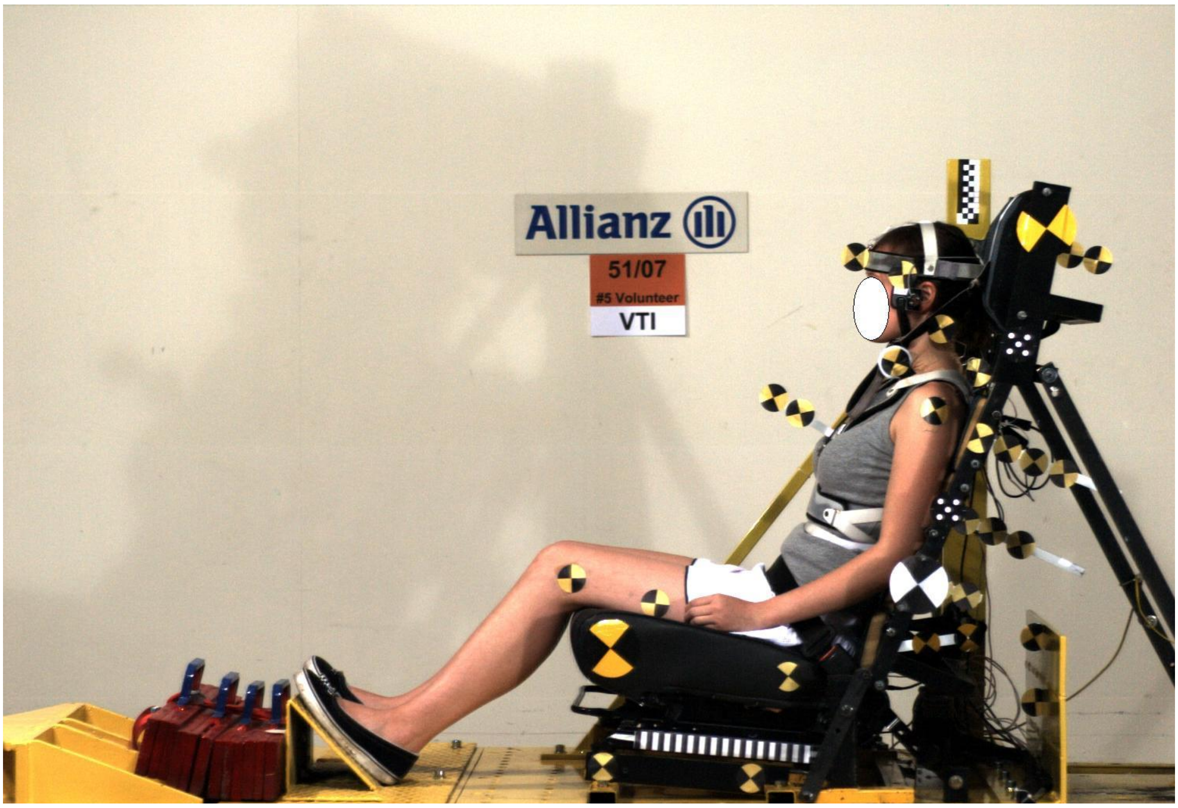

Test method – Upper neck force and moment

LAURA VILA GIRAUT

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ABSTRACT

Crash tests are used to develop and improve vehicle safety and evaluate the injuries caused after a crash. In the neck, injury criteria such as NIC and N_{km} estimate consequences of the crash. In a crash test dummy the upper neck load cell measures the force and the moments between the neck and the head. But in volunteer tests, always non-injurious and at low velocity, is not possible to attach sensors into the neck of the volunteers. Hence the forces and moments in volunteers need to be calculated with data from accelerometers or possible other sensors.

The aim of this thesis is to propose a method that can be used to calculate the upper neck forces and moments on human subjects.

A review of different methods to calculate the upper neck force and moments has been performed. Advantages and disadvantages have been discussed. Also the physical properties of the human head (mass, moment of inertia, position of the center of gravity and the occipital condyle) are investigated as they are important in the calculation of the upper neck loads.

In order to calculate the upper neck force and moment in a crash test carried out with a human subject, the head of the human is considered to be a solid rigid. Therefore, forces and moments in the upper neck are found by applying the dynamics of a solid rigid.

As a result of the research, a method is proposed: attach a new sensor in the market (IMT40) in both sides of the projection of the center of gravity in the human head, measure linear and angular acceleration and the angle of the head and finally calculate the neck loads.

Keywords: volunteer, human subject, forces and moments in the upper neck, female, rear impact.

Contents

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And finally, to my family and friends for constant support.

Notations

Abbreviations

AIS	Abbreviated Injury Scale
AM	Auditory Meatus
BMD	Biomedical Computer Program
C1-C7	Cervical vertebrae
CG	Center of Gravity of the head
IRCOBI	International Research Council on Biomechanics of Injury
MRI	Magnetic Resonance Imaging
NIC	Neck Injury Criteria
N_{km}	Neck Protection Criteria
OC	Occipital Condyle
R	Multiple correlation coefficient
SAHR	Saab Active Head Restraint
SD	Standard Deviation
SE EST	Standard error of estimate
SG	Specific Gravity
T1	First Thoracic Vertebra
WHIPS	Whiplash Protection System
3D	Three Dimensional

Terms

F_z, R_{OCz}, F_{OCz}	Axial force
F_x, R_{OCx}, F_{OCx}	Shear force
m	Mass of the head
a_{CGi}	Acceleration of the center of gravity in the i-axis
I_i	Mass moment of inertia of the head in the i-axis
α_i	Angular acceleration in the i-axis
M_{CG}	Moment of the force in the OC
L_o	Moment of momentum
ω_i	Angular velocity in the i-axis
∂	Derivative operator
x	Cross product operator
θ, φ	angle between the x-axis of the coordinate system and the horizontal line or the angle between the weight and the z-axis
R_{HRi}, F_{HRi}	Headrest load in i direction
d_{HRi}	Distance between R_{HRi} and i-axis
d_{OCi}, d_{OC/CG_i}	Distance between R_{OCi} and i-axis
OP_i	Distance between two arbitrary points (the O-point and the P-point) in i-direction
ρ	Density of the human body
ρ_{H_2O}	Density of the water
V	Volume of the head
F_{int} , M_{int}	Critical intercept values

Constants

g (9.81m/s^2) Acceleration due to the gravity

Concepts

- **Frankfort line**
  It's an imaginary line which with the human head situated in a profile position, connects the upper margin of the external auditory meatus (called porion) with the lower orbital margin. In crash tests where the motion of the head is studied, it's an important line because it is used as the reference of one axis of the coordinate system of the head.
- **Auditory meatus (AM)**
  The external ear canal
- **Orbit**
  The bony cavity on the skull containing the eye-ball
- **Occipital condyles (OC)**
  Situated on the rear part of the skull, belongs to the occipital bone and allows the articulation between the head and the first vertebra C1 (also called atlas)
- **Center of gravity of the head (CG)**

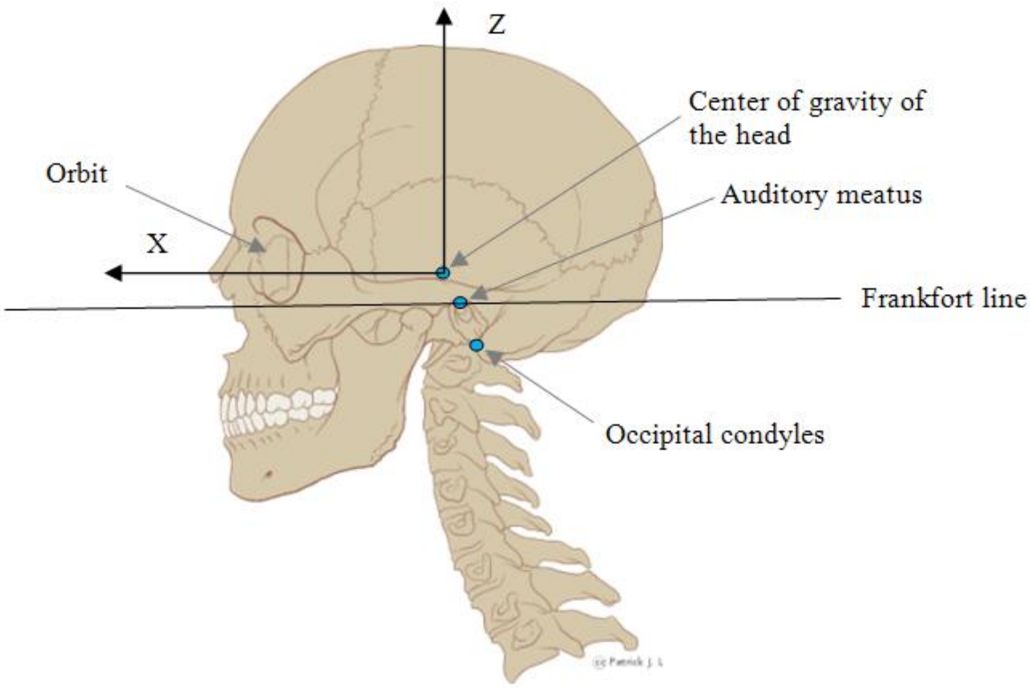

Figure I. Some concepts are shown

- **Midsagittal plane**
  A plane passing vertically through the midline, dividing the body into left and right halves of equal proportion

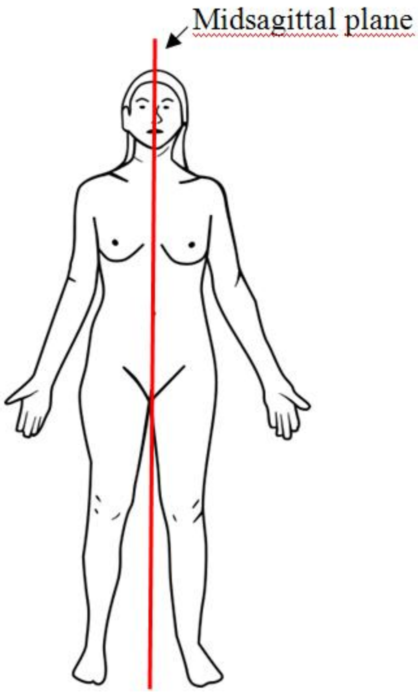

Figure II. Midsagittal plane

- **Kinematics**
  Describe the motion of objects without consideration of the causes which provoke the motion
- **Kinetics**
  It's the general term given to the forces that cause the movement
- **Shear force (F_x)**
  The force along the x-axis
- **Axial force (F_z)**
  The force along the z-axis
- **Coordinate reference system of the head (anatomically based coordinate reference system for the head)**
  It has its origin at the midpoint of a line between the external audiotry meatus from both sides in the midsagittal plane. The x-axis direction is posterior toward anterior and lies on the Frankfort plane. The z-axis lies in the midsagittal plane, with 90º from the x-axis and its direction is inferior toward superior. The y-axis is perpendicular to the midsagittal plane and its direction follows the right-hand rule, it goes from right to left.

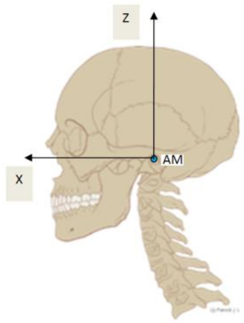

Figure III. Coordinate reference system of the head

1 Introduction

Nowadays that the population have grown and thus the number of cars too, car collisions have increased. In the cities during rush hours, when traffic jams are habitual, rear-end impacts happen usually. In this sort of accidents at a low velocity, the neck is damaged in most of them. These injuries are known with the name “whiplash injury”, although at present other names are used, for instance whiplash associated disorder (WAD), cervical spine injury… (Carlsson, 2010).

1.1 Whiplash injuries

Whiplash injuries occur in all impact directions (frontal, frontal-oblique, lateral, rear…) in vehicle collisions but also can occur diving. However, they are more frequent, and the risk is higher, in rear end impacts (Cappon et al. 2003).

The great majority of neck injuries caused by rear-end impacts are considered non-severe injuries, usually graded as AIS1 (minor injuries).

1.1.1 What is a whiplash

Whiplash is a neck injury caused by a fast and violent forced movement of the neck. However, they are normally non-life threatening.

The phases of the motion of the head in a typical rear-end impact are:

- Neutral position
  A relax position of the head and neck

Figure 1. Neck in the neutral position

- S-shape
  The lower part of the neck is in an extension position and the upper part of the neck is in a flexion position.

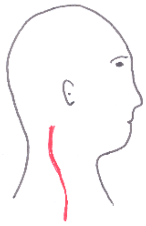

Figure 2. S-shape

- Extension
  The head has a rearward rotation

Figure 3. Neck in extension

- Flexion (rebound)
  The head has a forward rotation

Figure 4. Neck in flexion

Whiplash mechanism can be defined in three steps (Carlsson 2010):

1) When the vehicle is hit from the rear by another vehicle, the torso tends to move forward, pushed by the seatback; whereas the head remains at the same position. The neck achieves a position known as S-shape (or retraction).

2) The following phase is the extension, and it occurs because the torso is still pushed forward and the head will be bent backwards.

3) Finally, the seat belt stops the forward movement of the torso, but the head moves forward. The head achieves flexion.

Although it has been carried out many studies trying to find out the exactly mechanisms which causes the neck-injury, they are not fully understood (Koshiro Ono et al., Davidsson 2000, Chen HB et al. 2009).

According to the same authors, Chen HB et al. 2009, one reason might be that these injuries are not always accompanied by obvious tissue damage detectable by X-ray or magnetic resonance imaging (MRI).

More knowledge is needed in order to improve the existing anti-whiplash head restraint or designing new head restraints or other prevention strategies.

1.1.2 Symptoms of the whiplash

Even if the mechanisms of the whiplash are not well understood, the symptoms are well documented and have been described by several authors (Panjabi et al. 1998, Davidsson 2000, Ono et al. 1996).

The most common symptoms of the whiplash injury are detailed below. However, each subject can experience the symptoms in different ways.

- Pain in the neck
- Stiffness if the neck
- Headache
- Dizziness
- Pain in the shoulder
- Pain in the arms
- Pain in the back
- Fatigue
- Difficulty sleeping
- Ringing in the ears
- Nervousness or irritability
- Numbness
- Blurred vision
- …

The duration of the symptoms may vary. The symptoms begin to develop a few hours after the crash take place, and then get worse over the next 24 to 48 hours; while it is not habitual the symptoms appear just after the crash (Bierma 2009). Normally they are not long-lasting and in a few days or months after the crash, the symptoms disappear. But according to Krafft et al. 2005, a correlation was found between duration of symptoms and crash severity.

1.1.3 Some statistics of the whiplash

The most commonly injury reported in vehicle collisions is whiplash. This statement can be supported by the fact that in Europe, more than one million people suffer injuries from rear end collisions (ETSC 2007).

Approximately 80% of all injuries occurring in rear-end collisions are whiplash injuries (ETSC 2007).

During the last twenty years the number of whiplash injuries has increased. The previous statistic is not well understood (ETSC 2007) because some systems anti-whiplash are already in the market since several years ago, as the anti-whiplash head-restraint from Volvo (WHIPS: Whiplash Protection System), or SAHR (Saab Active Head Restraint), another anti-whiplash head-restraint… and one study in particular (Kraft et al. 2004) showed that the new anti-whiplash seats have decreased the whiplash injury risk (in more than 40%).

Comparing the risk between both genders, it can be said that females had a higher risk of sustaining neck injury (Ono et al. 2006, Krafft et al. 2005). Also, comparing passengers and drivers, drivers have a higher risk. The reason is not well known, but a possible explanation might be that passengers have a more relaxed position than drivers, and probably they rest their head in the head restraint. And within front passengers and rear passengers, front passengers have a higher risk than rear passengers (because of the difference on the rigidity between the front and rear seats) (ETSC 2007). Focusing on females, they have more than 5 times higher risk than males in the rear seat; and in the driver position the risk is around 3 times higher in female (Krafft et al. 2005).

That conclusion from Ono et al. 2006 and Krafft et al. 2005 among other authors is also supported by a Volkswagen whiplash injury database, which showed that females have a double whiplash injury risk compare with males. From the same study, it was found that females between the ages of 18 to 27 years have a higher risk. Another conclusion was that the risk to suffer a whiplash injury is higher as taller as the person are (Cappon et al. 2003).

Another reason to investigate the whiplash mechanism is that that kind of injury cost to the society a high amount of money every year. In 2007, the European society cost was estimated in more than 10 billion Euros (ETSC 2007).

1.2 Structure of the neck

The neck is the part of the human body which links the head with the torso. The cervical vertebrae are in the neck area. There are 7 cervical vertebrae: C1 to C7. The C1 vertebra, also called atlas, is the first vertebra immediately located under the skull and its function is to support the skull. Cervical vertebrae allow the head to have different movements: rotation, forward and rearward movement…

The atlas (C1) connects the occipital bone with the occipital condyles.

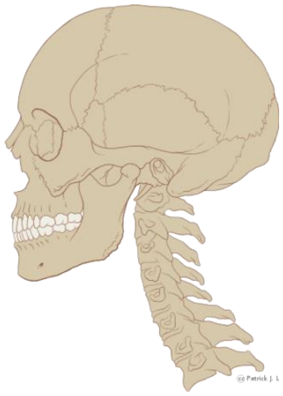

Figure 5. Human skull and cervical vertebrae. Picture extracted from www.wikimedia.org

1.3 Neck injury criteria

There are several neck injury criteria: NIC, N_{ij}, N_{km}, IV-NIC, NDC… But Kullgren et al. 2003 reported that NIC and N_{km} are applicable to detect the risk of whiplash injury when using a BioRID dummy. So, these two criteria should be used in the evaluation of the neck injury in rear-end collisions:

- NIC (Neck injury criterion)
- N_{km} (Neck protection criterion)

The formulae to calculate these criteria are:

$$NIC(t) = 0.2 * a_{rel}(t) + (v_{rel}(t))^2$$

Where:

- $a_{rel}(t)$ is the relative horizontal acceleration between the bottom (T1) and the top (C1) of the cervical spine
- $v_{rel}(t)$ is the relative horizontal velocity between the bottom (T1) and the top (C1) of the cervical spine

$$N_{km}(t) = \frac{F_x(t)}{F_{int}} + \frac{M_y(t)}{M_{int}}$$

Where:

- $F_x(t)$ is the shear force
- $M_y(t)$ is the flexion/extension bending moment
- F_{int} and M_{int} are critical intercept values used for normalisation and they are found in table

Looking the formulae, for N_{km} the forces and moments in the upper neck are needed. In the present project, it will be explained how to calculate these values when the experiments are carried out on human livings.

1.4 Rear impact dummies

To date, there is no female dummy specifically build to study the whiplash injuries in female gender, although there is the 5^{th} percentile dummy for frontal impact tests. All the dummies used in rear crash tests are based on the average man; they represent a 50^{th} percentile male.

At the end of the 90s, the BioRID (Biofidelic Rear Impact Dummy) was developed by a consortium (Saab, Volvo, Autoliv and Chalmers University of Technology). The first model has been evolving until the BioRID II, which is used in crash tests to evaluate the response of the neck and the injuries after a rear impact. The characteristics of the dummy are:

- Based on the Hybrid III dummy. The difference between both dummies is the biofidelity of the vertebral column. In the BioRID II, the vertebral column is reproduced with the 24 vertebrae (7 cervical, 12 thoracic, 5 lumbar) (see Figure 6).
- The biofidelity of the neck is given by torsion washers, urethane bumpers and muscle-simulating springs.

The other rear impact dummy in the market is RID-3D. It was develop in the early 2000s. To construct this dummy, the neck part has a new design, but the other parts are taken from other existing dummies (Hybrid III…).

The differences between Hybrid III, BioRID II and RID-3D, mainly in the neck design and its structure, can be seen in Figure 6.

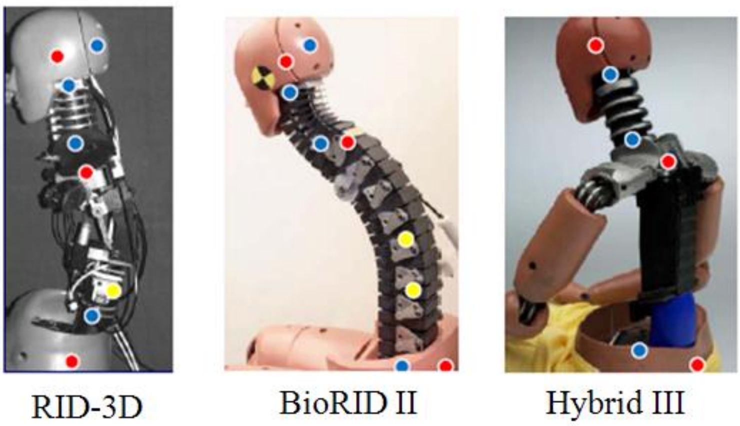

Figure 6. Rear impact dummies and Hybrid III

Since the neck of the males and females do not act in the same way during a rear end impact, and women have a higher risk to suffer whiplash, BioRID II and RID-3D cannot be used to evaluate the response of the neck in women. Hence, it's important to develop a model which represents a female.

Studies have indicated that females and males may have different dynamic responses in rear impacts. It is therefore worrying that new whiplash protection systems are developed with two possibilities to consider the female properties; in spite the higher whiplash injury risk for females.

1.5 Rear impact volunteer tests

Until now, several studies have been carried out with male volunteers in rear end impact to characterize a threshold for the forces and moments produced on the union between the neck and the head and also to study the whiplash injuries (Mertz et al. 1967, Mertz et al. 1971, A. van den Kroonenberg et al. 1998, Ono et al. 1993, 1997, 2006, Davidsson 2000). But there are fewer studies with females, only two: A. van den Kroonenberg et al. 1998, Ono et al. 2006, in which experiments participated 3 and 2 volunteer females, respectively. All experiments (except one, Mertz et al. 1967, which was carried out at an unusual high velocity (71 km/h) for volunteer experiments) were carried out always at low speed velocity and without severe damage for the volunteers.

Although the lack of information related with females, it is believed that head-neck union have different performance depend on the genders, this means that females and males do not support the same forces. Females are subjected to higher head and T1 accelerations in a crash with the same characteristics (Ono et al.2006, Carlsson 2010). There are other variables as the age, the velocity of the impact, the condition of the neck (if the muscle of the neck is tensed or relaxed), the stiffness of the vehicle, the head restraint design, the distance between the head and the head restraint and so on.

Several studies have been made relating to the kinematics of the head-neck union, but less concerning about the kinetics, i.e. the dynamics and forces that cause the movement.

1.5.1 Difficulties on volunteer tests

When one works with human volunteers, difficulties arise with the instrumentation, because it is not always possible to attach the instrumentation, as accelerometers or load cells, in the interested point (for example the center of gravity of the head or the upper neck). Luckily, the new technologies such as high-speed video camera and the newest sensors make these measurements easier.

Another limitation is the fact that volunteers cannot be exposed to any degree of physical damage; the crash has to be non-injurious for them. For that reason, there is a need to develop mechanical and mathematical models.

The last limitation of volunteer tests is that the age of the human subjects normally ranges from 18 to 50. Mostly young healthy people are used as volunteers, without any previous damage on the neck.

1.5.2 Advantages of volunteer tests

The most distinguished advantage is the use of the correct anatomy. The muscle activity only can be measured on volunteers.

1.6 Aim of the study

The main objectives of the present study are 1) to review existing test methods which calculate the forces and moments on the upper neck on human subjects, and 2) to develop mathematical equations. So, the present project will serve as an input to a rear impact test series with female and male volunteers in order to calculate the forces and the moments in the neck.

Once the experiment has been carried out, the information gathered and analyzed can be used in the development process of a new female mechanical human surrogate model (a dummy) and/or mathematical models, since currently there are no such models.

With this information, the response of the head-neck movement during rear impacts, which produce the whiplash damage, will be characterized.

2 Review of assessment methods

The project has been done after a research process where all the studies with human volunteers in rear impacts have been analyzed in depth, with the purpose to develop the equations needed to calculate the forces and moments in the upper neck.

To date, there are only two methods used to calculate the moments and the forces in the volunteers' neck during the rear impact.

The head is considered to be a rigid body, but the head can be considered to have planar movement (in the XZ-plane) or to have 3D motions. Hence, the equations of the dynamics of a solid rigid are applied.

2.1 The head is considered to be in plane motion

- Fundamental equation of the dynamics of the movement (Newton's second Law): when a force is applied in a body, then the body is accelerated.
  The relationship between a linear force F and the linear acceleration is described by the following law:

$$\sum \vec{F} = m \cdot \overrightarrow{a_{CG}} \qquad (1)$$

Where: m is the mass of the head

$\overrightarrow{a_{CG}}$ is the measured acceleration

Writing equation (1) for each axis of the plane motion:

$$\sum F_x = m \cdot a_{CGx}$$

$$\sum F_z = m \cdot a_{CGz}$$

- Fundamental equation of the dynamics of the rotation

$$\sum M_y = I_y \cdot \alpha \qquad (2)$$

Where: M_{CG} is the moment of force

α is the angular acceleration caused by M_{CG}

I_y is the mass moment of inertia of the head in the y-axis

2.2 The head is considered to be in 3D motion

- Newton's second law: is the same as the 2D motion but applied in the three axes (see equation 1).

$$\sum F_x = m \cdot a_{CGx}$$
$$\sum F_y = m \cdot a_{CGy}$$
$$\sum F_z = m \cdot a_{CGz}$$

- Euler's law: concerning about the rotation of the body because of the moment of an applied force.

  A rigid body which has rotation is controlled by the following equation:

$$M_o = \frac{d}{dt} L_o \qquad (3)$$

  Where:

    - M_o is the moment of the external forces about the chosen origin O
    - L_o is the moment of momentum (also called angular momentum) and for a rigid body which rotates around a principal axis, it is equal to:

$$L_o = I_o \cdot \omega$$

    - I_o is the moment of inertia matrix with respect to the origin point O and it's a symmetrically matrix
    - ω is the angular velocity of the body

  Furthermore, if a moving coordinate system is chosen, I_o keeps constant, so the calculations are easier. Then, equation (3) is written as:

$$\overrightarrow{M_o} = \frac{\partial \overrightarrow{L_o}}{\partial t} + \overrightarrow{\omega_R} \mathrm{x} \overrightarrow{L_o} \qquad (4)$$

  Where:

    - ω_R is the angular velocity of the moving axes

  If the axes are fixed to the body, $\overrightarrow{\omega_R} = \vec{\omega}$.

  Developing equation (4):

$$\overrightarrow{M_o} = \frac{\partial (I_o \cdot \vec{\omega})}{\partial t} + \vec{\omega} \mathrm{x} (I_o \cdot \vec{\omega}) = I_o \cdot \vec{\alpha} + \vec{\omega} \mathrm{x} (I_o \cdot \vec{\omega}) \qquad (5)$$

  Where $\frac{\partial (\vec{\omega})}{\partial t}$ was replaced by $\vec{\alpha}$ (the angular acceleration of the body).

  If the tensor of inertia I_o is calculated with respect to the principal anatomical axes of the head with their origin at the center of gravity of the head, then it becomes nonzero diagonal:

$$I_o = \begin{bmatrix} I_x & 0 & 0 \\ 0 & I_y & 0 \\ 0 & 0 & I_z \end{bmatrix}$$

  Equation (5) is now written in vector form:

$$\begin{Bmatrix} M_x \\ M_y \\ M_z \end{Bmatrix} = \begin{bmatrix} I_x & 0 & 0 \\ 0 & I_y & 0 \\ 0 & 0 & I_z \end{bmatrix} \cdot \begin{Bmatrix} \alpha_x \\ \alpha_y \\ \alpha_z \end{Bmatrix} + \begin{Bmatrix} \omega_x \\ \omega_y \\ \omega_z \end{Bmatrix} \mathrm{x} \begin{bmatrix} I_x & 0 & 0 \\ 0 & I_y & 0 \\ 0 & 0 & I_z \end{bmatrix} \cdot \begin{Bmatrix} \omega_x \\ \omega_y \\ \omega_z \end{Bmatrix} \qquad (6)$$

  Developing equation (6) the final result is:

$$\left.\begin{aligned} \sum M_x &= I_x \cdot \alpha_x + (I_z - I_y) \cdot \omega_y \cdot \omega_z \\ \sum M_y &= I_y \cdot \alpha_y + (I_x - I_z) \cdot \omega_x \cdot \omega_z \\ \sum M_z &= I_z \cdot \alpha_z + (I_y - I_x) \cdot \omega_x \cdot \omega_y \end{aligned}\right\} \qquad (7)$$

The three previous equations are known as the **Euler equations** and they are the equations of motion for the 3D kinetic analyses.

Observation: For the case where the head is assumed to have plane motion (XZ-plane) (see section 2.1), its equation for the moment is a particular case of the Euler equations, because $\alpha_x, \alpha_z, \omega_z, \omega_x = 0$. Thus the Euler equations are written as (see equation 2):

$$\sum M_y = I_y \cdot \alpha_y$$

Forces in the upper neck and also upper neck moment are assumed to act at the OC joint.

Although there is only one way to calculate forces and moments on the neck, i.e. considering the head as a solid rigid, the acceleration in the head of the human subjects can be measured using different methods to attach the accelerometers in the volunteer's head.

2.3 Chronology of the studies

The following chronology is only focused in rear impacts with volunteers where not only the kinematics of the head-neck were analyzed, but also the upper-neck forces and moments.

In 1967 H.J. Mertz Jr. and L.M. Patrick from Wayne State University presented a paper (*Investigations of the kinematics and kinetics of whiplash)* where forces and moments in the neck were calculated. In that study, the authors compared the response of anthropomorphic dummies, human cadavers and a volunteer in a rear impact. It was one of the first tests using human subjects with the objective of analyze the forces and moments in the neck.

Four years later, in 1971, the same authors presented another study (*Strength and response of the human neck*) with one volunteer and one of the objective of the mentioned study was to present dynamic response and strength data for the human neck in flexion and extension.

After 1971, there was a long period (until 1993) where any study was presented concerning about the forces and moments in the upper neck of a human subject.

In 1993 Koshiro Ono and Munekazu Kanno (Japan) presented at the IRCOBI Conference another study (*Influences of the physical parameters on the risk to neck injuries in low impact speed rear-end collisions*) where the kinematics of the head and neck were studied and also the kinetics of the human subject.

Four years after, in 1997, Koshiro Ono, the same author of the previous study, but now working with Koji Kaneoka and Adam Wittek and Janusz Kajzer, presented a study with the objective of clarify the neck injury mechanism according to the characteristic motion of cervical vertebrae during impact (*Cervical injury mechanism based on the analysis of human cervical vertebral motion and head-neck-torso kinematics during low speed rear impacts*).

In 1998, A.van den Kroonenberg et al. (Germany) published another study with human subjects (*Human head-neck response during low-speed rear end impacts)* where the neck forces and moment were calculated.

In 2000, Koshiro Ono et al. published another study (*Analysis of seat properties on human cervical vertebral motion in low-speed rear-end impacts*) related with the whiplash on the rear impacts using volunteers. The main objective of the study was clarify the motion of the neck with respect to the difference in seat characteristics and from the results, be able to design a new seat system which reduces the whiplash injury.

Davidsson et al. 1998-2000 carried out a few studies (*Human volunteer kinematics in rear-end sled collisions, Human volunteer kinematics in low-speed rear-end sled impacts*) with the main purpose for the validation of a crash test dummies and mathematical models and also the information gathered have been useful in the development of the BioRID. They used the same method as Koshiro Ono et al. used in their experiments: a device which consists with a strap around the head and a mouthpiece. It will be described later on more detail (see Section 2.6.1).

Koshiro Ono et al., in 2006, did another study (*Prediction of neck injury risk based on the analysis of localized cervical vertebral motion of human volunteers during low-speed rear impacts*) with human subjects and the neck forces and the moment were also analysed.

As it is said previously, all methods consider the head to be a rigid body. The difference between the studies is the instrumentation of the volunteers where the accelerometers are attached.

Below, all the studies are analysed and explained deeply, so the differences can be observed.

2.4 Mertz and Patrick study

2.4.1 Characteristics of the method used

- To evaluate the severity of the whiplash simulation and the effectiveness of the safety devices, the neck reactions were determined (see Section 2.4.4).
- The headrest loads were measured directly with a load cell.
- The neck reactions were obtained by applying the equations of dynamic equilibrium (1) and (2) to the head.
- The neck reactions are calculated on the occipital condyle (OC), at the base of the skull (see Section 2.4.4).
- In this analysis the head is considered to be a rigid body undergoing plane motion (see Section 2.1).

Since it is considered the head moves in the plane X-Z (the head is considered to have plane motion), there is only acting shear force (F_x) and axial force (F_z).

2.4.2 Coordinate system

The origin of the coordinate system is the center of gravity of the head (CG). The x-axis is parallel to the Frankfort line and its direction is posterior toward anterior. The z-axis is perpendicular to x-axis and upwards (see Figure 7).

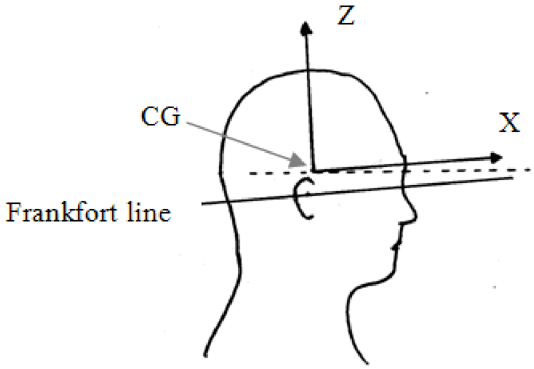

Figure 7. Coordinate system of the head

2.4.3 Free body diagram of the head

All the forces and moments apply in the head of the human subject and the neck reactions are shown in Figure 8.

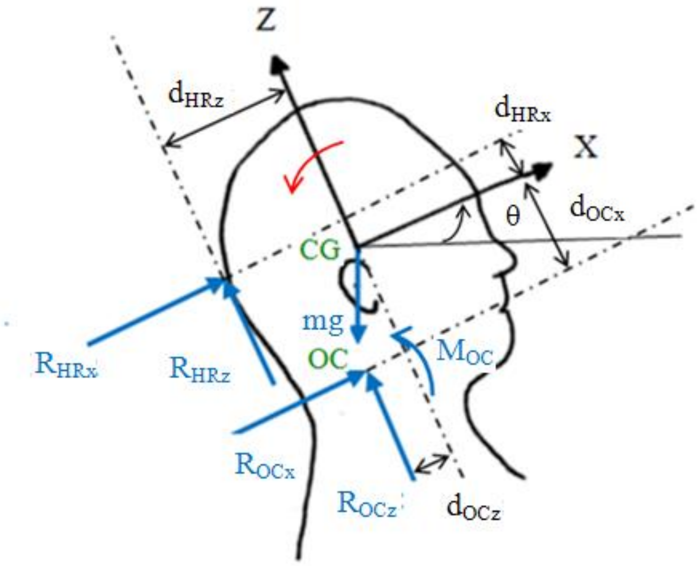

Figure 8. Free body diagram of the head (See Table 1 for more details)

Table 1. Summary of the variables used in Mertz et al. 1967, 1971

Variable	**Description**	**Received from**	**See**
θ	the angle between the x-axis of the coordinate system and the horizontal line	Film analysis	-

α	absolute angular acceleration of head	Calculated	Equations (15) and (16)
ω	absolute angular velocity of head	Calculated	Equations (15) and (16)
R_{HRi}	the headrest load in i-direction	Measured with a load cell	-
R_{OCi}	the force in the i-direction	Calculated	Equations (10) and (11)
M_{OC}	the moment in the neck	Calculated	Equation (12)
d_{HRi}	distance between R_{HRi} and i-axis	Measured from film	-
d_{OCi}	distance between R_{OCi} and i-axis	Measured from film	-
I_y	Moment of inertia of the head in the y-axis	Determined from literature	Reference Dempster et al. 1976
m	Mass of the head	Determined from literature	Reference Dempster et al. 1976
O, P	Two arbitrary points where the acclerometers were attached		Figure 9
OP_i	Distance between the two points in the i-axis	Film analysis	-
a_{Pi} , a_{Oi}	Linear acceleration of O and P points	Measured from accelerometers	Figure 9
a_{CGi}	Acceleration on the center of gravity of the head in the i-axis	Calculated	Equations (17) and (18)

2.4.4 Equations applied

As it is said previously, the head is considered to be a rigid body, so the equations applied to calculate the forces and moments in the neck are (see section 2.1):

$$\sum \vec{F} = m \cdot \overrightarrow{a_{CG}} \qquad (8)$$

$$\sum M_{CG} = I_y \cdot \alpha \qquad (9)$$

The equation (8) allows calculating the shear and axial forces which are caused because of the linear acceleration, and with the equation (9) the moment in the y-axis in the neck can be calculated because during the rear end impact the head rotates.

Developing (9) in both directions (X and Z) (see Figure 8), the equations obtained are:

$$R_{HRx} + R_{OCx} - m \cdot g \cdot sin\theta = m \cdot a_{CGx}$$

$$R_{HRz} + R_{OCz} - m \cdot g \cdot cos\theta = m \cdot a_{CGz}$$

Hence, R_{OCx} (the shear force) is calculated from:

$$\boxed{R_{OCx} = m \cdot a_{CGx} - R_{HRx} + m \cdot g \cdot sin\theta} \qquad (10)$$

And R_{OCz} (the axial force) is calculated from:

$$\boxed{R_{OCz} = m \cdot a_{CGz} - R_{HRz} + m \cdot g \cdot cos\theta} \qquad (11)$$

Developing the equation (9):

$$-R_{HRx} \cdot d_{HRx} - R_{HRz} \cdot d_{HRz} + R_{OCx} \cdot d_{OCx} - R_{OCz} \cdot d_{OCz} + M_{OC} = I_y \cdot \alpha$$

Hence, the moment M_{OC} is given by:

$$\boxed{M_{OC} = I_y \cdot \alpha + R_{HRx} \cdot d_{HRx} + R_{HRz} \cdot d_{HRz} - R_{OCx} \cdot d_{OCx} + R_{OCz} \cdot d_{OCz}} \qquad (12)$$

The equations of dynamic equilibrium are applied in the center of gravity of the head because the calculations are easier and also because the moment of inertia (I_y) can be found in some anthropometric studies about humans (see Section 3.3 and Table 1).

2.4.5 Calculation of the accelerations of the center of gravity of the head

With two accelerometers, the acceleration of two different points of the head is measured (see Section 2.6). In order to measure the accelerations of the center of gravity of the head, the kinematics of the solid rigid are used.

The relationship between the accelerations of two different points, for instance P and O is:

$$\vec{a}(P) = \vec{a}(O) + \vec{\omega} \text{x} \left(\vec{\omega} \text{x} \overrightarrow{OP}\right) + \vec{\alpha} \text{x} \overrightarrow{OP} \qquad (13)$$

The distance between these two points ($\overrightarrow{OP}$) is known (by film analysis), the acceleration of both points (P and O) is measured and the only unknown vectors are $\vec{\omega}$ (the angular velocity of the head) and $\vec{\alpha}$ (the angular acceleration of the head). Then, considering that the head has only motion in the X-Z plane, the unknown vectors are:

$$\vec{\omega} = \begin{Bmatrix} 0 \\ \omega \\ 0 \end{Bmatrix} \qquad \vec{\alpha} = \begin{Bmatrix} 0 \\ \alpha \\ 0 \end{Bmatrix}$$

Therefore, the two values are obtained solving the vector equation (13):

$$\begin{Bmatrix} a_{Px} \\ 0 \\ a_{Pz} \end{Bmatrix} = \begin{Bmatrix} a_{Ox} \\ 0 \\ a_{Oz} \end{Bmatrix} + \begin{Bmatrix} 0 \\ \omega \\ 0 \end{Bmatrix} \text{x} \left[\begin{Bmatrix} 0 \\ \omega \\ 0 \end{Bmatrix} \text{x} \begin{Bmatrix} OP_x \\ 0 \\ OP_z \end{Bmatrix} \right] + \begin{Bmatrix} 0 \\ \alpha \\ 0 \end{Bmatrix} \text{x} \begin{Bmatrix} OP_x \\ 0 \\ OP_z \end{Bmatrix} \tag{14}$$

Developing equation (14):

$$a_{Px} = a_{Ox} - \omega^2 \cdot OP_x + \alpha \cdot OP_z \tag{15}$$

$$a_{Pz} = a_{Oz} - \omega^2 \cdot OP_z - \alpha \cdot OP_x \tag{16}$$

Solving the previous system, α and ω can be calculated.

Once the values of α and ω are known, the same relationship between either O or P and the center of gravity is used again to calculate the acceleration of the center of gravity of the head.

$$a_{CGx} = a_{Ox} - \omega^2 \cdot OCG_x + \alpha \cdot OCG_z \tag{17}$$

$$a_{CGz} = a_{Oz} - \omega^2 \cdot OCG_z - \alpha \cdot OCG_x \tag{18}$$

With these accelerations determined, equations (10), (11) and (12) can be used to obtain the neck reactions. The other values needed are the position of the center of gravity of the head, the mass of the head and the mass moment of inertia which can be determined or found in different anthropometric human studies (see Section 3); the moment arms for the forces which can be measured from images of a camera; and the headrest load which is also measured with a load cell.

2.4.6 Human subject head instrumentation

In the first study (1967), two uniaxial accelerometers whose axes were orthogonal were fitted at two points of the volunteer human head. One pair of accelerometers was fitted to a plastic head and in the front head region. The other pair of accelerometers was mounted to a fitted biteplate made of dental acrylic (see Figure 9).

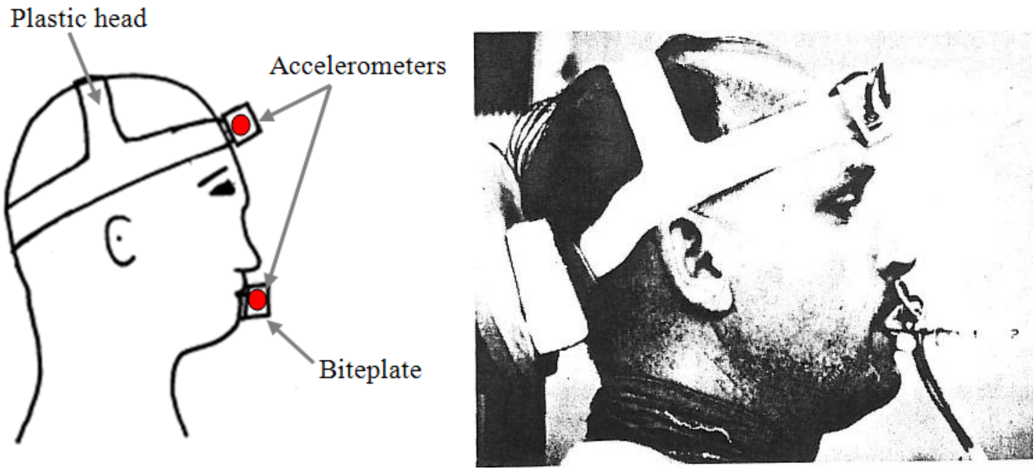

Figure 9. Sketch of the head subject system and photograph of the human volunteer from Mertz et al. 1967

In their second study (1971), one pair of uniaxial accelerometers was mounted to a fitted biteplate (as the same way as the previous experiment), but in this case, the second pair of accelerometers was fitted to a lightweight fiberglass helmet which was securely fastened to the subject's head (see Figure 10).

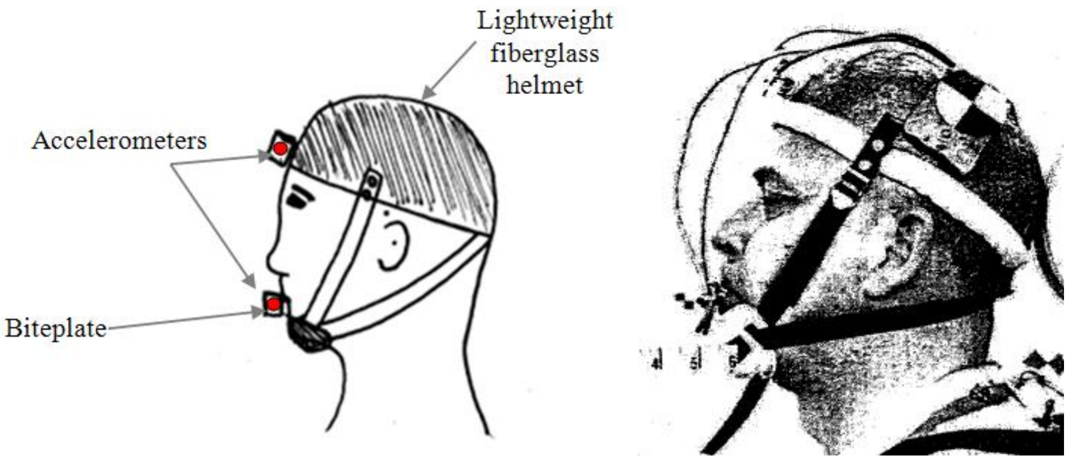

Figure 10. Sketch of the head human system and photograph of the volunteer with the system from Mertz et al. 1971

2.5 A. van den Kroonenberg et al. study

2.5.1 Characteristics of the method used

- The head restraint was used; hence the head restraint impact force was measured.
- The human subjects were belted with a three point safety belt.
- The head is also considered to be plane motion (see Section 2.1).

2.5.2 Head anatomical coordinate system

The origin of the coordinate system is in the midsagittal and in the imaginary line that links the left and right auditory meatus (AM). The x-axis lies in the Frankfort plane from posterior to anterior and the z-axis is perpendicular to the Frankfort plane in the upward direction (see Figure 11).

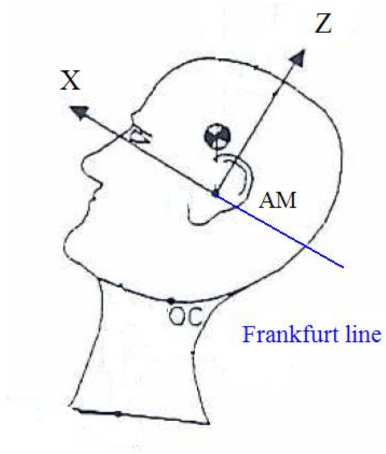

Figure 11. Head anatomical coordinate system from Kroonenberg et al. (1998)

2.5.3 Free body diagram of the head

All the forces and moments apply in the head's human subject and also the neck reactions are shown in Figure 12:

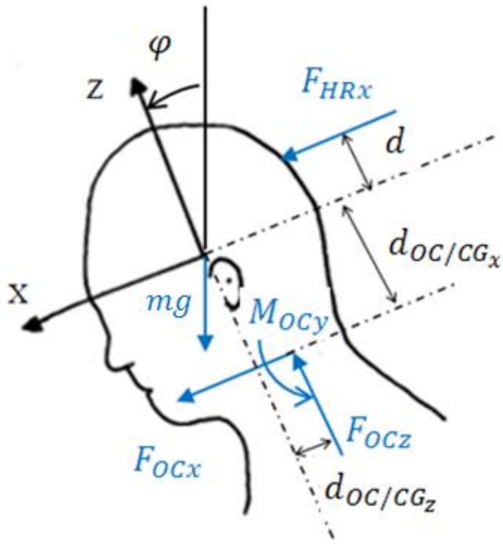

Figure 12. Free body diagram with all the forces in the head (See Table 2 for more details)

Table 2. Summary of the variables used in Kroonenberg et al. 1998

Variable	Description	Received from	See
φ	the angle of z-axis relative to the vertical line	Film images	-
F_{OCi}	force at the OC joint in the i-direction	Calculated	Equations (19) and (20)
M_{OCy}	the moment in the y direction	Calculated	Equation (21)
a_i	linear acceleration of the center of gravity of the head in the i direction	Measured from accelerometers	Figure 13
α	angular acceleration of the head	Measured	Figure 13
d	the distance between the forces F_{HRx} and F_{OCx}	Film images	Figure 12
d_{OC/CG_i}	the distance between the force of the mass in the i direction and F_{OCi}	Film images	Figure 12
F_{HRx}	the head restraint impact forces	Measured	-
I_y	the moment of inertia in the y-axis	Determined from literature	Reference McConville et al. 1980 (for males)
m	the mass of the head	Determined from literature	Reference McConville et al. 1980 (for males)

2.5.4 Neck loads

Upper neck axial and shear force and upper neck moment were expressed in the head anatomical coordinate system.

Since the head is considered to have motion only in the X-Z plane (see Section 2.1), it is calculated the shear force (Fx), the axial force (Fz) and the moment in the Y-direction. Applying equations (1) and (2) on the occipital condyles

$$\sum F_x = m \cdot a_x$$

$$\sum F_z = m \cdot a_z$$

$$\sum M_{OCy} = I_y \cdot \alpha$$

and observing the free body diagram of the head (see Figure 12), the resultant equations are:

$$F_{OCx} = m \cdot (a_x - g \cdot sin\varphi) - F_{HRx} \quad (19)$$

$$F_{OCz} = m \cdot (a_z - g \cdot cos\varphi) \quad (20)$$

$$M_{OCy} = I_y \cdot \alpha - d \cdot F_{HRx} - d_{OC/CG} \cdot m \cdot g \cdot \sin\varphi \quad (21)$$

The mass of the head, the moment of inertia in the y-axis and the position of the center of gravity of the head can be calculated from the data of previous studies (see Section 3). Finally, the geometrical properties (distances and angle φ) can be measured from the film images.

2.5.5 Calculation of the accelerations of the center of gravity of the head

The linear and angular head accelerations were measured using accelerometers. The linear acceleration of the center of gravity of the head was measured with an accelerometer attached in the projection of the center of gravity in one side of the head (see Figure 13).

2.5.6 Instrumentation

Linear and angular accelerations of the head were measured. Film markers were attached to the volunteer in order to study the motion by video images.

One accelerometer was located in the projection of the centre of gravity of the head in the strap system in one side of the human subject. With this accelerometer, linear acceleration was measured. Another accelerometer was attached to the head band enabling to measure angular accelerations.

Film targets were used for recording displacements and rotations. Three film marks were attached on the head: one in the anatomical origin, i.e. the auditory meatus, the other in the centre of gravity and the last one in the infra orbital notch.

2.5.7 Human subject head instrumentation

Straps were tied around the chin, the forehead and the posterior part of the neck. The head sensors were mounted in aluminium plates fixed to the straps with screws (see Figure 13).

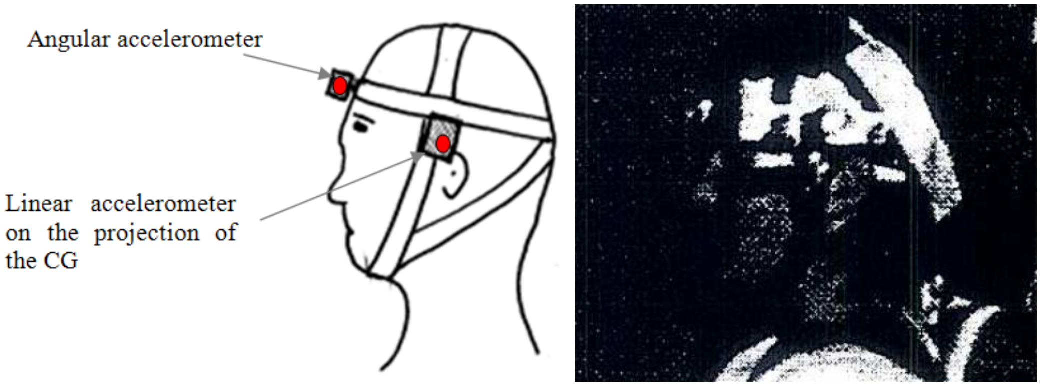

Figure 13. Sketch of the head sytem and photograph of the volunteer with the head strap from Kroonenberg et al. (1998)

2.6 Japanese studies (Ono et al. 1996, 1997, 2000, 2006)

In his manifold studies, Koshiro Ono et al. used two different systems to attach all the instrumentation needed to measure the accelerations:

- Head straps + mouthpiece (Ono et al. 1996, 1997, 2000)
- Mouthpiece (Ono et al. 2006)

2.6.1 Head strap + mouthpiece (Ono et al. 1996, 1997, 2000)

In the first studies by Ono et al. accelerometers were placed on a head strap and a mouthpiece. The head was supposed to have planar motion (see section 2.1).

A teeth form made of a dental resin was moulded for each voluntary. One bi-axial accelerometer was fitted in that part. The other bi-axial accelerometer was fitted in the upper part, just in front of the forehead, with a strap around the head to fasten the device (Figure 14).

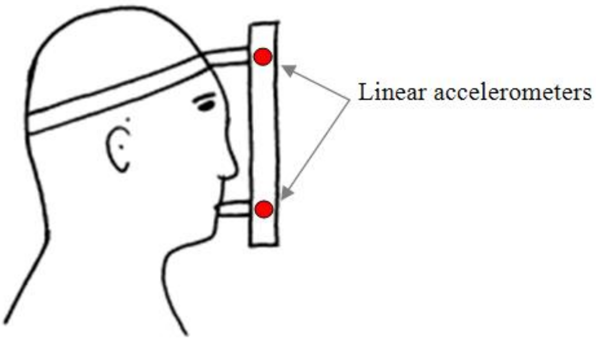

Figure 14. Sketch

2.6.1.1 Calculation of the angular acceleration and the linear acceleration in the center of gravity

See Section 2.4.5.

2.6.1.2 Calculation of the forces and moments in the upper neck

Using equations (1) and (2).

2.6.2 Mouthpiece (Ono et al. 2006)

In the most recent study the accelerometers were attached on the mouthpiece (Ono et al. 2006).

In this study, the head is supposed to have 3D motion (see section 2.2).

Figure 15. Sketch

2.6.2.1 Acceleration and angular speed measured

A mouthpiece which was bitten by the human subject was used to measure the acceleration of the head. Each human subject has his own moulded form.

In the mouthpiece, an angular speedometer and an accelerometer were fixed, so the angular velocity and the acceleration of this point were measured respectively.

In order to receive the acceleration at the center of gravity of the head, the kinematics of a solid rigid was used:

$$\vec{a} = \vec{a}_{CG} + \vec{\omega}\text{x}(\vec{\omega}\text{x}\vec{r}) + \vec{\alpha}\text{x}\vec{r} \qquad (22)$$

Where:

- $\vec{a}$ is the acceleration measured with the accelerometer
- $\vec{\omega}$ is the angular velocity measured with the angular speedometer
- $\vec{r}$ is the vector position with the origin on the center of gravity of the head to the position where the sensors are attached
- $\vec{\alpha}$ is the angular acceleration. It is possible to calculate its value by the 1st floor differentiating of the angular velocity

$$\begin{Bmatrix} \alpha_x \\ \alpha_y \\ \alpha_z \end{Bmatrix} = \begin{Bmatrix} \frac{d\omega_x}{dx} \\ \frac{d\omega_y}{dy} \\ \frac{d\omega_z}{dz} \end{Bmatrix}$$

- $\vec{a}_{CG}$ is the acceleration on the center of gravity and its value is calculated

Developing equation (22) for each component of $\vec{a}_{CG}$, this acceleration can be calculated as follow:

$$\left.\begin{aligned} a_{CGx} &= a_x - \left(\frac{d\omega_y}{dy} r_z - \frac{d\omega_z}{dz} r_y\right) + r_x\left(\omega_y^2 + \omega_z^2\right) - \left(r_y \omega_x \omega_y + r_z \omega_z \omega_x\right) \\ a_{CGy} &= a_y - \left(\frac{d\omega_z}{dz} r_x - \frac{d\omega_x}{dx} r_z\right) + r_y\left(\omega_z^2 + \omega_x^2\right) - \left(r_z \omega_y \omega_z + r_x \omega_x \omega_y\right) \\ a_{CGz} &= a_z - \left(\frac{d\omega_x}{dx} r_y - \frac{d\omega_y}{dy} r_x\right) + r_z\left(\omega_x^2 + \omega_y^2\right) - \left(r_x \omega_z \omega_x + r_y \omega_y \omega_z\right) \end{aligned}\right\} \quad (23)$$

2.6.2.2 Forces and moments

Once the acceleration at the center of gravity is calculated, the forces can be found by applying:

$$\left.\boxed{\begin{aligned} F_x &= m \cdot a_{CGx} \\ F_y &= m \cdot a_{CGy} \\ F_z &= m \cdot a_{CGz} \end{aligned}}\right\} \quad (24)$$

And finally, Euler equations explained in section 2.2 were used to calculate the neck forces and the moments in the joint between the head and the neck.

$$\left.\boxed{\begin{aligned} M_x &= I_x \cdot \alpha_x + \left(I_z - I_y\right) \cdot \omega_y \cdot \omega_z + F_y \cdot r_{OCy} - F_z \cdot r_{OCy} \\ M_y &= I_y \cdot \alpha_y + \left(I_x - I_z\right) \cdot \omega_x \cdot \omega_z - F_x \cdot r_{OCz} + F_z \cdot r_{OCx} \\ M_z &= I_z \cdot \alpha_z + \left(I_y - I_x\right) \cdot \omega_x \cdot \omega_y + F_x \cdot r_{OCy} + F_z \cdot r_{OCx} \end{aligned}}\right\} \quad (25)$$

2.7 Advantages and disadvantages of the different methods

Method	Advantages	Disadvantages
Plastic Head + Biteplate		Biteplate made of dental acrylic moulded for each volunteer

Fiberglass helmet + Biteplate	Lightweight Securely fastened	Biteplate made of dental acrylic moulded for each volunteer
Straps tied around the chin, the forehead and the posterior part of the neck. Accelerometer located on the projection of the center of gravity of the head	With the accelerometer positioned on the projection of the center of gravity, errors in calculations due to the distances taken from the images are avoided	Difficulty to attach the accelerometer exactly on the projection of the center of gravity in one side of the head
Head strap + Mouthpiece		Each volunteer has his own moulded form for the mouthpiece Very dependent on the distances between the accelerometers and the CG and the OC
Mouthpiece	Head is considered to have 3D motion More accurate method, less dependent on the distances	Each volunteer has his own moulded form for the mouthpiece

3 Review of human head properties

In order to calculate the kinematics and kinetics of the neck during a rear impact, physical properties of the human head, i.e. the mass, location of the centre of gravity and mass moment of inertia of the head are important parameters. Forces and moments at the occipital condyles (OC) (the head-neck junction) can be obtained once linear and rotational head accelerations are measured, mass of the head and moments of inertia are calculated and the occipital condyles are located.

To date, many studies have been done in both human cadavers and living humans, and the results have been used in some studies to calculate accelerations, forces and moments of the neck during a rear impact.

Crash test studies with human cadavers are:

- Mass, volume, center of mass and mass moment of inertia of head and head neck of human body (Walker et al. 1973).
- Determination of physical data of the human head such as the center of gravity and moments of inertia (Beier et al. 1979).

There are more studies concerning the physical properties of the head, for example Chandler et al. (1975) and Clauser et al. (1969)…

However there are not many studies on living humans:

- Anthropometric and mass distribution characteristics of the adult female (Young & Chandler 1983).
  46 female adults were treated in this study, with a mean age of 31.2 years old, mean weight of 63.9 kg and mean stature of 1.61 m.
- Anthropometric relationships of body and body segment moments of inertia (McConville & Churchill 1980).
  31 male adults which represent U.S. Air Force male flying population specifically, and the U.S. adult male population in general.

In these studies, regression equations were developed in order to estimate mass distribution of the body parts based on anthropometric body measurements. Stereophotogrammetry techniques were used in order to estimate the volume and the mass moment of inertia of the living subject.

Stereophotogrammetry technique consists on taking different images from different positions so different 3 dimensional coordinates of points on the body surface. And then, with mathematical models, mass, volume and moments of inertia of the human livings are generated.

Most of the studies are focused on males, only a few works with females, but not focus on them. Only Young (1983) did a study with 46 female adult living.

3.1 Center of gravity of the head

The localization of the center of gravity of the human head is very important to understand the forces which keep or modify the equilibrium of the head.

In the human subjects, the center of gravity of the head is located just in front of the occipital condyles.

It should have be carefully when extrapolate conclusions from studies on cadavers to living human subjects, because the localization of the center of gravity may change slightly due to the movement of the brain and the alteration of the blood flow in the living humans.

There are many studies both in cadavers and in living humans as mentioned above.

Beier et al. **1980** did a study with 19 male and 2 female cadavers. The results of the center of gravity locations are summarized in Table3:

Table 3. Center of gravity for 19 male + 2 female cadavers from Beier et al.1980

With respect to the AM	Range [cm]		Mean [cm]	SD (*) [cm]
x-axis	0.28	1.37	0.83	0.26
y-axis	-0.26	0.34	-0.03	0.14
z-axis	2.18	4.34	3.13	0.56

(*) SD (Standard Deviation): is a statistical measure the dispersion of a group. The formula to calculate it is $\boldsymbol{SD} = \sqrt{\frac{1}{N} \cdot \sum_{i=n}^{N} (x_i - \boldsymbol{Mean})^2}$. A small SD indicates that all the values of the group are very compact to the mean value.
Data obtained from the paper from Yoganandan et al. 2009.

Table 4 shows the results for the two female cadavers in the study.

Table 4. Center of gravity for the 2 female cadavers from by Beier et al.1980

With respect to the AM	Range [cm]		Mean [cm]	SD [cm]
x-axis	0.28	0.66	0.47	0.27
y-axis	0.05	-0.17	-0.06	0.16
z-axis	2.96	2.87	2.92	0.06

Data obtained from the paper from Yoganandan et al. 2009.

Walker et al. **1973** also did a study based on the physical properties from 20 human male cadavers. X-rays were taken to measure the geometry. The location of the center of gravity (received from X-rays and photos) were (see Table 5):

Table 5. Center of gravity of the head from Walker et al. 1973

With respect to the AM	X-Ray [cm]	Photo [cm]
x-axis	0.91	1.49
z-axis	2.22	2.448

Young et al. 1983 did a study with 46 adult living female subjects. In this case, the authors gave the location of the center of volume of the head (see Table 6).

Table 6. Center of volume of the head of 46 female subjects from Young et al.1983

With respect to the AM	Range [cm]		Mean [cm]	SD [cm]
x-axis	-2.43	0.05	-1.08	0.53
y-axis	-0.6	0.84	0.01	0.35
z-axis	2.24	4.79	3.42	0.45

In the study the relationship between the center of volume and the center of gravity is non-well explained. The authors wrote that "the center of volume as reported in this study is not coincident with the center of mass of the head", but they also stated that for the purpose of their study (establish the relationship between human body size and its mass distribution properties) the use of the center of volume instead the exactly position of the center of mass is believed to be valid.

In all the papers by **Koshiro Ono et al. 1996, 1997, 2000, 2006**:

- *Cervical injury mechanism based on the analysis of human cervical vertebral motion and head-neck-torso kinematics during low speed rear imp*acts (1997)
- *Analysis of seat properties on human cervical vertebral motion in low-speed rear-end impacts (2000)*
- *Prediction of neck injury risk based on the analysis of localized cervical vertebral motion of human volunteers during low-speed rear impacts (2006)*

Where the forces and the moments were calculated on experiments with human subjects, the position of the center of gravity of the head was situated 5 mm in the forward direction from the auditory meatus and 20 mm on the vertical line of the Frankfort line.

The position of the center of gravity of the head in the 5th percentile female dummy (small female) which has been taken, with respect to the auditory meatus is according to Robbins et al. 1983:

- X= -2mm
- Y= 0mm
- Z= 33mm

3.1.1 Summary

In Table 7 all the data to locate the center of gravity relative to the auditory meatus is summarized.

Table 7. Summary of the different studies for the location of the center of gravity relative to the AM [cm]

Author	**x-axis**	**y-axis**	**z-axis**
Beier et al. 1980 – 19 males + 2 females cadavers	0.83	-0.03	3.13
Beier et al. 1980 – 2 females cadavers	0.47	-0.06	2.92
Walker et al. 1973 – 20 males cadavers (Photo)	1.49	-	2.488
Walker et al. 1973 – 20 males (X-Ray)	0.91	-	2.22
Young et al. 1983 – 46 living females	-1.08	0.01	3.42
Ono – used in his studies (males)	0.5	0	2
5th percentile female dummy	-0.2	0	3.3

3.2 Mass of the head

In the study by **Walker et al. (1973),** the mean head mass for the 20 male cadavers was 4.4 ±0.6 kg.

In the **Beier et al.** (**1980)** study the mean head mass was 4.324 kg with a SD of 0.395 kg. (for 19 males + 2 females).

The average head mass for the 2 females in the study was 4.125 ±0.6 kg

Young et al. (1983) did not calculate the mass of the head directly, but in their study the mean volume of the head was calculated, as well as regression equations to predict the volume of the head of the females.

The range of the head volume of the 46 living adult females was 3386 – 4514 cm^3, with a mean value of 3.894 cm^3 (SD= 267 cm^3). The regression equations based on stature and height (easy to measure these values in living humans) and using other measurements of body sizes of the human head are (see section 3.3.1 for descriptions of the anthropometric measurements):

Table 8. Regression equations for the volume of the female head by Young et al. (1983) (See Section 3.3.1 for the anthropometric measurements)

	R (*)	**SE EST (**)**
$-1.25 * Stature + 4.45 * Weight + 3469$	0.450	6.3%
$147.05 * Head\ circ. -4161.23$	0.661	5.2%
$108.73 * Head\ circ. +137.28 * Head\ height - 4202.24$	0.754	4.6%
$132.85 * Head\ circ. +163.75 * Head\ height - 13.73 * Stature - 3722.51$	0.799	4.3%

(*) R: Multiple correlation coefficient. It's a statistical measure which measure the strength between the predictive variable and the variable used in the regression equations. The closer R is to one, the stronger is the linear association.
(**) SE EST: Standard error of estimate. It's a measure of the accuracy of predictions given by a regression line. It is given as a percent of the predicted variable mean value.

In order to obtain the regression equations, BMD (Biomedical Computer Program) stepwise regression computer program, and the anthropometric variables, was used to better predict the head properties.

Once the head volume is estimated, the mass of the head can be easily calculated by using the concept of specific gravity (SG) (the ratio of a density of a sample of the human to the density of the water):

$$SG = \frac{\rho}{\rho_{H_2O}} \qquad (26)$$

Where:

- ρ is the density of the human body
- ρ_{H_2O} is the density of the water, which equals to 1g/cm^3
- SG is the specific gravity

The mass of the head can be obtained in three steps:

1) Assume a value for SG
2) Calculate the density of the human body by using equation (26)
3) Use the next formula to find the mass of the head:

$$\rho = \frac{m}{V}$$

Where:

- m is the mass of the head
- V is the head volume

Some previous studies have arrived to the conclusion that each segment of the body has its own specific gravity, but Young et al. (1983) used a value for the specific gravity of 1.066 for the whole parts of the body. In their study the volume of each segment was calculated from the mass using the above specific gravity value.

Hence, the regression equations used to find the volume of the head can be used to find the mass of the head, only by multiplying the result by the value of specific gravity 1.066.

Table 9. *Regression equations for the mass of the female's head by Young et al.1983 (See Section 3.3.1 for the anthropometric measurements)*

	R	**SE EST**
$(-1.25 * Stature + 4.45 * Weight + 3469) * 1.066$	0.450	6.3%
$(147.05 * Head\ circ. -4161.23) * 1.066$	0.661	5.2%
$(108.73 * Head\ circ. +137.28 * Head\ height - 4202.24) * 1.066$	0.754	4.6%
$(132.85 * Head\ circ. +163.75 * Head\ height - 13.73 * Stature - 3722.51) * 1.066$	0.799	4.3%

The units of the mass are [g]

The head mass for the **Hybrid III 5th percentile female** is 3.733 kg.

The head mass for the **BioRID II** (represents a 50th percentile male) is 4.54 kg.

3.2.1 Summary

In Table 10 the mean value for the head mass of the different studies is summarized.

Table 10. Summary of the different studies for mass of the female's head

Author	N (Females)	N (Males)	Subjects	Mean mass [kg]
Walker et al. (1973)	-	20	Cadavers	4.4
Beier et al. (1980)	2	19	Cadavers	4.324
Beier et al. (1980)	2	-	Cadavers	4.125
Young et al. (1983) (*)	46	-	Volunteers	4.15
Hybrid III 5th percentile female	-	-	Dummy	3.733
BioRID II (50th percentile male)	-	-	Dummy	4.54

(*) The mass is calculated from the volume of the head

3.3 Moment of inertia of the head

From **Walker et al. 1973** study (20 male cadavers) the mean moment of inertia in the y-axis was 233 ±37 kg·cm^2. In the other axis, they weren't calculated.

One observation given by the same authors of this paper is that the position of the center of gravity of the head seems to be more reliable than the value of the mass moment of inertia.

From **Beier et al. 1980**, the moments of inertia of the head (19 males + 2 females) were calculated in all directions. The table below summarized the min. and max. values and also the mean.

Table 11. Moments of inertia by Beier et al.1980

	Range [kg·cm^2]		Mean [kg·cm^2]	SD
I_x	136	274	205.9	34.6
I_y	159	298	223.4	34.4
I_z	110	198	148.4	25.5

Data from Beier indicate that exist a good correlation (R^2=0.77, 0.93, 0.74 for I_x, I_y, I_z respectively) between head mass and the principal moments of inertia of the head.

Hence, predictive equations for mass moment of inertia as a function of the head mass were proposed by the author. These are the following equations:

$$I_x = 11.746 * Head\ weigth - 40.964$$

$$I_y = 12.788 * Head\ weigth - 44.826$$

$$I_z = 8.4519 * Head\ weigth - 29.386$$

The head weight is measured in lbs, and I is the mass moment of inertia of the head in lb·in^2.

Also from **Young et al. 1983** study (46 living females), regression equations were extracted which can be used for predicting the moment of inertia of the head. It is possible because this study demonstrates that body size and moments of inertia are related.

On these regression equations, stature and weight are used because of the facility to measure these values on a human subject, but also the most highly correlated variables are used.

The whole regression equations for the three axes are summarized in Table 12:

Table 12. Regression equations for the moment of inertia of the head in the x-axis from Young et al. 1983 (See Section 3.3.1 for the anthropometric measurements)

	Head x-moment of inertia	**R**	**SE EST**
I_x	$-384 * Stature + 476 * Weight + 155137$	0.419	17.1%
	$21363 * Head\ height - 172855$	0.567	15.4%
	$16909 * Head\ height + 17129 * Head\ breadth - 353147$	0.609	14.9%
	$21363 * Head\ height + 17142 * Head\ breadth - 723 * Stature - 271345$	0.624	14.9%
	Head y-moment of inertia	**R**	**SE EST**
I_y	$-25 * Stature + 357 * Weight + 143627$	0.409	11.8%
	$12704 * Head\ circ. -505983$	0.635	9.9%
	$9784 * Head\ circ. +10461 * Head\ height - 509109$	0.706	9.2%
	$11702 * Head\ circ. +125666 * Head\ height - 1092 * Stature - 470950$	0.743	8.8%

Head z-moment of inertia		R	SE EST
I_z	$-220 * Stature + 88 * Weight + 92585$	0.154	15%
	$8746 * Head\ circ. -338641$	0.503	13%
	$9985 * Head\ circ. -9252 * Head\ breadth - 271640$	0.534	12.8%
	$11158 * Head\ circ. -9089 * Head\ breadth - 521 * Stature - 254325$	0.550	12.8%

The units of the moments of inertia of the head are: $g \cdot cm^2$

3.3.1 Anthropometric measurements

The measurements of the head size which appear in the above regression equations are calculated as follow:

- Head circumference (cm): with the tape passing above the forehead and parallel to the Frankfort plane, measure the maximum circumference of the head
- Head breadth (cm): with a spreading caliper, measure the maximum horizontal breadth of the head.
- Head height (cm): Stature – mastoid height
  Where: the mastoid is the bony eminence on the inferior posterior aspect of the temporal bone behind the ear.
- Weight (lbs)
- Stature (cm)

[The equivalence between pounds and kg is: 1 kg = 2.205 lbs]

3.3.2 Comparison between males and females

In Table 14, there are the mean values for the moment of inertia of the head for both genders. The data is extracted from studies on living humans (See section 3).

Table 13. Comparison between the mean value of the moment of inertia for living males (McConville et al.1980) and females (Young et al. 1983)

	Males [$g \cdot cm^2$]	Females [$g \cdot cm^2$]
I_x	204117	160208
I_y	232888	189917
I_z	150832	140438

3.4 Position of the occipital condyle

The location of the occipital condyle relative to the coordinate reference system of the head (see Figure III) used in previous studies (Yoganandan et al. 2009, Wismans et al. 1986) for the calculation of the dynamics of the neck is:

- x= -11 mm
- y= 0 mm
- z= -26 mm

In such study, the location of occipital condyles are assumed to be subjects independents, instead of locate this point for each volunteer as it has been done in most recent experiments with volunteers. The position of the occipital condyles was the average values based on human volunteer data.

Another location for the occipital condyles (OC) relative to the coordinate reference system of the head (see Figure III) extracted from literature (Yoganandan et al. 2009, Plaga et al. 2005) is: 8.89 mm anterior and 31.75 mm inferior to the origin of anatomic coordinate system reference (see Figure III).

- x= -8.89 mm
- y= 0 mm
- z= -31.75 mm

Another position for the occipital condyles relative to the coordinate reference system of the head (see Figure III), in that case specific for small females, which has been taken when constructing the respective dummy (5th percentile female dummy Hybrid), is (Robbins et al. 1983):

- x= -11 mm
- y= 0 mm
- z= -25 mm

The anthropometric characteristics of the small female are:

- Stature: 151 cm
- Weight: 47 kg

The position of the occipital condyles (in this case, the position of the occipital condyles is given with respect to the center of gravity instead of the auditory meatus) in the BioRID II is:

- x= -19 mm
- y= 0 mm
- z= -51 mm

The author of the present study has been investigating another way to find out the position of the occipital condyles in human without using X-ray, but the research has been unsuccessful.

3.4.1 Summary

Table 14. Position of the OC relative to the coordinate reference system of the head

Author	x-axis [mm]	y-axis [mm]	z-axis [mm]
Wismans et al. 1986	-11	0	-26
Plaga et al. 2005	-8.89	0	-31.75
5th percentile female dummy	-11	0	-25
BioRID II (50th percentile male) (*)	-19	0	-51

(*) Position given with respect to the center of gravity instead of the auditory meatus

3.5 Important aspects of the head properties

A recent study (Yoganandan et al. 2009) demonstrates the importance of using specimen-specific head physical properties in the head-neck dynamics. Although that study is focused on side impacts with male human subjects, the authors concluded the forces and moments calculated in rear end impacts would be different using literature-based regression equations or specimen-specific head physical properties.But they do not specify which could be the error. They only indicated the errors would be higher in the moments due to the "lever arm" parameter in the calculations than the forces.

As it is mentioned in a previous section, the stature and the body mass do not necessary provide the best estimate possible, but in this study indicated that these anthropometric measurements (stature and weight) provide the closes match to the actual specimen-specific results.

To estimate the position of the occipital condyles and the center of gravity of the head, there are no regression equations which allow doing that.

4 IMT40

IMT40 is a new sensor market by the company IMEGO.

IMEGO is a Swedish company founded in 1999. It has a great experience in sensors, since IMEGO has launched many.

IMEGO does not have any experience with volunteer experiments, but its products have been used by many cars manufactures on dummies, allowing them to obtain certain data and improve the vehicle safety.

IMT40 is designed for measuring all details of rapid, violent motions. The product includes the sensor and the PC software for the calculations.

Such product measures:

- Position
- Velocity
- Acceleration
- Attitude/angular rate
- Angular acceleration

One good advantage of the new sensor is that with its software the accelerations of different points of the solid can be calculated in an easy way. Another advantage is the fact that the frequency in which the information can be taken could be very high (up to 7.8 kHz); thus, each second lots of information are recorded, so the errors decrease.

Other characteristics of the sensor are:

- Dimensions: 64x38.2x28.2 mm^3
- Weight: < 100g
- Cost: around 400 000 SEK

The information was found in the webpage of the company: www.imego.com and also from and a personal interview with Kenneth Malmström and Peter Björkholm, workers on IMEGO.

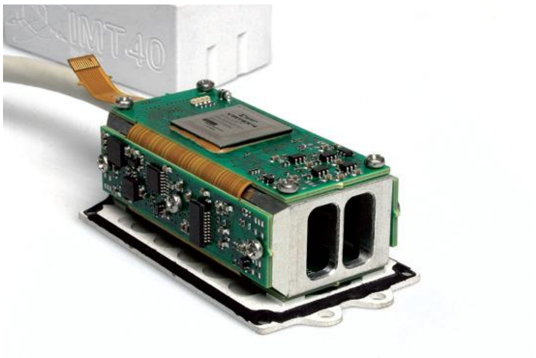

Figure 16. View of the IMT40. Picture extracted from www.imego.com

The company does not sell any additional equipment to fix the sensor on the volunteer head, but they are willing to help in the construction of the adequate head rig if it's necessary.

5 Sensitivity regarding the position of the OC

The objective of the following section is to evaluate the error in the upper neck loads when the position of the occipital condyle is varied.

Data recorded from one male volunteer in a rear end impact is used to estimate the sensitivity regarding the position of the OC. The data was provided by Johan Davidsson from his experiments at the end of 90s.

The characteristics of the experiment were:

- No head restraint was used
- No tension, in a relax position
- Low velocity (8 km/h)
- The method used to fix the accelerometers was a head strap + mouthpiece (see Figure 17 and section 2.6.1)

The characteristics of the male volunteer were:

- Age: 22 years
- Mass of the head: 4.24 kg. (Estimated from McConville et al. 1980)
- Moment of inertia of the head: $2.22 \cdot 10^5\ g \cdot cm^2$. (Estimated from McConville et al. 1980)
- Location of the CG relative to the coordinate reference system of the head (see Figure III):
    - $d_x = 5\ mm$
    - $d_z = 20\ mm$

  The position of the CG is the same as in Ono et al. studies.
- Location of the OC relative to the coordinate reference system of the head (see Figure III):
    - $d_x = -8\ mm$
    - $d_z = -35\ mm$

  Extracted from X-rays of the volunteer's head.
- Distances between accelerometers/center of gravity/occipital condyles: see Figure 17.

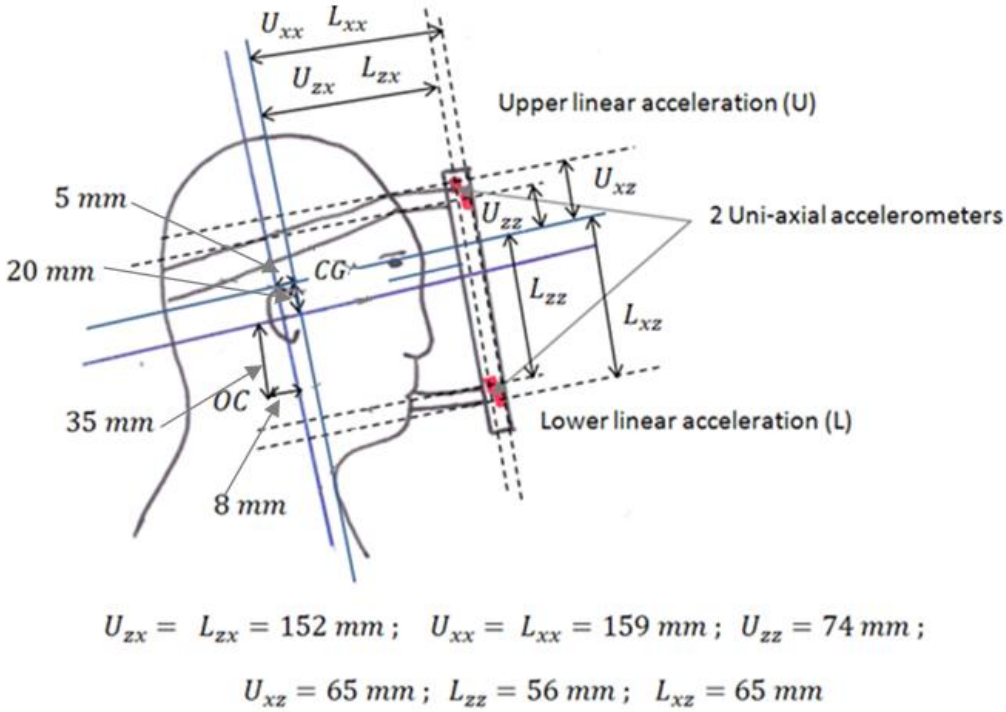

Figure 17. Volunteer head with the position of the 2 uni-axial accelerometers, the occipital condyle and the center of gravity and the distances between these points

From the experiment, linear acceleration from the upper and lower position was measured in x- and z- direction.

As it can be observed from section 2, the location of the occipital condyles only affects the bending moment in the upper neck; the loads are not influence by such point. Hence, in this part is only studied the error in the moment.

To calculate the bending moment with the linear acceleration measured, the next steps are followed:

1) Equations (15) and (16) are used to calculate the head angular acceleration and the head angular velocity.

$$a_{Lx} = a_{Ux} - \omega^2 \cdot UL_x + \alpha \cdot UL_z$$
$$a_{Lz} = a_{Uz} - \omega^2 \cdot UL_z - \alpha \cdot UL_x$$

Where (see Figure 17):

- $a_{Lx}, a_{Ux}, a_{Lz}, a_{Uz}$ is the acceleration measured
- $UL_x = 0$ is the distance between the accelerometers in the x-direction
- $UL_z = 130\ mm$ is the distance between the accelerometers in the z-direction

2) Acceleration of the center of gravity is calculated with equation (13) applied in the upper point (U)

$$\vec{a}(CG) = \vec{a}(U) + \vec{\omega}\mathrm{x}\left(\vec{\omega}\mathrm{x}\overrightarrow{UCG}\right) + \vec{\alpha}\mathrm{x}\overrightarrow{UCG}$$

Developing the last equation:

$$a_{CGx} = a_{Ux} - \omega^2 \cdot UCG_{xx} + \alpha \cdot UCG_{xz}$$
$$a_{CGz} = a_{Uz} - \omega^2 \cdot UCG_{zz} - \alpha \cdot UCG_{zx}$$

Where:

- $UCG_{xx} = -152\,mm$ is the distance in the x-direction between the x-accelerometer in the upper part and the center of gravity
- $UCG_{xz} = -65\,mm$ is the distance in the z-direction between the x-accelerometer in the upper part and the center of gravity
- $UCG_{zz} = -74\,mm$ is the distance in the z-direction between the z-accelerometer in the upper part and the center of gravity
- $UCG_{zx} = -152\,mm$ is the distance in the x-direction between the z-accelerometer in the upper part and the center of gravity

3) Then using equation (1) the forces are calculated:

$$F_x = m \cdot a_{CGx}$$
$$F_z = m \cdot a_{CGz}$$

4) And finally the bending moment is calculated:

$$M_y = I_y \cdot \alpha - F_x \cdot |d_z| - F_z \cdot |d_x|$$

Where:

- $|d_z|$ is the distance between the center of gravity of the head and the occipital condyles in the z-direction
- $|d_x|$ is the distance between the center of gravity of the head and the occipital condyles in the x-direction

The graph with the real position of the occipital condyle ($|d_z| = 20 + 35\,mm, |d_x| = 5 + 8\,mm$) of the volunteer is:

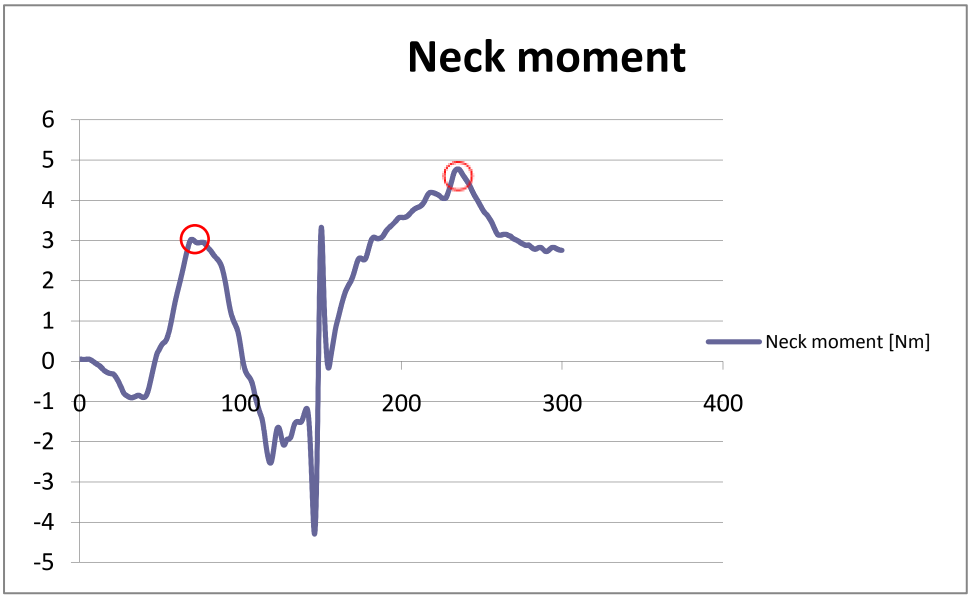

Figure 18.Neck moment in the OC of the volunteer

The difference in two peaks will be calculated (see Figure 18):

- Peak 1: $Moment_{real}$ = 3.03 Nm at 70 ms
- Peak 2: $Moment_{real}$ = 4.78 Nm at 235.5 ms

The difference is given by the following formula:

$$difference(\%)|_{x\,ms} = \left|\frac{Peak\ moment_{\ real} - Peak\ moment_{\ calcula\ ted}}{Peak\ moment_{\ real}}\right| \cdot 100$$

In order to study the differences caused by the location of the OC, the position of the center of gravity of the head doesn't vary; it is considered to be 5 mm forward and 20 mm upward from the auditory meatus as in Davidsson experiments.

5.1 Differences varying the OC position in x and z directions

The following step is study in which direction (x or z) the position of the occipital condyle has a greater influence in the bending moment. Hence, the OC position is modified $\pm 1\ mm$ and $\pm 2\ mm$ in each direction and it is compared separately with the "real" bending moment on the male volunteer experiment.

Table 15. Differences varying the OC position

	Peak 1 (70 ms)		Peak 2 (235.5 ms)	
	$Moment_{calculated}$ [Nm]	Difference (%)	$Moment_{calculated}$ [Nm]	Difference (%)
$d_x + 1\ mm$	2.73	9.95	4.67	2.33
$d_x - 1\ mm$	3.33	9.95	4.89	2.33
$d_z + 1\ mm$	3.06	1.03	4.86	1.78
$d_z - 1\ mm$	3.00	1.03	4.69	1.78
$d_x + 2\ mm$	2.43	19.89	4.56	4.65
$d_x - 2\ mm$	3.63	19.89	5.00	4.65
$d_z + 2\ mm$	3.63	2.07	4.95	3.55
$d_z - 2\ mm$	2.97	2.07	4.61	3.55

Observation 1: Before start to do any calculation on differences, it has been compared the acceleration of the center of gravity, angular acceleration and the loads on the

upper neck with the data given by Davidsson and the data calculated from the 2 uni-axial accelerometers (see Section 5). Some differences have been found (see Appendix). Reasons that could explain such fact: the use of a different program to do all the calculations (perhaps the difference of the decimals used in the calculations), the inaccuracy of the method use (see Section 2.7), the data used in Section 5 haven't been filtered.

Observation 2: Due to observation 2, all the comparisons have been done with respect to the calculated data, in order to avoid the problem above. From Davidsson's data, it only has been used the linear acceleration measured by the upper (U) and lower (L) accelerometers, the characteristics of the human volunteer and the distances.

6 Conclusions

The conclusions of the present research project are:

- The position of the occipital condyles only affects the moment. The upper neck forces are independent with the location of such point.
- From all the anthropometric studies:
  - The head can be considered symmetric midsagittally. It means the center of gravity of the head is situated on the X-Z plane of the anatomical coordinate reference.
  - Although from the literature related with cadavers it cannot be extracted any conclusion for the females because there is no specific data; from the studies with living humans (Young et al. 1983 and McConville et al. 1980): the average value for the principal moments of inertia is smaller for females than those obtained on the male subjects (see Table 13). Hence, it can be concluded that males and females do not have the same anthropometry, so each gender has its own values and it cannot mix, otherwise an error, which could be avoided, is introduced to the results of the calculations.
  - Regression equations from Young show a better correlation using 3 measurements of head body sizes than less.
  - Comparing regression equations from Beier (19 males + 2 females, cadavers) and Young (46 living females): Beier's equations show a greater correlation than those of Young.
- From Section 5. Errors:
  - The location of the occipital condyle has a great influence in the calculation of the moment in the upper neck.
  - In the x-direction the influence is greater than in the z-direction, comparing relative errors, when OC position is modified.

7 Recommendations

- All the devices needed to fix the accelerometers on the head should weigh as less as possible to avoid modifying the position of the center of gravity of the volunteer head.
- When using the information gathered from the anthropometric studies, avoid mixing information from different studies, due to the different ways to calculate the mass and the moment of inertia of the head.
- The information from the anthropometric studies to calculate the mass and the moment of inertia of the head should be used only in the humans in whom the study has focused. For example, if the study is based on females between 35-45 years old, it shouldn't be used to calculate the anthropometric characteristics for a woman who is 22 years old, due to the differences between them.
- Do not use a head-rest during the experiments. Reason:
    - o The contact between the head and the head restraint is not a contact point, although in previous volunteer studies with males (Kroonenberg et al. 1998) this approximation was used and the position of the contact point was estimated from the video. But it has one disadvantage, and is the fact that the head doesn't have the typical motion in a rear crash, where the head is stopped by the head-rest.
- Do not use the system with the head strap + mouthpiece to fix the accelerometers; it has a greater dependence on the distances between the different points.
- The use of the mouthpiece (Ono et al. 2006) to attach all the sensors is a good method and also more accurate than the previous method he used (Ono et al. 1996, 1997, 2000), but the inconvenient is that the volunteer has to bite the mouthpiece and it's unknown but the tension on his mouth may affect the muscles on the neck and therefore, the forces and the moments on the upper neck.
- If the sensors are fixed on the head with a light helmet or another system like straps, it's better to fix the sensors in the projection of the center of gravity in both sides of the head. Hence, the head still keep the symmetry in the midsagittal plane and the position of the center of gravity of the head doesn't change its location. There are no errors due to the distances taken from image analysis. In that case, the difficulty of the method is to attach the sensors exactly in the projection of the center of gravity.

If such method is used in the experiment with volunteers:

1) Put the sensors in the projection of the center of gravity in both side of the human head.
2) Measure linear acceleration (a_{CGx}, a_{CGy}, a_{CGz}), angular acceleration (α), angular velocity ($\omega_x, \omega_y, \omega_z$) and the angle ➔ the new sensor IMT40 allows all these measurements.
3) Use equations (1) and (7) to calculate the forces and moments in the upper neck:

$$\sum \vec{F} = m \cdot \overrightarrow{a_{CG}}$$

$$\sum M_x = I_x \cdot \alpha_x + \left(I_z - I_y\right) \cdot \omega_y \cdot \omega_z$$

$$\sum M_y = I_y \cdot \alpha_y + (I_x - I_z) \cdot \omega_x \cdot \omega_z$$

$$\sum M_z = I_z \cdot \alpha_z + \left(I_y - I_x\right) \cdot \omega_x \cdot \omega_y$$

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9 Appendix

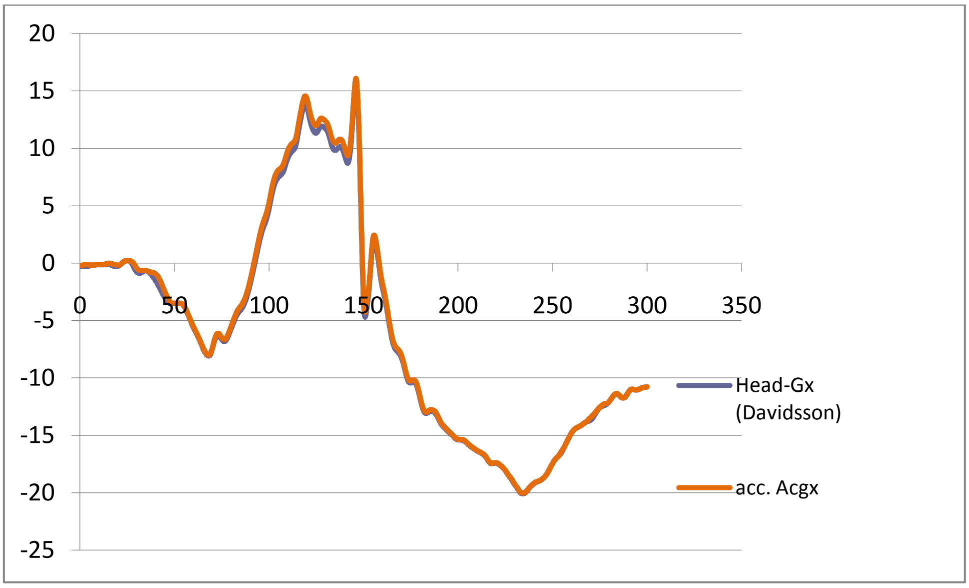

Figure 19. Linear acceleration of the center of gravity of the head in x-direction

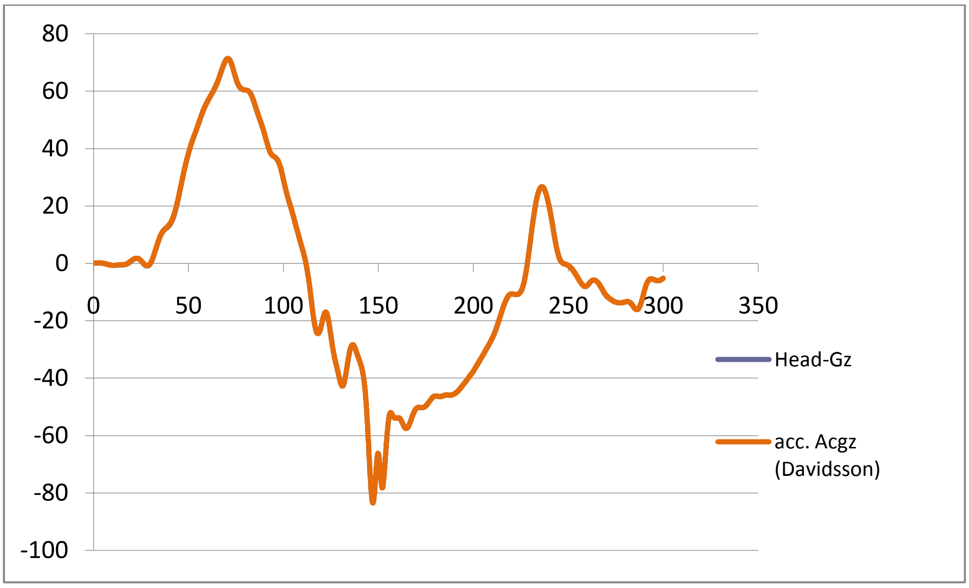

Figure 20. Linear acceleration of the center of gravity of the head in z-direction

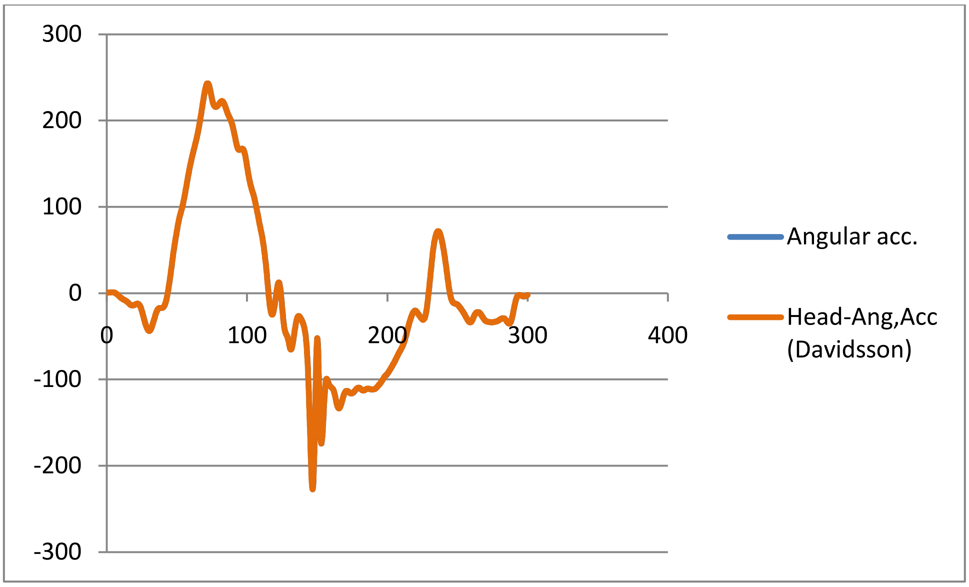

Figure 21. Angular acceleration of the head

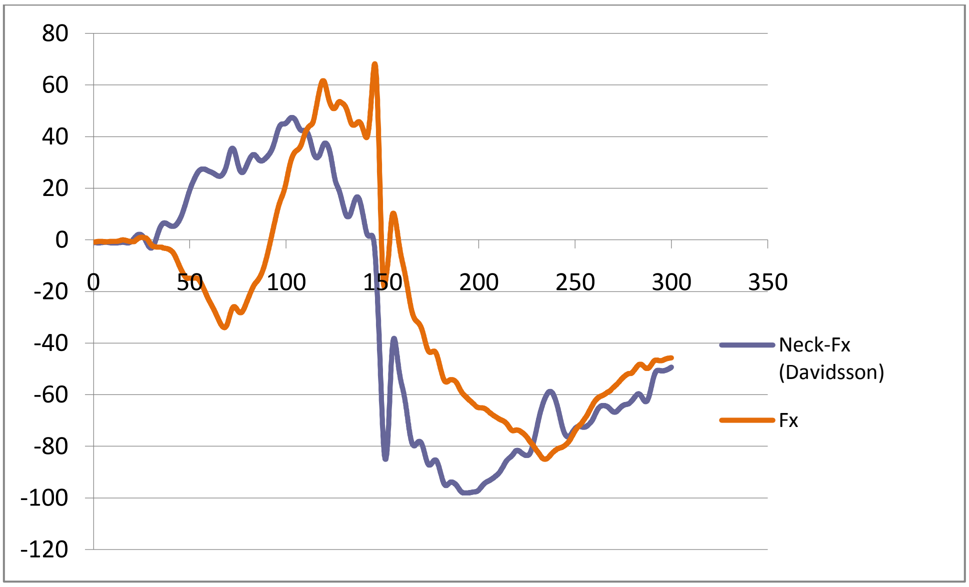

Figure 22. Upper neck force in the x-direction

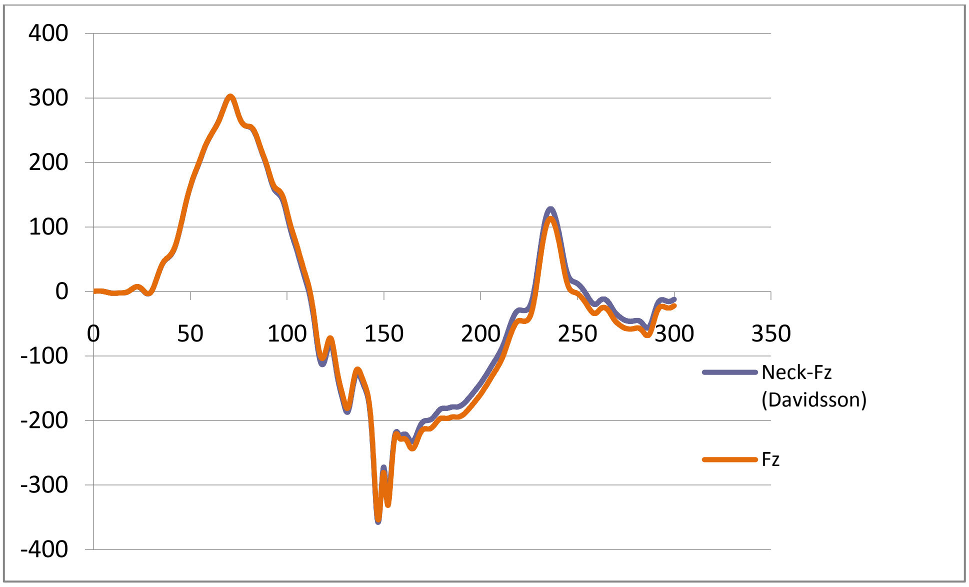

Figure 23. Upper neck force in the z-direction

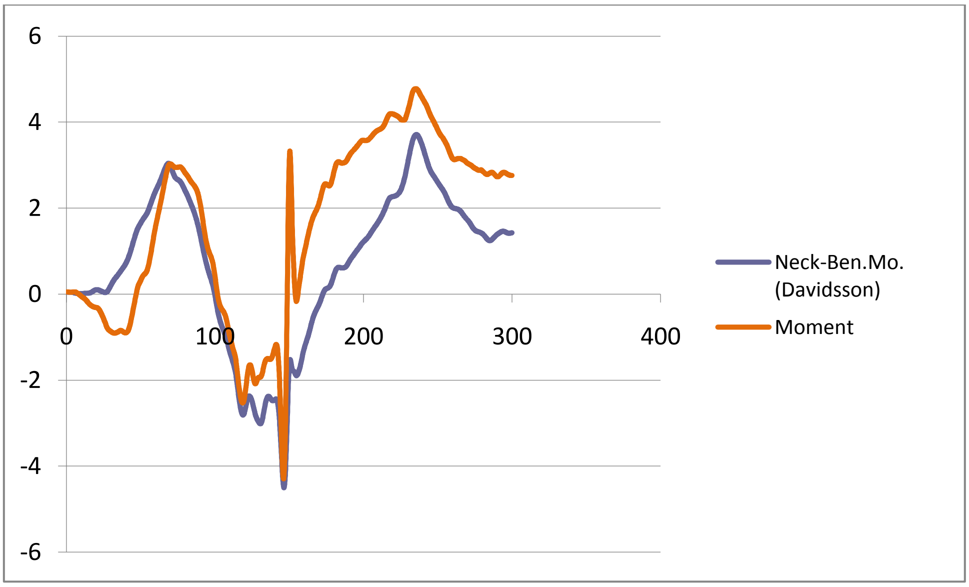

Figure 24. Upper neck moment