T1 position for THOR and Hybrid-III neck

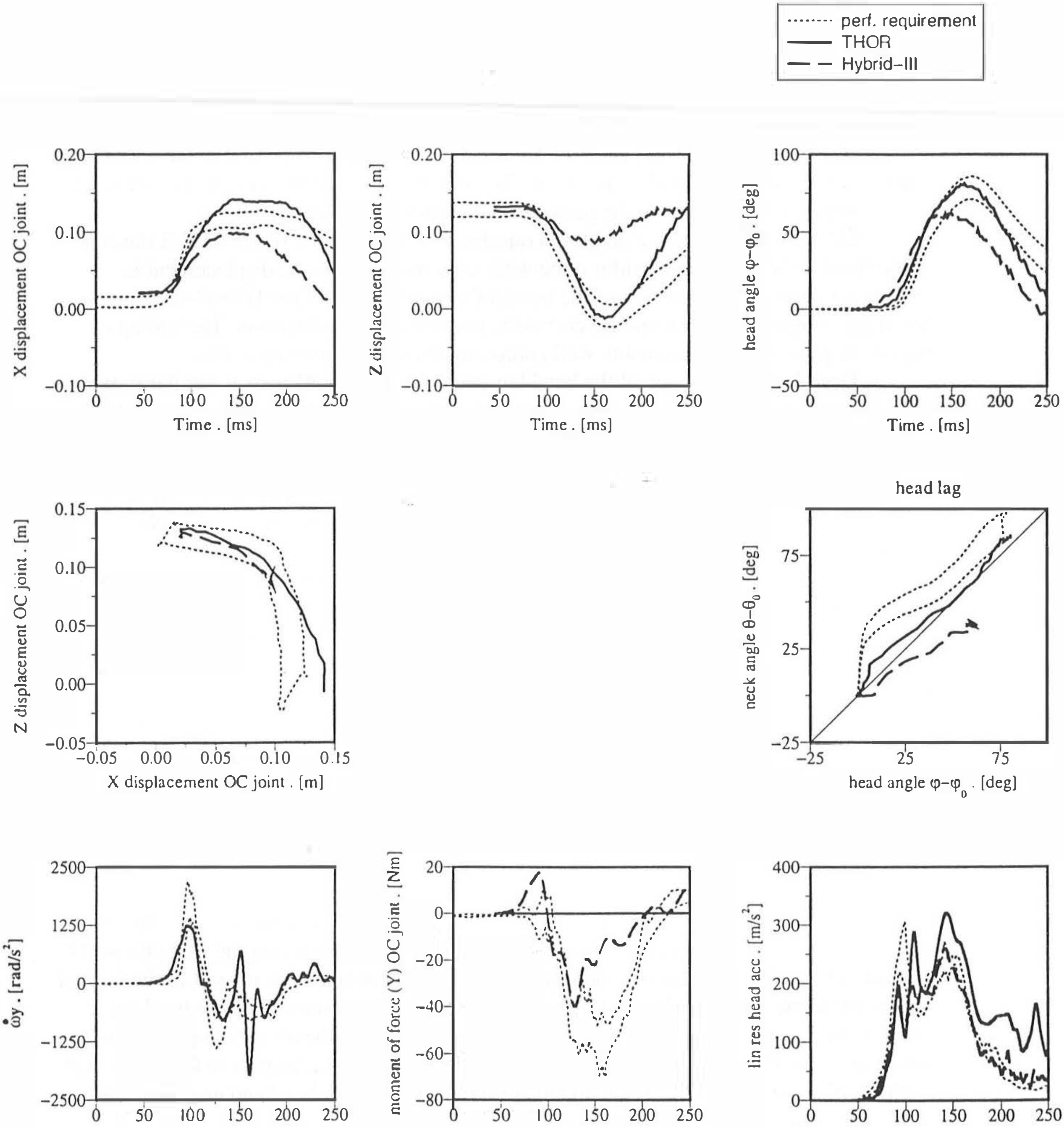

Figure 6 - The frontal THOR response (thick solid line), Hybrid-III response (thick dashed line) compared with the frontal performance requirements (thin dotted lines).

Figure 6 shows the output signals of the Hybrid-III head-neck system (thick dashed line) and the THOR head-neck system (thick solid line), as well as the frontal neck performance corridors (thin dotted lines). The acceleration and torque output signals of THOR and Hybrid-III are CFC60 filtered.

Head Angle - The head angle of Hybrid-III is too small compared to the corridor and timing of the peak is slightly too early. The magnitude and timing of the THOR head angle compares very well with the performance requirement corridor.

OC Joint Displacement and OC Trajectory - The trajectory of the THOR dummy approximates the response corridor quite well; only the forward (X) displacement is slightly too large. The excursion of the occipital condyles joint of the Hybrid-III is much too small compared to the response corridors, particularly in Z-direction. The timing of the OC displacement is reasonably well approximated by both dummy necks.

Head Lag - The shape of the head lag curve for the THOR neck is similar to the head lag performance requirement corridor, but still not within the corridor. The Hybrid-III head-neck system shows no head lag at all.

Resultant Linear Head Acceleration - The resultant linear head center of gravity accelerations of THOR and Hybrid-III are similar, except for the peak in the THOR signal at t = 100 msec. Both acceleration signals are close to the performance requirement corridor.

Rotational Head Acceleration - The method used to calculate the angular head acceleration about the Y-axis is based on Padgoankar et al (1975). The angular acceleration of the THOR head-neck system about the axis perpendicular to the plane of impact is similar to the corridor, except for the unexpected peak between 150 and 170 msec. The Hybrid-III head was not equipped with a nine accelerometer array.

Torque at OC Joint - The torque at the occipital condyles joint of the Hybrid-III is too low compared to the requirement. No torque was generated at the THOR occipital condyles joint, due to the design of the THOR neck construction, described in the 'Discussion' section.

DISCUSSION

THOR HEAD-NECK SYSTEM KINEMATICS - During a frontal impact, the THOR head construction is designed to function as shown in Figure 7: during the first part of the impact, the head should translate and show a negligible rotation with respect to the inertial space, while the neck should bend forward (the neck angle increases and the head angle stays constant, the so-called head lag) (a). At a certain point, the aft soft stop contacts the upper neck load cell surface (b), the orientation of the head with respect to the upper neck is 'locked' by the rear cable at the aft side of the neck and both head and neck will start flex further forward as one system (c).

Analysis of high speed video recordings however showed that the THOR head rotation during the first part of the impact is not negligible. This is also shown in the first part of the THOR head lag curve in Figure 6.

The head lag curve also shows that the aft cable in the THOR neck locks the head orientation with respect to the neck during the second part of the impact. The second part of the THOR head lag curve would have been more horizontal and would even have crossed the 45°-line in the curve if the cable construction would have failed.

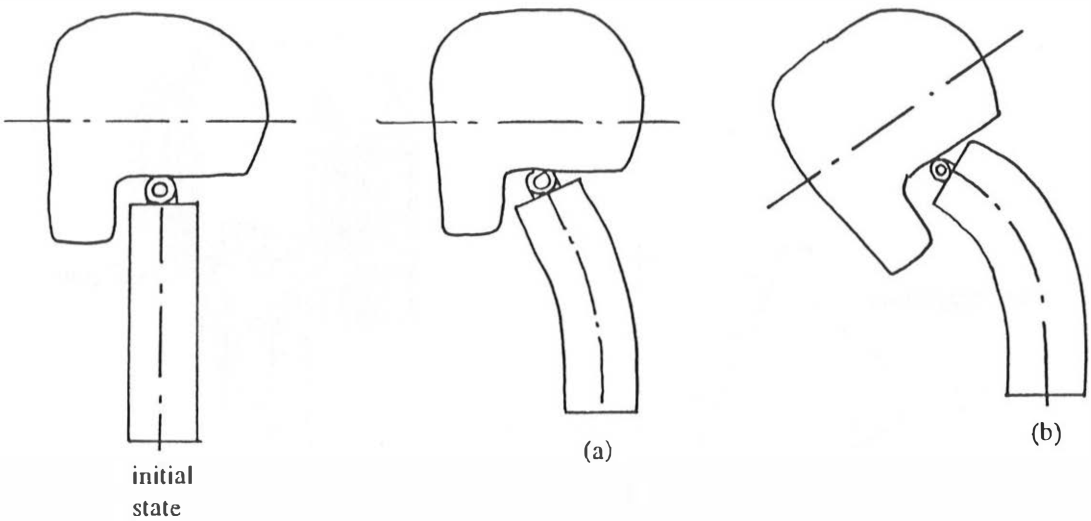

Figure 7 - Behaviour of THOR head-neck system during frontal impact

UPPER NECK LOAD CELL RECORDINGS THOR - The neck constructions (Figure 5) of THOR and Hybrid-III differ a lot. Therefore, the upper neck load cell loads are not immediately comparable.

The Hybrid-III upper neck load cell is attached to the head. Forces and moments are passed directly from the neck to the head via the nodding blocks. The THOR upper neck load cell is attached to the upper neck of the THOR. As the neck allows a certain amount of rotation between head and upper neck, neck loads are transmitted from neck to head through the aft and front cables as well as the occipital condyles pin. The THOR upper neck load cell does not measure the loads at the OC joint directly. The upper neck load cell loads, front and aft spring loads and the relative rotation between head and upper neck must be combined to calculate the occipital condyles pin forces and torques. A method was derived to do so and is described in Appendix B.

The method for calculating occipital condyles joint loads in the THOR neck allows a variety of errors, e.g. due to incorrect polarity of the signals. Software that comes with the THOR dummy would be a possible improvement.

OC JOINT DISPLACEMENT - During the frontal tests, the average neck length (distance between T1 and the occipital condyles joint) of the NBDL volunteers increased with about 20-25 mm. The X displacement of the THOR occipital condyles joint during frontal impact is slightly too large compared to the performance requirement, while the Z displacement of the THOR occipital condyles joint is located within the performance requirement corridor. This implies that the THOR neck would even elongate more than the human neck during a frontal impact. But this is physically impossible, as the neck is equipped with a cable through the rubber neck column, which prevents the neck from changes in its length.

This phenomenon can simply be explained by the fact that the THOR neck is much longer than a human volunteer neck, as is illustrated in Figure 8. It clearly can be seen that the distance between the OC joint and T1 strongly increases while the actual THOR neck design shows a shortening between its two end points.

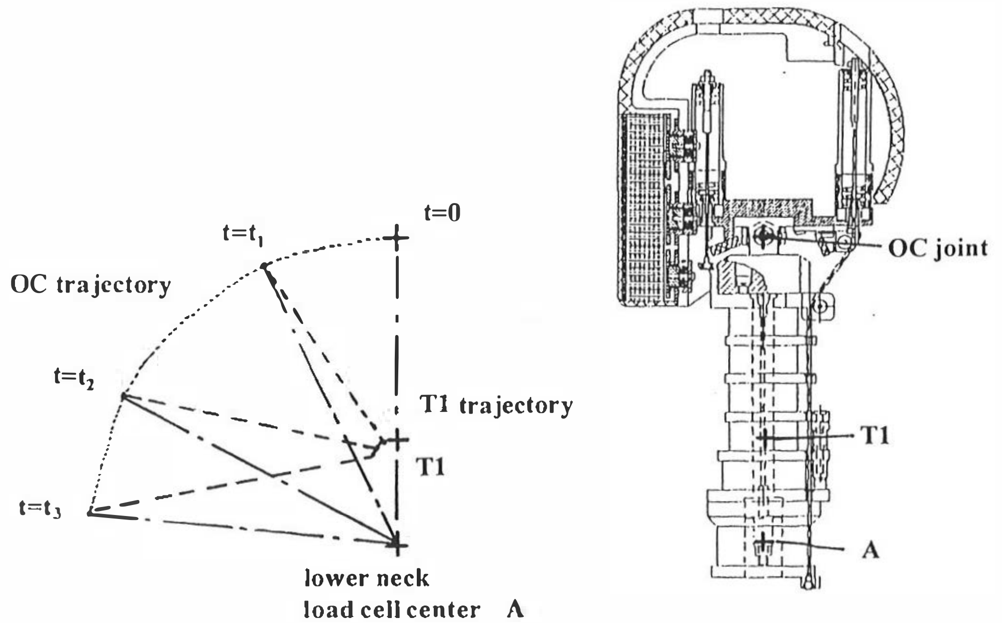

Figure 8 - THOR neck length influence on OC displacement

NON-ROTATING VERSUS ROTATING T1 FRAME - In this paper, the THOR and Hybrid-III head-neck response are compared with performance requirements defined with respect to a non-rotating T1 co-ordinate system. Using these requirements assumes limited flexibility of the dummy in the upper torso area. Earlier studies and use of the Hybrid-III showed that the flexibility of the Hybrid-III in the upper thorax is small. Flexibility of the THOR upper thorax however is not exactly known, as the dummy is still new. Further research seems necessary to check whether the assumption mentioned above is justified, because of the changed thorax design and articulation point at T7/T8 in addition to the 'usual' dummy articulation in the lumbar spine.

REPEATABILITY AND DURABILITY - Originally, ten pendulum tests with the THOR head-neck system had been planned, five tests loading the neck in flexion and five in extension. Five extension tests were carried out without any problems. During the sixth test (flexion) the neck was so badly damaged that further testing was impossible. As shown in Figure 8, the rubber of the neck had totally debonded from the lower neck load cell surface. As the THOR neck unit had not been used before, the durability of the THOR prototype neck was questioned. Considering the durability of the THOR neck, no conclusion about the neck's repeatability will be drawn at this point.

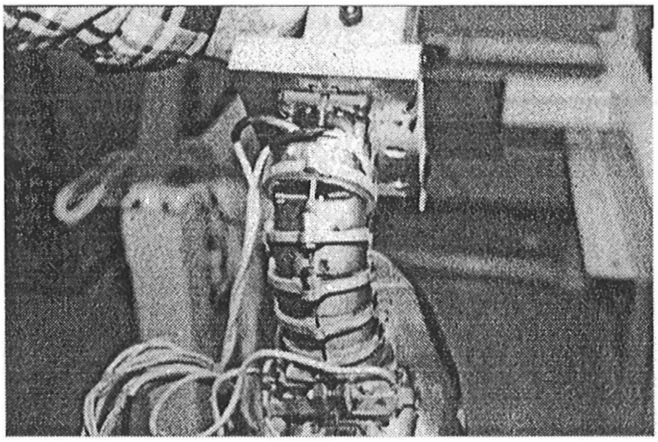

Figure 9 - Damage to THOR neck

CONCLUSIONS

The THOR frontal neck performance is more biofidelic than the Hybrid-III neck response in frontal flexion. However, the THOR neck needs improvement as HyGe sled tests with the THOR head-neck system showed that the THOR neck incorporates too much elongation compared to the human head-neck response in frontal flexion expressed with respect to a non-rotating T1 co-ordinate system.

In the initial part of the impact, the construction of the THOR head-neck system is not yet completely working as designed:

- the head rotation was not negligible during the first part of the impact (necessary for correct amount of head lag) and
- the aft stop did not hit the upper neck load cell surface, so no torque was generated at the occipital condyles joint.

In the second part of the impact, the aft cable in the THOR neck locks the THOR head orientation with respect to the neck, as intended in the THOR neck design.

The upper neck load cell recordings of THOR cannot be compared with Hybrid-III upper neck load cell recordings without complicated calculations due to the fact that the load cell is located in the upper part of the neck and not rigidly attached to the head. Errors are easily made due to e.g. signal polarities. Software that comes with the dummy would be a possible solution.

The durability of the provided THOR prototype neck is not sufficient for a frontal impact dummy neck. So this is an aspect which needs further attention.

In this study, the THOR and Hybrid-III neck response were calibrated against performance requirements defined with respect to a non-rotating co-ordinate system. Further research is necessary to check whether this approach is correct. For the Hybrid-III is known that it has a stiff thorax. For the THOR thorax, further research into total spine kinematics is necessary to check this assumption.

ACKNOWLEDGEMENTS

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All opinions given in this paper are those of the authors and not necessarily those of the EC, NHTSA and GESAC.

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APPENDIX A

NBDL studies concluded that the motions of the human head-neck system can be characterised by means of a two pivot linkage system. One link represents the head, the other link the neck. The head link has a constant length, the neck link length is variable.
Head lag is defined as the relation between head link rotation and neck link rotation. The head link rotation is defined as the angle between the Z-axis of the head anatomical co-ordinate system and the Z-axis of the T1-co-ordinate system, measured in the plane of impact. The neck link rotation is defined as the angle between the neck link (= straight line between occipital condyles and T1 position) and the Z-axis of a T1 co-ordinate system. Head lag is shown during the first part of a frontal impact in the cross plot of the head and neck link angle, the head rotation (flexion) is much smaller (almost negligible) than the neck link rotation. As soon as the relative angle between head and neck link reaches a certain level, (approximately 27 degrees) the head and neck link can be considered as locked and start flexing further forward as one system.

APPENDIX B

To be able to compare the Hybrid-III upper neck loads with the THOR upper neck loads, the THOR occipital condyles loads expressed with respect to a head co-ordinate system should be calculated. The method to do so is described in this Appendix.

RELATIVE ROTATION BETWEEN HEAD AND UPPER NECK - The maximum relative rotation between head and upper neck, (β), was determined, using technical drawings of the THOR neck. The maximum angle is reached when either the front or aft stop contacts the upper neck load cell surface, for the front stop the maximum β is 8° and for the aft stop the maximum rotation is 25°.
For the generated moment of force at the occipital condyles pin follows:

$M_{oc} = 0$ for $-25° < \beta < 8°$	no soft stop contact
$M_{oc} \neq 0$ for $\beta \leq -25°$ or $\beta \geq 8°$	soft stop contact

NO SOFT STOP CONTACT ($-25° < \beta < 8°$) - Figure 12 schematically shows the forces and moments acting on the upper neck load cell and the THOR head in case the soft stop does not contact the upper neck load cell surface.

The resultant loads at the joint, F_{jx} and F_{jz}, are calculated using equations (1) and (2)

$$F_{xlc} = F_{jx} \quad (1)$$

$$F_{zlc} = F_{jz} \quad (2)$$

$$M_{jy} = 0 \quad (3)$$

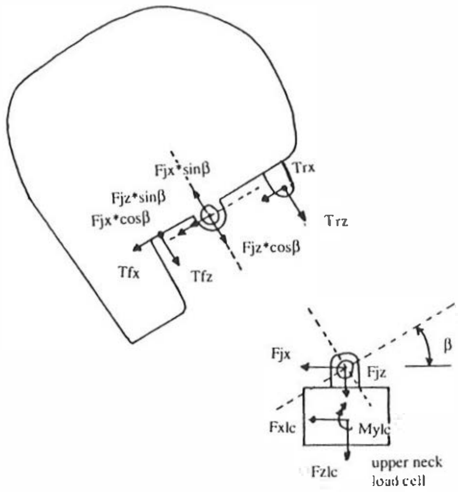

Figure 10 - Forces and moments acting on the upper neck load cell and the THOR head in case the soft stop does not contact the upper neck load cell surface

with
F_{xlc} = upper neck load cell force in X-direction (expressed w.r.t. upper neck co-ordinate system)
F_{zlc} = upper neck load cell force in Z-direction (expressed w.r.t. upper neck co-ordinate system)
F_{jx} = occipital condyles joint force in X-direction (expressed w.r.t. head co-ordinate system)
F_{jz} = occipital condyles joint force in Z-direction (expressed w.r.t. head co-ordinate system)
M_{jy} = occipital condyles joint torque about Y-axis (expressed w.r.t. head co-ordinate system)

The resultant loads at the occipital condyles joint (F_{xh}, F_{zh}, M_{yh}) are calculated using equations (4) till (6)

$$F_{xh} = T_{fx} + T_{rx} + F_{jx} * \cos\beta + F_{jz} * \sin\beta \quad (4)$$

$$F_{zh} = T_{fz} + T_{rz} - F_{jz} * \cos\beta + F_{jx} * \sin\beta \quad (5)$$

$$M_{yh} = 0 \quad (6)$$

β = relative rotation between head and upper neck
T_{fx} = front cable force in X-direction (expressed w.r.t head co-ordinate system)
T_{fz} = front cable force in Z-direction (expressed w.r.t. head co-ordinate system)
T_{rx} = rear cable force in X-direction (expressed w.r.t. head co-ordinate system)
T_{rz} = rear cable force in Z-direction (expressed w.r.t. head co-ordinate system)

SOFT STOP CONTACT - Figure 13 schematically shows the forces and moments acting on the upper neck load cell and THOR head in case of soft stop contact with the upper neck load cell surface.

Equations (1) and (2) are also used to calculate F_{jx} and F_{jz}. The resulting forces are used in equation (7) to calculate M_{jy} :

$$M_{ylc} = M_{jy} - F_{jx} * l \qquad (7)$$

with

l distance between upper neck load cell center and occipital condyles center

M_{LC} upper neck load cell resultant moment

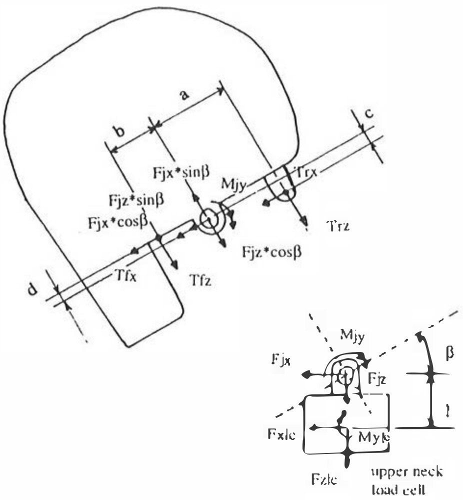

Figure 11 - Forces and moments acting on the upper neck load cell and the THOR head in case the soft stop contacts the upper neck load cell surface

The resultant force at the occipital condyles joint (F_{xh}, F_{zh}) are calculated using equations (4) and (5). For the resultant torque about the Y-axis at the occipital condyles joint, M_{yh} is calculated using equation (8):

$$M_{yh} = T_{rx} * c + T_{rz} * a - T_{fx} * d - T_{fz} * b + M_{jy} \qquad (8)$$