HUMAN VOLUNTEER HEAD-T1 RESPONSE FOR OBLIQUE IMPACT CONDITIONS

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ABSTRACT

The development of modern smart restraint systems requires access to human surrogates with a biofidelic performance, which includes details on timing and local deformations. Therefore volunteer head neck responses for oblique impacts from the Naval BioDynamics Laboratory are re-analysed using a method developed by Thunnissen (1995). Response parameters were chosen to allow a straightforward comparison of crash dummies with volunteers. The response parameters are time histories of 3D kinematics relative to the sled of the head centre of gravity and the anatomical defined T1, in extension to work by Wismans (1968a, 1987). Kinematics of the head relative to a rotating T1 and all six occipital load components are presented. A general applicable method to calculate 3D head flexion and twist is developed. The result is a set of time history corridors and mean peak ± standard deviation windows, which can be used in the evaluation of human surrogates in addition to existing frontal and lateral response specifications.

VOLUNTEERS, HEAD, NECK, SLED TEST, OBLIQUE IMPACT

CURRENT METHODS to evaluate the crash safety of a vehicle include the use of instrumented, physical, human surrogates in specific test conditions to estimate a human's injury risk under the same conditions. The surrogates, i.e. anthropomorphic test dummies or ATD's, must possess the general mechanical properties of the humans of interest and have sufficient mechanical impact response likeness to interact with the vehicle's interior in a human-like manner. Most importantly, dummies must mimic those specific, localized, impact responses of the body that are known to be predictive of the occurrence and severity of human injury. To develop a particular surrogate or evaluate the performance of various types of these physical surrogates, ATD designers and analytical models need quantitative definitions of how the human responds to mechanical stimuli. Although dummies are principally developed to cope with a single impact direction, there is an increasing need for multi-directional definitions reflecting the complexity of the loading environment that today's dummies are being exposed to in crash tests. This is especially valid for the neck that governs the head trajectory during a vehicle collision.

In the automotive crash environment, direct impact to the neck is relatively uncommon. Realistic simulation of neck response is an obvious concern in the prediction of the nature of human head contact with vehicle interior or active restraint systems and in the assessment of the effects of inertial loading due to head acceleration. Current knowledge on the dynamic human head neck responses is to a large extent based on human volunteer experiments conducted by Ewing (1973a) at the Naval BioDynamics Laboratory (NBDL) in New Orleans between 1981 and 1985. Wismans (1986a) determined omni-directional dummy head-neck performance requirements relative to a sled oriented, non-rotating, T1 co-ordinate system for frontal, lateral, and oblique impact conditions. Although head motions and loads were reported, the requirements did not include any time history information.

A procedure developed by Thunnissen (1995) to correct an artefact in the thoracal 1 (T1) rotation was based on an extension of the NBDL frontal tests using post mortem human subjects (Wismans, 1987). Response parameters were presented as trajectories, now with implicit time information. This artefact, the correction is only explicitly validated for frontal tests, is absent or just slightly present for the oblique test results. Supplementing the work by Thunnissen, the objective of this paper is to develop a set of response parameters for the oblique impact condition, which is straight forward applicable for crash dummy evaluations. Thus accelerations and loads have to be specified in body segment related co-ordinates as dummy accelerations and loads are segment coupled. Kinematics need to be expressed in a sled related co-ordinate system for the head centre of gravity and the dummy equivalent of the anatomical thoracal 1 origin. For dummy design it is very convenient to have the relative head-T1 motion available, where the T1 co-ordinate system is rotating with the T1. The response parameters are partial different from the parameters used in previous publications (Wismans 1986a, 1987) as modern active restraint system require biofidelic timing. Responses are characterised by mean ± 1 standard deviation time history corridors and by mean peak ± 1 standard deviation amplitude-time windows. The oblique response references presented here are to be used in combination with existing response references for frontal or lateral impacts.

METHOD

TEST CONFIGURATION

The human volunteers in the NBDL experiments are seated in an upright position on a sled driven HyGe accelerator. This was a maximum 225000 lbs thrust Bendix HyGe accelerator with stroke limited to 0.9 m. A 2573 kg sled was accelerated along a track of 275 m usable length and decelerated by coasting with a constant drag of 0.2-0.3 g. Subjects are exposed to an acceleration pulse simulating frontal, oblique or lateral impacts. During the impact experiments, the subjects were restrained by shoulder straps, a lap belt and an inverted V-pelvic strap tied to the lap belt. These belts were as tight as the subject could sustain for a 20 to 30 minute period. In addition a safety belt around the chest was employed (Ewing, 1973a) and for the lateral and oblique test the left shoulder was initially positioned against a sideboard, which is considered to be rigid. The resulting three dimensional motions of the volunteers head and first thoracic vertebral body (T1) are monitored by anatomical mounted clusters of accelerometers and photographic targets (Becker, 1973 and 1975). The rigid seat is positioned at a 45 degree angle to the sled trust vector with the subject left shoulder leading.

CO-ORDINATE SYSTEMS

The parameters used to specify the volunteers' response are all related to specific co-ordinate systems. The relevant co-ordinate systems are:

Sled Co-ordinate System

- X-axis: horizontal opposite direction of sled thrust vector (parallel to the sled motion vector);
- Y-axis: horizontal, perpendicular to X-axis, right lateral with respect to sled thrust vector;
- Z-axis: vertical upward;
- Origin: arbitrary point on sled.

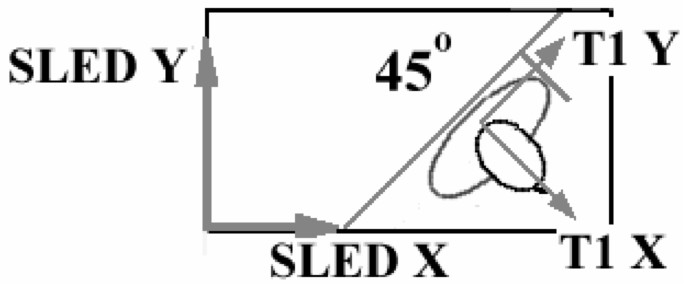

Figure 1 Illustration of the global sled co-ordinate system and the T1 anatomical co-ordinate system.

T1-Anatomical Co-ordinate System (Figure 1, Figure 2)

- X-axis: from spinous process posterior tip through anterior superior edge of the T1 vertebral body
- Y-axis: perpendicular to X and Z axis, left lateral with respect to subjects mid sagittal plane;
- Z-axis: perpendicular to X-axis upward;
- Origin: anterior superior edge of T1 vertebral body.

Note that the T1 z axis is not shown in Figure 1, but the initial orientation of the T1 anatomical z axis is generally not vertical. The $T1_{anatomical}$ co-ordinate system is linked rigidly to T1 and rotates with T1.

By definition of the oblique configuration the T1 anatomical co-ordinate system is twisted 45^{o} about the z-axis relative to the sled co-ordinate system

Head-Anatomical Co-ordinate System

- X-axis: from midpoint of left and right auditory meati to midpoint of left and right infra-orbital notches (intersection of mid-sagittal and Francfort plane);
- Y-axis: from right to left auditory meati;
- Z-axis: perpendicular to X and Y axis, upwards;
- Origin: midpoint between left and right auditory meati.

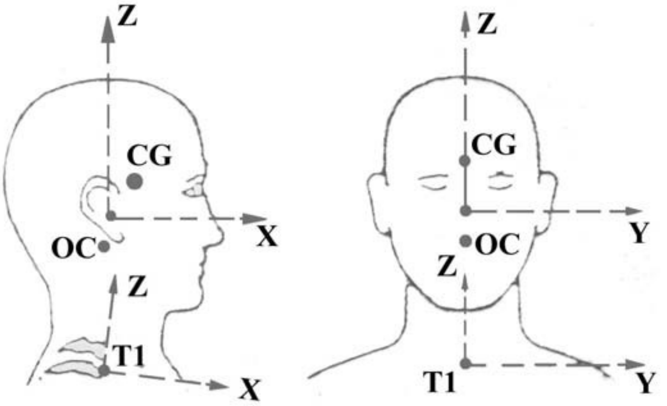

Figure 2 Head and T1 anatomical co-ordinate systems

As specified for $T1_{anatomical}$, the $Head_{anatomical}$ co-ordinate system will initially be twisted 45^{o}about the z-axis, and slightly backwards.

RESPONSE PARAMETERS

The response parameters are based on experiences with evaluating dummy responses, and should accommodate a straightforward comparison of the volunteer kinematics and dynamics for future dummy evaluation. The volunteer responses for oblique impacts, as published before by Wismans, (1986a) and the dummy performance requirements (Van Don 2003) require rather complex post-processing of the dummy readings to allow comparison of dummy and volunteer responses. Wismans (1986a) did not specify explicitly the time phase of the response parameters. As an extension the dynamic kinematic response presented here is characterized as time histories of the change in position with respect to the initial position. The positions and angles with respect to the sled are specified only for the initial starting position and orientation.

Kinematic Response Parameters The global motion of the head and T1 is specified by the displacement-time histories of respectively the head center of gravity and T1 anatomical origin expressed in the sled co-ordinate system by:

- $x(t)_{sled}-x(t0)_{sled}$
- $y(t)_{sled}-y(t0)_{sled}$
- $z(t)_{sled}-z(t0)_{sled}$

The angular motion is specified by the flexion and twist angles:

$\varphi(t)$ and $\gamma(t)$ for respectively the head and T1 flexion. This is the screw angle between the actual anatomical z-axis at time t and the z-axis at t0;

$\psi(t)$ and $\chi(t)$ for the twist angles of head and T1. This is the rotation about the screw angle rotated z-axis. The algorithm used to calculate these angles is included in the appendix to this paper. The appendix also presents the relative head-neck motion by the head cg displacement with respect to the T1 anatomical co-ordinate system as the relative motion between head and neck is important for characterizing internal neck deformations and neck loads. The flexion and twist angles between head and T1 co-ordinate system are presented also. Thus the kinematic head-T1 response parameters are:

$x(t)_{T1}-x(t0)_{T1}$	$\Phi\_\gamma(t)$
$Y(t)_{T1}-y(t0)_{T1}$	$\Psi\_\chi(t)$
$z(t)_{T1}-z(t0)_{T1}$	

Dynamic Response Parameters The dynamic response parameters are all linear and angular accelerations, all expressed in the anatomical co-ordinate systems w.r.t. inertial space:

- Head cg $acc_{j=x,y,z}(t)_{head\ anatomical}$ - Head $ang\_acc_{j=x,y,z}(t)_{head\ anatomical}$

The T1 accelerations proved not to be usable due to low frequency oscillations of the instrumentation mount.

Head Neck Loads The loads applied from neck to head at the occipital condyles level are expressed in the head anatomical co-ordinate system:

- OC $F_{j=x,y,z}(t)_{head\ anatomical}$ - OC $M_{j=x,y,z}(t)_{head\ anatomical}$

The responses for all tests are merged by the mean ± 1 standard deviation for each moment in time, thus creating a response corridor. If applicable an amplitude time window for peak amplitude is given, which is the mean of all peak amplitudes ± standard deviation combined with the mean of moment in time of each individual peak amplitude ± standard deviation.

TEST MATRIX

The current analysis presented here is a set of six out of the most severe oblique experiments, peak mean sled acceleration 11.25 g, mean velocity change 14.6 m/s. This is the same set as used in an earlier analysis by Wismans (1986a) and Van Don (2003). Table 1 lists the test matrix, including the initial position of the head center of gravity w.r.t. the $T1_{sled}$ co-ordinate system and the initial angular orientation of head and T1 anatomical co-ordinate system by the flexion φ_0 and twist angle ψ_0 related to the sled co-ordinate system. The relative initial flexion and twist angles between head and T1 are listed in the last two columns.

Table 1 High severity human volunteer oblique experiments also used in the earlier analysis (Wismans 1986a), Van Don (2003). A total 6 experiments with 6 different subjects.

Test	Subj.	Max sled acc. [m/s^2]	Initial position head cg w.r.t. $T1_{sled}$ [m]* 10^{-3}			Initial flexion & twist angle w.r.t. sled [deg]				Initial flexion & twist angle of head w.r.t. $T1_{anatomical}$ [deg]	
			x	y	z	T1 γ_0	T1 χ_0	Head φ_0	Head ψ_0	$(\varphi-\gamma)_0$	$(\psi-\chi)_0$
LX4303	H139	110	12	28	191	15	48	-3.5	45.	18.7	3.3
LX4305	H138	111	14	40	223	24	52	-4.5	43	28.4	9.6
LX4306	H132	109	24	47	163	21	52	-3.0	34	23.3	18.2
LX4307	H134	112	3	13	193	17	50	-6.5	45	23.7	4.3
LX4309	H130	110	-6	28	203	14	46	-5.0	45	18.8	1.9
LX4310	H140	110	26	61	206	11	50	-5.0	41	16.5	9.5

HUMAN SUBJECT ANTHROPOMETRY

The significant external anthropometric measurements for the subjects are summarized in Table 2. These were obtained with detailed external and X-ray anthropometric measurements conducted for each subject as part of the test protocol. In order to determine the loads at the head-neck pivot, occipital condyles, the subjects head mass and the principal moments of inertia are calculated from regression equations (McConville, 1980), (Wismans 1986a and 1986b). The head mass distribution is corrected for added instrumentation. The added masses were reduced to a minimum in order to limit artifacts in the human response (Becker, 1978). The center of gravity is shifted a few millimeters due to the instrumentation mass, see Table 3 and Becker (1978b). The increase in the moment of inertia about the principal y-axis is about a third of the average determined by Beier (1980). The correction for head mass is +0.53 kg and for the moment of inertia about the principal y-axis +0.0075 kgm^2. A similar correction is made for the moment of inertia about the principal x-axis, while the correction for the moment of inertia about the principal z-axis is estimated to be very small: 0.0005 kgm^2. T1 instrumentation mass is 0.46 kg.

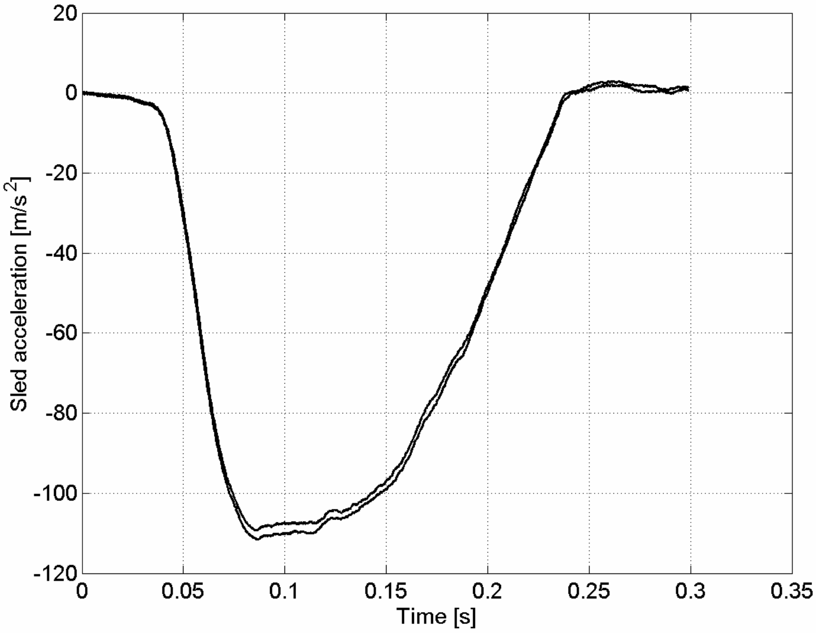

Figure 3 Sled acceleration time history for the most severe oblique volunteer impacts, mean ± standard deviation, t0 is 0.0425 sec before –10 m/s^2 level of the average sled acceleration.

Table 2 Human subject anthropometry and head inertia characteristics more details can be found in Ewing (1973a), Schneider (1976).

Subj.	Anthropometric measurements at NBDL						Head mass and inertia estimates [1)]			
	Standing height	Body Weight	Sitting height	Head circum-ference	Head Width	Head length	Mass	Principal moments of inertia		
								Ixx	Iyy	Izz
	[m] $*10^{-2}$	[kg]	[m] $*10^{-2}$	[m] $*10^{-2}$	[m] $*10^{-2}$	[m] $*10^{-2}$	[kg]	[kgm^2]	[kgm^2]	[kgm^2]
H130	180.1	72.6	94.5	56.5	14.9	19.7	4.75	0.0266	0.0294	0.0148
H132	172.9	79.8	89.6	57.9	15.7	19.7	5.05	0.0290	0.0319	0.0164
H134	178.3	75.3	93.0	56.6	14.4	19.4	4.81	0.0261	0.0295	0.0151
H138	186.0	78.9	99.2	57.1	15.4	19.8	4.87	0.0278	0.0304	0.0154
H139	174.4	72.6	94.3	57.2	15.7	19.4	4.94	0.0282	0.0306	0.0158
H140	177.3	86.2	94.5	56.7	15.4	19.0	4.89	0.0273	0.0297	0.0155
Mean	178.2	77.6	94.2	57.0	15.2	19.5	4.88	0.0275	0.0302	0.0155

[1)]Includes the correction for instrumentation

Table 3 Subject independent anthropometric data estimated from literature. Co-ordinates relative to the head anatomical co-ordinate system.

Head center of gravity	X [m]	Y[m]	Z[m]
Beier (1980)	0.0083	0	0.0321
Shift due to instrumentation (Ewing 1973b)	0.0035	0	-0.002
Resulting location	0.012	0	0.029
Occipital condylar point	-0.011	0	-0.026

Table 3 shows the location of the head center of gravity and the occipital condyles relative to the head anatomical origin (Wismans, 1986b). The location of the center of gravity is based data of Beier (1980). These values are assumed to be subject independent and mass is corrected for instrumentation. They will be used to determine head center of gravity trajectories and the occipital condyle loads.

RESULTS

The individual responses are specified as time histories for each test. Each parameter for all tests is merged by a response corridor, which is the mean ± 1 standard deviation of the amplitude for each time sample. The response parameters are defined in the methods section and are chosen to be one to one compliable with potential dummy measurements. The minimum set to define the responses are kinematics with respect to a sled related co-ordinate system and loads at OC joint expressed in a head anatomical oriented co-ordinate system. Documentation of the response is completed by the kinematics of head w.r.t. the T1 anatomical coordinates and the linear and angular accelerations of the head center of gravity expressed in the head anatomical co-ordinate system. These are presented in the appendix. A table listing the mean and standard deviation of peak values, time of mean peak value and the mean and standard deviation of the time for the individual peak values are presented as key-numbers characterizing the responses in numbers.

KINEMATICS

The head displacement relative to the initial position expressed in the sled co-ordinate system is presented in Figure 4 to Figure 6.The time window is limited to 0.3 seconds which covers the loading phase and almost the full rebound where the head returns to the initial almost upright position and the flexion angle φ returns to 0 (Figure 7). Two groups of data sets can be distinguished for the head motion. Test 4303 and 4307 as one group having similar displacements at the lower end. Test 4305, 4306, 4309 and 4310 showing also similar displacements at the upper boundary.

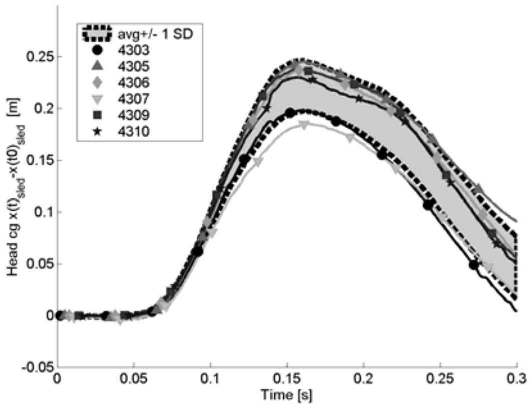

Figure 4 Head centre of gravity x(t) displacement in sled co-ordinates

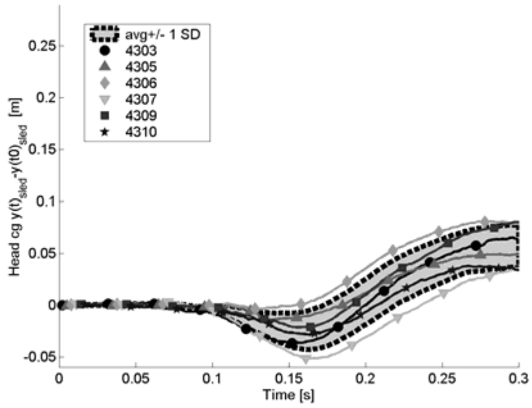

Figure 5 Head centre of gravity y(t) displacement in sled co-ordinates

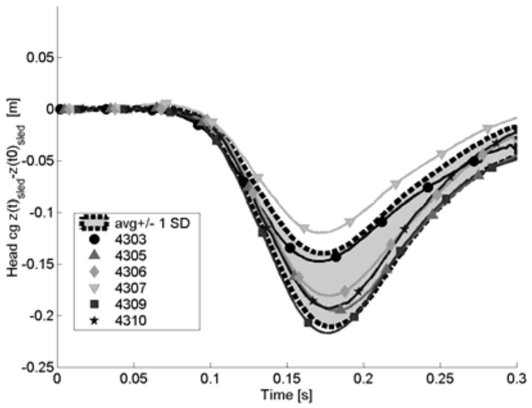

Figure 6 Head centre of gravity z(t) displacement in sled co-ordinates

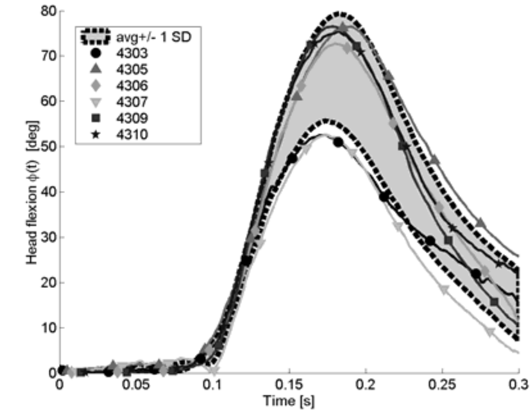

Figure 7 Head flexion φ(t) relative to initial orientation

The main motion of the head center of gravity is in x and z direction, with the maximum mean for x: 0.222, forward and z: –0.175 [m], downward, at respectively 0.161 and 0.177 seconds. Both have an uni-modal phase. The y displacement is significantly small compared to x and z. Here the head translates initially to the right, away from the leading shoulder, to a maximum mean of 0.025 [m] at

0.159 [s]. Followed by a lateral displacement towards the leading shoulder of maximal 0.057 [m] at 0.295 [s]. This means that the head cg moves principally parallel to the sled thrust vector, at a 45 degree angle to the mid sagittal plane, resulting in a more or less 2D motion. Head flexion is also uni-modal, with a maximum average of 67 degrees at 0.18 seconds. Head twist shows an initial rightward rotation towards the non-leading right shoulder until 0.1 seconds, followed by a leftward rotation with maximum of –27 degrees at 0.1780 seconds. Note that the phase of the responses is similar for especially the z displacement and flexion. Time of peak excursion is almost equal and the standard deviation of the time of maximum excursion is respectively 0.0039 and 0.006 seconds. The head twist for the 0.3 to 0.5-second time interval is positive, see Figure 9. This is a rightward rotation away from the leading shoulder. This is considered to be due to muscle activity of the volunteers, which indicates that major part of the rebound is induced/controlled by muscle activity.

The T1 x displacement relative to the sled is split also into the same 2 groups, 4303-4307 and the other remaining tests as a second group. The T1 displacements relative to the sled are small compared to the head displacement, Figure 10-Figure 11. The x and y displacements have a distinguishable uni-modal phase, with a maximum displacement of respectively 0.072 and –0.023 [m] at 0.164 and 0.159 seconds. The main displacement is in sled x direction which is similar to the findings for the head motion. The z displacement is less than 0.01 meter and no general phase or pattern is detectable. T1 rotations are also uni-modal, maximum average flexion is 11 degrees and maximum average twist is 10 degrees, see Figure 12 and Figure 13. Test 4303 and 4307 do show a small maximum flexion angle.

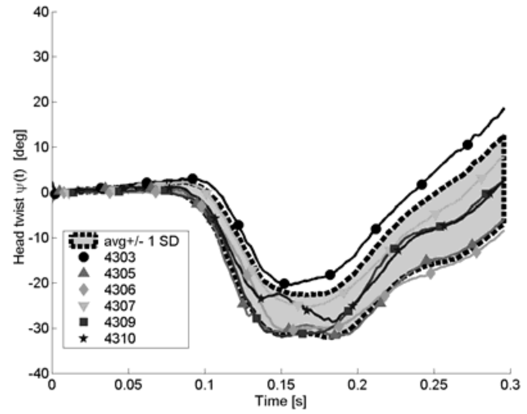

Figure 8 Head twist angle ψ relative to initial orientation

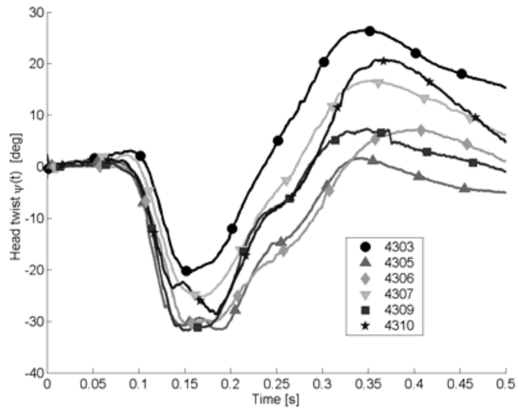

Figure 9 Full time window for head twist ψ

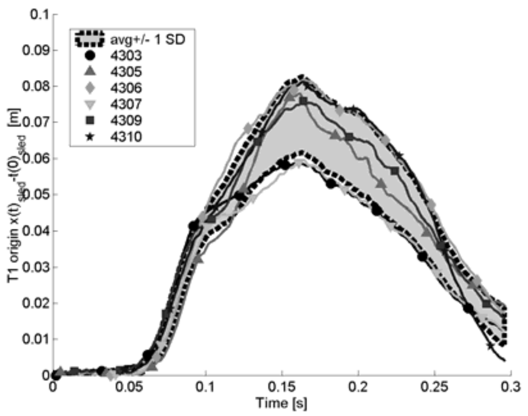

Figure 10 T1 x(t) displacement in sled co-ordinates

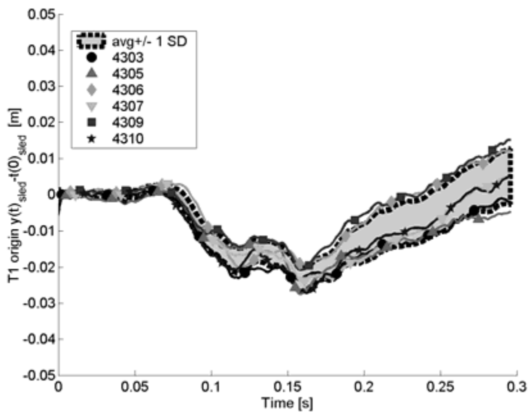

Figure 11 T1 y(t) displacement in sled co-ordinates

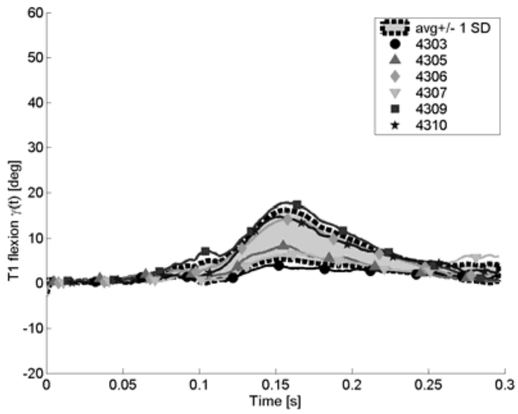

Figure 12 T1 flexion angle γ(t) relative to intial orientation

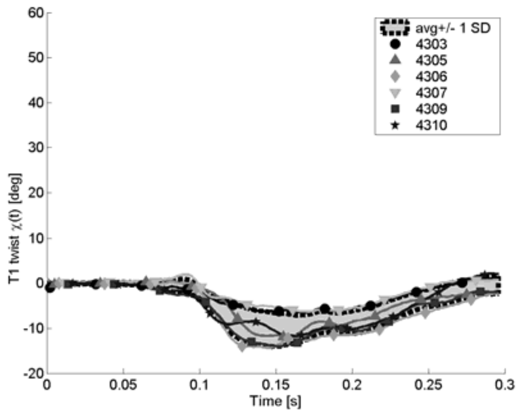

Figure 13 T1 twist angle χ(t) relative top initial orientation

The maximum values for the average displacements and angular rotations with corresponding time of the maxima are given in Table 4, columns 2 and 3. Column 4 lists the average and standard deviation of the time for the maximum displacement/rotation found for each individual test. A large difference between the time of the average amplitude and the average of the time of each individual maximum amplitude is found for specially the head y displacement (Δt .080 [s]), head twist (Δt 0.108 [s]) and T1 flexion (Δt 0.238 [s]).

Table 4 Maximum values with standard deviations and time variations of maximum values for head and T1 kinematics relative to sled co-ordinate system

Kinematic response parameter	Max. mean ± standard deviation [m]	Time of max. mean	Mean time of maximum ± standard deviation [s]
Head cg $x(t)_{sled}$	0.222 ± 0.025 [m]	0.1610 [s]	0.1593 ± 0.0029 [s]
Head cg $y(t)_{sled}$ [1)]	-0.025 ± 0.018 [m]	0.1590 [s]	0.1507 ± 0.0130 [s]
	0.057 ± 0.020 [m]	0.2950 [s]	0.2870 ± 0.0135 [s]
Head cg $z(t)_{sled}$	-0.175 ± 0.036 [m]	0.1770 [s]	0.1757 ± 0.0039 [s]
Head flexion φ	67 ± 12 [deg]	0.1800 [s]	0.1798 ± 0.0060 [s]
Head twist ψ	-27 ± 5 [deg]	0.1780 [s]	0.1672 ± 0.0163 [s]
T1 $x(t)_{sled}$	0.072 ± 0.011 [m]	0.1640 [s]	0.1630 ± 0.0022 [s]
T1 $y(t)_{sled}$	-0.023 ± 0.0032 [m]	0.1590 [s]	0.1598 ± 0.0021 [s]
T1 flexion γ(t)	11 ± 5.5 [deg]	0.1550 [s]	0.1558 ± 0.0057 [s]
T1 twist χ(t)	-10 ± 3.7 [deg]	0.1530 [s]	0.1595 ± 0.0099 [s]

[1)] The head cg y displacement has a characteristic minimum and maximum.

OCCIPITAL CONDYLE LOADS.

The shear forces appear to have a bi-modal phase, except for the posterior-anterior Fx in test 4305 and for the lateral shear Fy in test 4303 and 4305. The tension force Fz is bi-modal where the second maximum appears to be more or less a flat top (test 4305 and 4307). Test 4303 has no distinct maximum. The moments Mx and My are uni-modal, where maximum Mx is about 25 Nm, half of the My maximum, 50 Nm. The individual time traces for Mx shows also a larger scatter than My. My is slightly positive for a short period just before 0.1 seconds which indicates a minor head lag phase. The head goes initially slightly into extension while it is translating forward. A similar behavior is seen for the torsion moment, where a slight negative torque around 0.1 seconds is observed. Here also a bi-modal phase with a tendency to a flat second top is seen. The maximum moment 15 Nm is found at the first top, the second top is about 10 Nm. The maximum average and standard deviation and the time of the maximum are listed in columns 2 and 3 of Table 5. The average time and standard deviation for the maximum for each individual test is given in column 4.

Table 5 Mean and standard deviation of peak loads and mean time of individual peak loads at the Occipital Condyle level

Load response parameter	Max. mean ± standard deviation [m]	Time of max. mean	Mean time of maximum ± standard deviation [s]
OC $Fx(t)_{Anatomical}$	-751 ± 54 [N]	0.1600 [s]	0.1505 ± 0.0197 [s]
OC $Fy(t)_{Anatomical}$	418 ± 59 [N]	0.1630 [s]	0.1635 ± 0.0033 [s]
OC $Fz(t)_{Anatomical}$	-511 ± 146 [N]	0.1100 [s]	0.1160 ± 0.0138 [s]
OC $Mx(t)_{Anatomical}$	-25 ± 6.5 [Nm]	0.1500 [s]	0.1605 ± 0.0158 [s]
OC $My(t)_{Anatomical}$	-48 ± 6.8 [Nm]	0.1690 [s]	0.1700 ± 0.0054 [s]
OC $Mz(t)_{Anatomical}$	14 ± 2.5 [Nm]	0.1430 [s]	0.1493 ± 0.0148 [s]

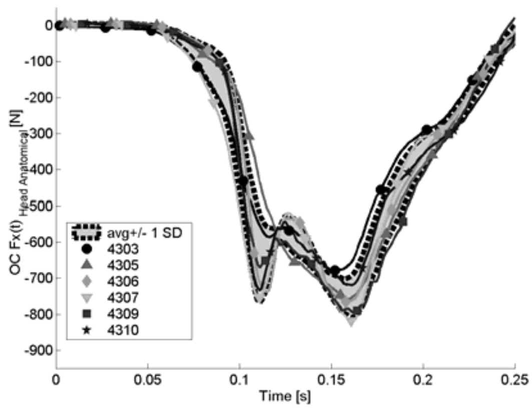

Figure 14 Occipital Condyles shear force Fx(t) in anatomical co-ordinates

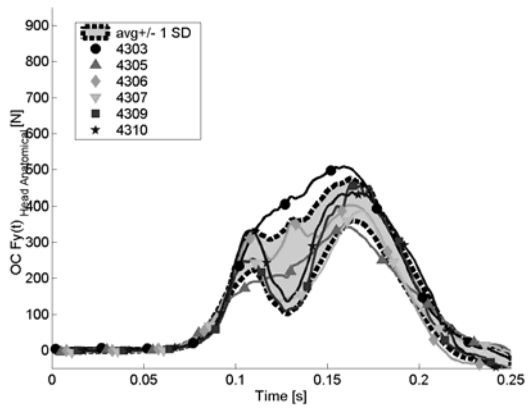

Figure 15 Occipital Condyles shear force Fy(t) in anatomical co-ordinates

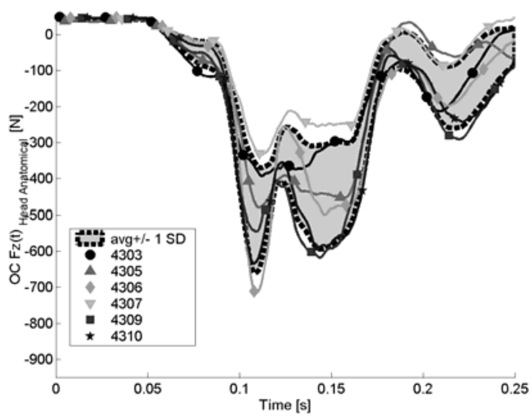

Figure 16 Occipital Condyles tension force Fz(t) in anatomical co-ordinates

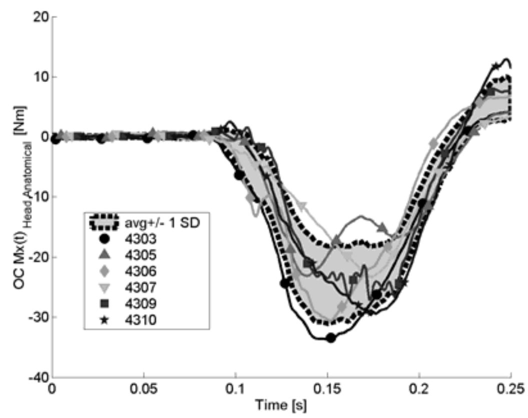

Figure 17 Occipital Condyles lateral flexion moment Mx(t) in anatomical co-ordinates

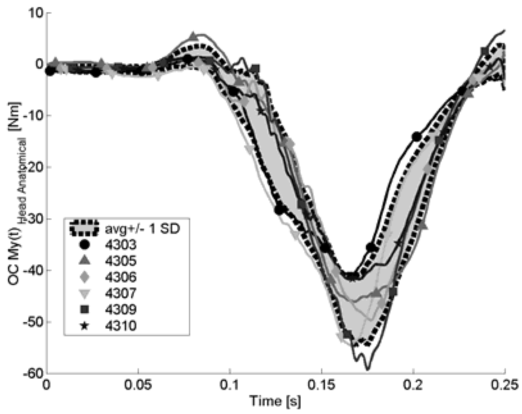

Figure 18 Occipital Condyles frontal flexion moment My(t) in anatomical co-ordinates

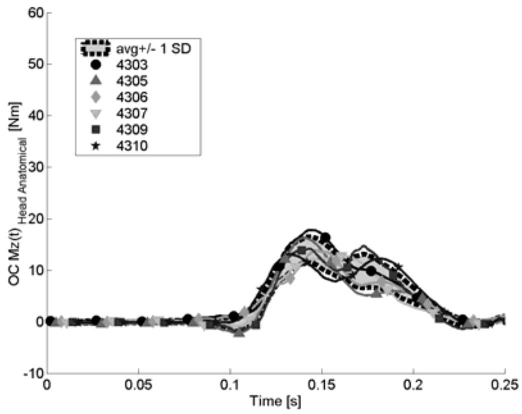

Figure 19 Occipital Condyles torsion moment Mz(t) in anatomical co-ordinates

DISCUSSION

The major translation of the head is in the x-z plane of the sled. This is a vertical plane at 45 degrees with the subject's mid-sagittal plane. The rebound phase appears to be controlled by muscle activity, which makes this part more subject dependent. T1 linear accelerations do show a low frequency vibration especially for the z direction, which is most significant in test 4307. This appears to be a vibration of the T1 instrumentation bracket, but does not show in the kinematics determined from film.

The correction for T1 instrumentation as presented by Thunnissen for frontal has a minor effect for the oblique tests as the artifacts in the T1 instrumentation angular orientation are explicitly visible for the frontal tests and almost absent in the oblique tests. The correction for the T1 rotation artifact is only validated explicitly for the frontal loading condition. However, this method is also used for the oblique loading condition and thus the oblique kinematics includes a rotating T1 co-ordinate frame. The responses presented here incorporate explicit timing information that was not included in the publication by Wismans (1986a). The same estimate for head mass and addition of instrumentation mass as used by Wismans (1986a) and Thunnissen (1995) is used. The responses will have a systematic error due to this method. An estimate of the maximum possible error can be made: 4 to 15 % increase of the occipital loads assuming the kinematics will not change. However, the kinematics of the head will change also. A more accurate estimate of the change in response due to the extra mass could be made only by for instance a numerical model study, which is beyond the scope of this paper.

The windows for peak amplitude and corresponding time presented by Van Don (2003) are sufficient in case of uni-modal responses to be used as requirement. In general such a peak amplitude window can be useful as a requirement for a (injury) tolerance level which is only related to the peak value of a certain parameter. In case of a bi or multi-modal response it is more appropriate to use a time history corridor, or multiple amplitude-time windows to characterize the response.

The definition of the flexion and twist (Wismans 1986a, Van Don 2003) is based on an approximated 2D motion and related to a 2 linkage model with a non-anatomical based T1 location. As a consequence it is rather complex to interpret the motion of a human surrogate which can have a more explicit 3D motion. The method to calculate the flexion and twist, as presented here is generally applicable. The peak values for the flexion and twist are slightly different compared to the values published by Van Don (2003). The same author used the n-1 standard deviation for the range of peak amplitude and peak time. As the number of tests is limited to six, consequently a poor statistical significance, it seems more appropriate to use the root mean square error, the mean difference relative to the mean amplitude for each time sample. Therefore the amplitude and time windows published here are slightly smaller than the values as published by van Don (2003).

The mean amplitude-time windows are useful in application were only the maximum values are relevant e.g. injury criteria and tolerances. For the lateral test condition, such approach was applied by ISO when developing neck biofidelity response requirements based on NBDL tests (TR9790 neck test 1). However, if interaction with environment and especially modern restraint systems is considered it is more appropriate to use the corridors based on the mean value and standard deviation for each time sample.

It is well known that the NBDL configuration is different from the standard automotive position and therefore the responses should be interpreted carefully. The subjects are seated upright instead of a 20 to 25 backward torso, and the five point harness belt is as tight as allowed by the subject. However, the responses presented here are the only available for oblique under automotive loading levels.

CONCLUSIONS

The responses as presented appear to be consistent enough to be used as biofidelity reference for oblique human head neck response, although the numbers of tests is limited to six. The presented oblique responses are useful as completion of the frontal (Thunnissen, 1995) and lateral responses (Wismans, 1986a).

The mass added to the head by the instrumentation is estimated to add 10 to 15 % at most to the neck loads, assuming the kinematics and accelerations stay the same.

The human subject head motion in the analyzed oblique impact condition is almost a plain 2D motion in the plane of impact.

The head accelerations, linear and angular are implicitly specified by the loads at the occipital condyles and are therefor not required to describe the volunteer response.

Time phase of the responses is included as corridors, which is important for evaluating the biofidelity to a more detailed level extending the application of previously published results (Wismans 1986a and van Don, 2003).

A general applicable definition for head and T1 flexion and twist is developed, using an anatomical system.

Time history response corridors are considered to be essential as a reference for correct interaction between a crash dummy, mechanical or numerical, and modern restraint systems. Peak values presented as amplitude-time windows appear to be mostly useful to evaluate the correct reflection of an injury tolerance level.

ACKNOWLEDGEMENT

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APPENDIX

HEAD LINEAR AND ANGULAR ACCELERATIONS

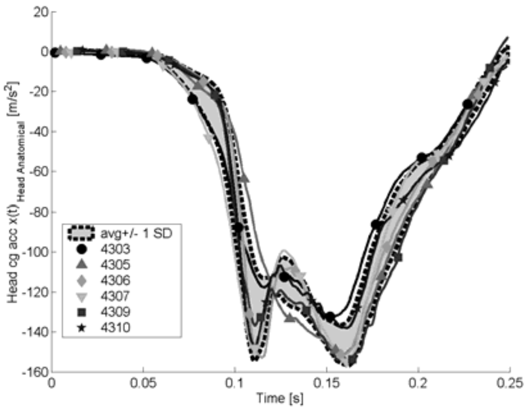

Figure A20 Head cg linear x acceleration in head anatomical co-ordinate system

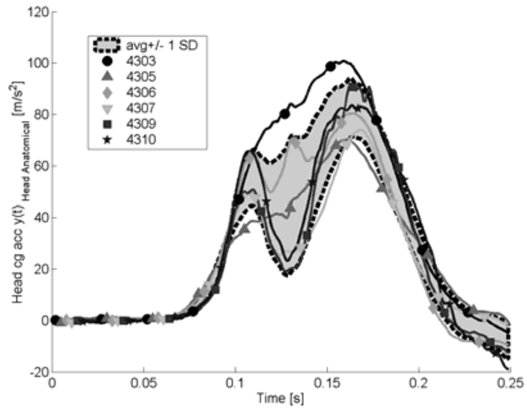

Figure A21 Head cg linear y acceleration in anatomical co-ordinate system

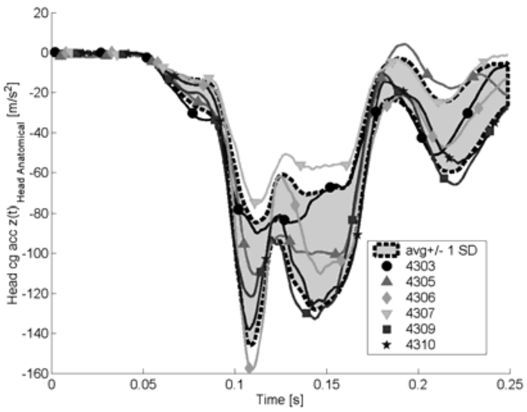

Figure A22 Head linear z acceleration in anatomical co-ordinate system

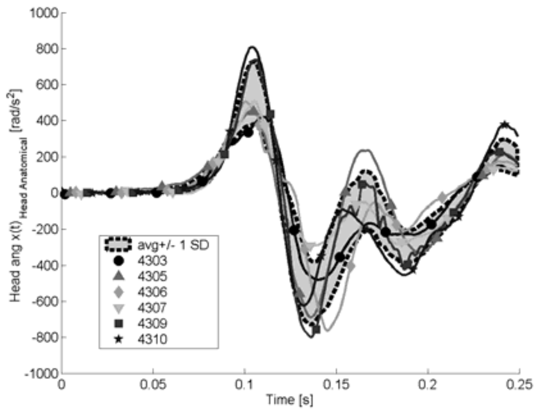

Figure A23 Head angular x acceleration in anatomical co-ordinate system

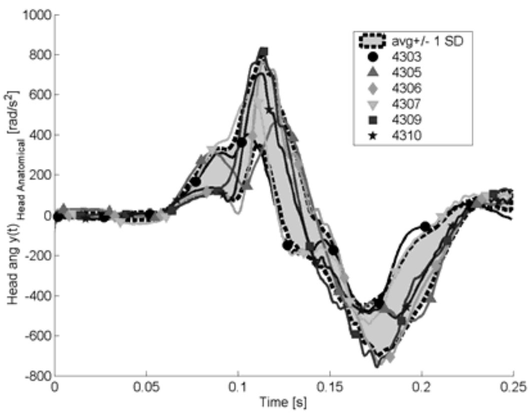

Figure A24 Head angular y acceleration in anatomical co-ordinate system

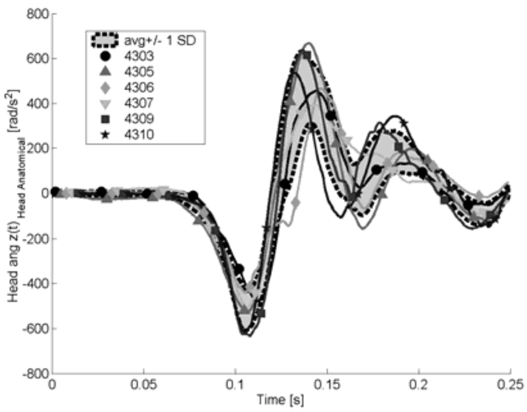

Figure A25 Head angular z acceleration in anatomical co-ordinate system

T1 LINEAR ACCELERATIONS

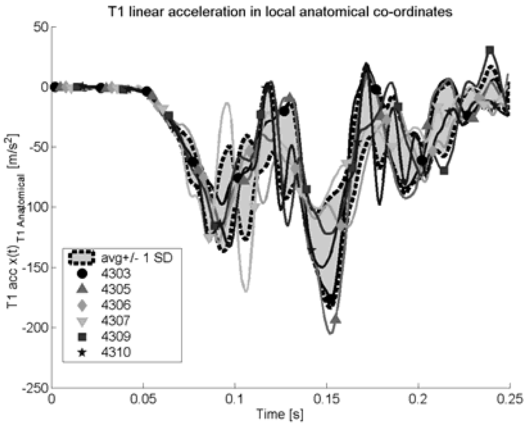

Figure A26 T1 linear x acceleration in anatomical co-ordinate system

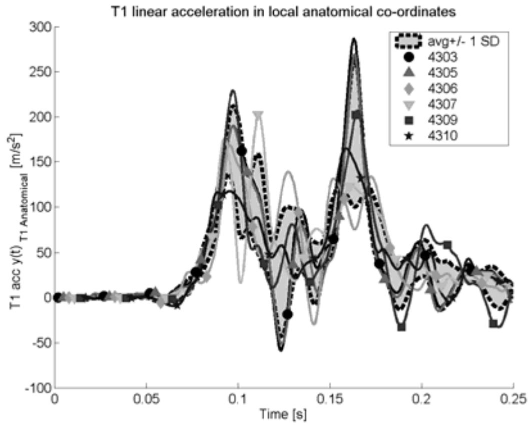

Figure A27 T1 linear y acceleration in anatomical co-ordinate system

HEAD KINEMATICS RELATIVE TO T1

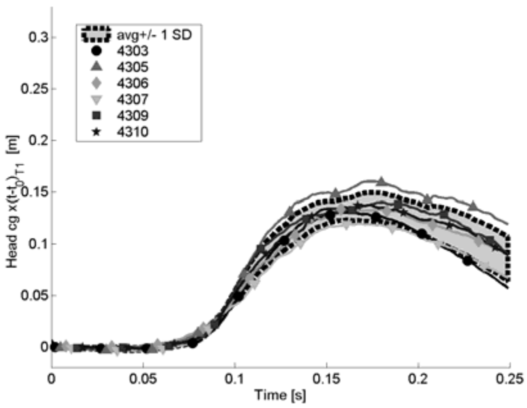

Figure A28 X displacement of head centre of gravity with respect to the T1 anatomical co-ordinate system

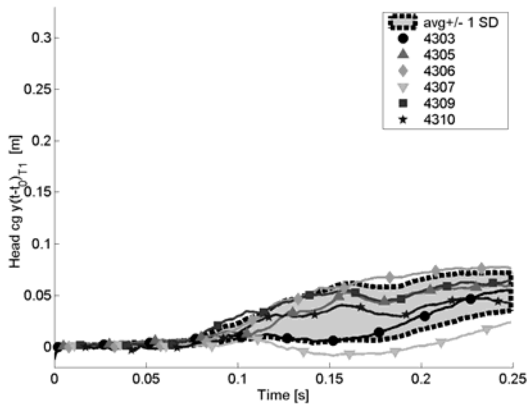

Figure A29 Y displacement of head center of gravity with respect to the T1 anatomical co-ordinate system

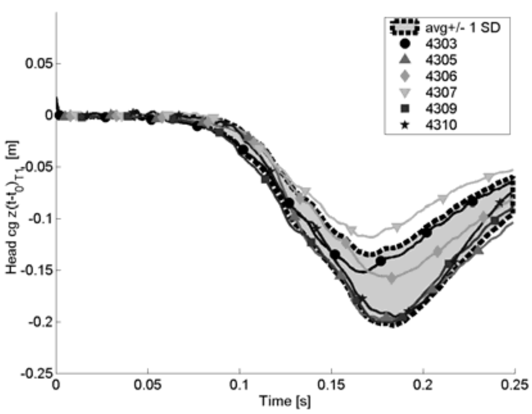

Figure A30 Z displacement of head center of gravity with respect to the T1 anatomical co-ordinate system

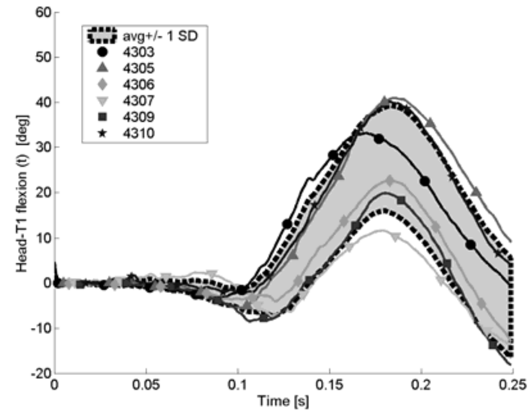

Figure A31 Flexion angle between head z-axis and T1 z-axis

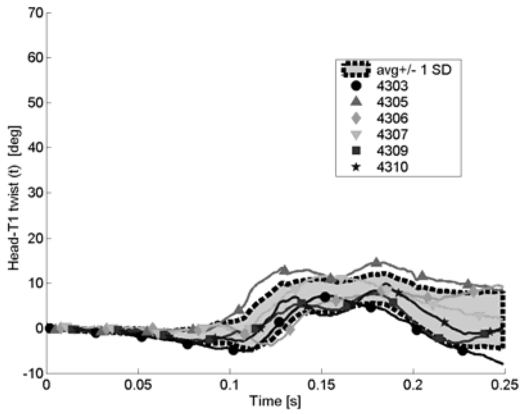

Figure A32 Twist angle between head and T1 anatomical co-ordinate systems

CALCULATION OF FLEXION AND TWIST ANGLES

The position and orientation of the anatomical co-ordinate system at time t in 3D co-ordinates is defined by a position vector of the origin P(t) and the rotation matrix R(t) expressed in sled co-ordinates. The rotation matrix at t=0 would then be R_0, defining Xinit, Yinit and Zinit. The current state at time t would have rotation matrix R_t defining Xcur, Ycur and Zcur. The flexion angle is the 3D (screw) angle between the z-axis at current time t (Zcur) and the z-axis in the initial orientation at t=0 (Zinit). The flexion angle is determined as follows:

- Create a new co-ordinate system R1, x-axis is the cross product between the two z-axes. The y-axis is the cross product of the initial z-axis and the new x-axis, z-axis is Zorg.

-Xr1 = cross(Zcur,Zinit);

-Yr1 = cross(Zinit, Xr1);

-Zr1 = Zinit;

- Create a second co-ordinate system R2 with the x-axis based on the cross product of the initial Z-axis and the current Z-axis (which is thus Xr1) and with the y-axis based on current Z-axis and new x-axis. This means:
  - Xr2 = Xr1;
  - Zr2 = Zcur;
  - Yr2 = cross(Zr2,Xr2);
- The rotation matrix R1_2 that transforms R1 to R2 contains only the rotation about the Xr1 axis, which is denoted flexion and the corresponding angle is the flexion angle. The flexion angle is by definition positive, instead the rotation axis will have a varying orientation.

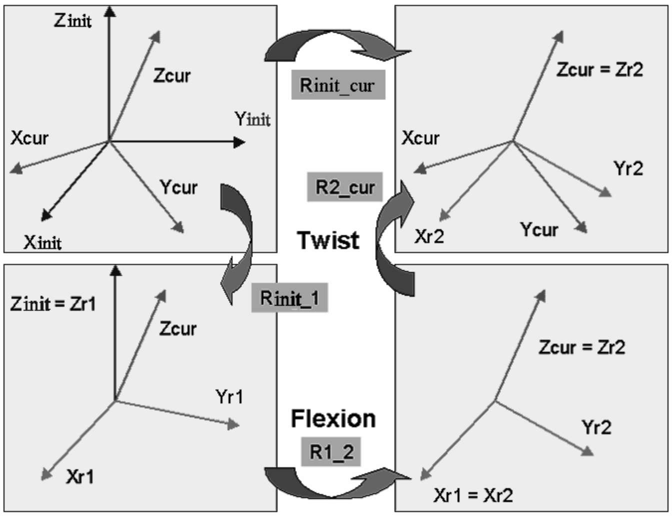

Figure A33 Total rotation matrix split into a flexion component around a temporary x-axis, Xr1, and a twist component around the current z-axis, Zcur.

The twist angle is the rotation about the current z-axis that aligns the x- and y-axis of the flexion rotated initial co-ordinate system with the x- and y-axis of the current co-ordinate system.

- The rotation matrix from the initial system to the current system is:
  Rinit_cur = [Xcur Ycur Zcur] \ [Xorg Yorg Zorg]
- This rotation is built up as Rinit_cur = R2_cur * R1_2 * Rinit_1 where
- R2_cur = [Xcur Ycur Zcur] \ [Xr2 Yr2 Zr2];
- R1_2 = [Xr2 Yr2 Zr2] \ [Xr1 Yr1 Zr1];
- Rinit_1 = [Xr1 Yr1 Zr1] \ [Xinit Yinit Zinit];
- The initial co-ordinate system is rotated about the temporary Xr1 axis using the flexion angle, resulting in an intermediate co-ordinate system (not shown in the figure). Note that the z-axes are now aligned, but not the x- and y- axes of both systems. This is because Xr1 and Yr1 are not part of either the original, nor the current system.
- This intermediate system is rotated about its z-axis until the current situation is obtained. The rotation matrix, which is then found, incorporates only the twist angle. The corresponding rotation matrix must be equal to R_twist = R2_cur * Rinit_1.

Thus Xr1, the flexion angle and the twist angle form a unique transformation from the initial state to the current state.