Parametric Computational Head-and-Neck Model and Anthropometric Effects on Whiplash Loading

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ABSTRACT

Currently, computational models are used to investigate potential injury mechanisms for whiplash associated disorders (WAD). These models are often designed to represent the average male subject only; therefore anthropometric subject differences are mostly not accounted for. In this research a simplified parametric computational model of the head and neck is designed to investigate how anthropometric subject differences affect the dynamics of head-and-neck behavior.

A lumped parameter approach, consisting of the head and cervical spine with segmental mass and inertia, is used to develop a model to investigate the head and neck responses to typical whiplash acceleration pulses. There are two stages for the model: first, the anthropometric model is generated. The geometry and the inertia properties are predicted based on regression equations using anthropometric subject data, therefore not a simple scaled approach. Lumped nonlinear joint functions are used to represent the viscoelastic neck behavior. Second, the generated anthropometric model is driven by a dynamic pulse applied at the first thoracic vertebra.

Six models were generated to represent the 5th, 50th and 95th percentile male and female subjects respectively. The models' prediction for mass and moment of inertia have been verified using anthropometric data in the literature for each respective model/subject. Then, the 50th percentile male subject model was dynamically tested and verified against published volunteer rear-end experiments. Finally, further male models with different anthropometric parameters were generated and their dynamic head-and-neck response was investigated.

For anthropometric parameter changes, dynamic behavior differences are visible for global (gross) head motion and intervertebral (segmental) motion. It is concluded that anthropometric subject differences are likely to have an effect on the whiplash injury risk for individuals, as subjects respond differently in similar crash condition.

INTRODUCTION

Whiplash Associated Disorder (WAD) is a condition of the cervical spine, occurring particular in rear-end crashes. Currently, detailed human body computational models, in particular finite element and multi-body models, are used to investigate the potential injury mechanisms for WAD. These models are mostly designed to represent the average male subject; some models have an equivalent small female and/or tall male subject. However, there is no

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model especially designed to take other anthropometric data into account. Also, NCAP (New Car Assessment Program) rates the whiplash risk of new car seats based on kinematic and dynamic performance criteria using the 50th percentile male BioRID II dummy; therefore it does not take anthropometric subject differences into account either. This research addresses such a shortfall. A lumped parametric computational model of the head and neck is designed to investigate how anthropometric subject differences affect the kinematics and dynamics of head-and-neck behavior.

Lumped-parameter computational models have shown their effectiveness for automotive impact simulations (de Jager, 1996; Himmetoglu, 2008; Hoover, 2015). Such models have the advantage that they are easy to adapt and that their required computational power is low. The disadvantage of a lumped parameter model is that it is not possible to investigate detailed tissue data. So the model cannot be used to investigate the whiplash injury mechanism or the actual location of a soft tissue injury. However, for the current research the biofidelic representation of head and neck motion is prioritized. Hence, the model can be used to calculate commonly used whiplash injury criteria, e.g. Neck Injury Criterion (NIC). This allows the simplified model to evaluate the injury risk of a subject.

METHODS

A lumped parameter approach, using multi-body dynamics, consisting of the head and cervical spine in the midsagittal plane with segmental mass and inertia, is used to develop the model to simulate the head and neck responses at typical whiplash acceleration pulses.

The lateral mid-sagittal two-dimensional geometry of the model is shown in Figure 1. The model consists of nine rigid bodies and uses simplified geometries. The rigid bodies represent the head (C0), the seven cervical vertebrae (C1-C7) of the neck and the first thoracic vertebrae (T1). The head is approximated to a circle and the first cervical vertebra (C1) is simplified to a line. The vertebrae bodies (C2-T1) are simplified to tetragons with two additional lines forming a triangle with the vertebrae body to indicate the spinous process.

All dimensions in the mid-sagittal plane geometry are accurate representations of actual anatomic dimensions. These dimensions are calculated (not scaled) with prediction equations derived on basis of lateral X-Ray images by Klinich (2004). The head and neck circumference are estimated based on stature and weight using anthropometric data published by Gordon (1989). The Instantaneous Axis of Rotation (IAR) between two adjacent bodies is derived from a graphical representation by Dvorak (1991), the locations of the Centre of Gravity (CoG) for each body are according to Jager (1996) and Merrill (1984). Mainstream anthropometric parameters such as height, BMI and gender are used to generate the anthropometric model before the dynamic analysis.

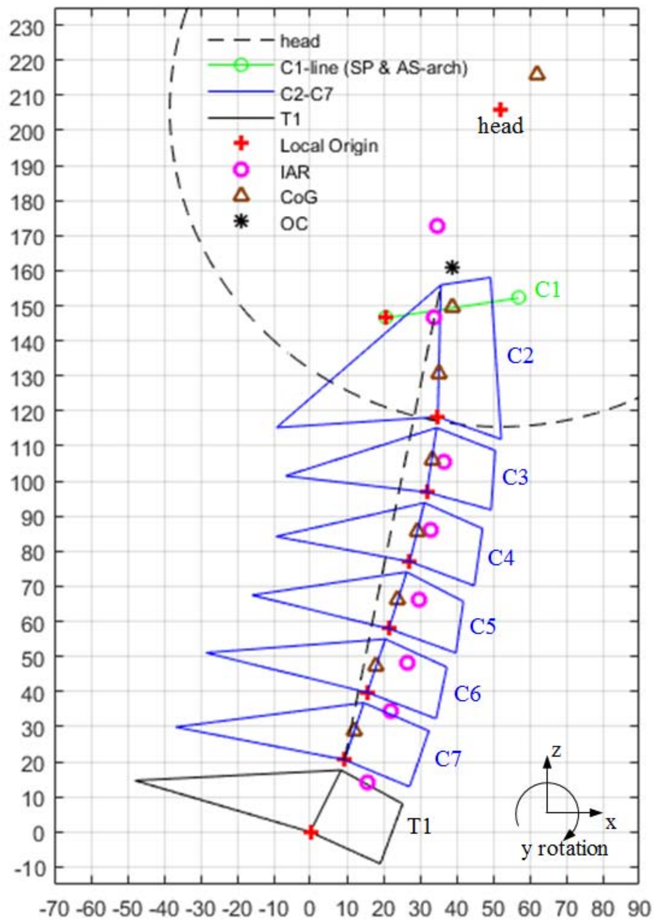

Figure 1. The two-dimensional geometry of the cervical spine for a 35-year-old and 176 cm tall male subject; this geometry is linked to the dynamic model. It shows the locations of the local origin of the coordinate system, the Instantaneous Axis of Rotation (IAR) and the Centre of Gravity (CoG) for each body. Additionally the occipital condyle (OC) is shown.

Each rigid body of the cervical spine (C1 to C7) represents one neck segment with proportional mass and inertia properties. The sum of these segments results in the same mass and inertia as the whole neck, i.e. vertebrae and surrounding soft tissues. The inertia properties, i.e. the head and segmental neck mass and moment of inertia properties are obtained by equations derived by McConville (1980) and Young (1983).

The intervertebral joints connecting the rigid bodies are represented with lumped non-linear stiffness and damping functions. These functions simulate the viscoelastic intervertebral joint behavior including the surrounding neck muscles. Each joint has one degree of freedom for rotation, i.e. flexion and extension motions. The stiffness is represented as shown in Equation (1) by a term of third order, because published stiffness-displacement graphs show cubic characteristics. The damping is represented as shown in Equation (2) by linear and quadratic terms, because previous lumped models showed good results using linear and/or quadratic damping.

$$T_{stiffness} = c\ \varphi^3 \quad (1)$$

$T_{stiffness}$ represents the stiffness moment, φ represents angular displacement, c is a coefficient chosen to give biofidelic response of the model.

$$T_{damping} = d1\ \upsilon + d2\ \upsilon\ |\upsilon| \quad (2)$$

$T_{damping}$ represents the damping moment, υ represents angular velocity, $d1$ and $d2$ are coefficients chosen to give biofidelic response of the model.

The head-and-neck model is driven by the motion of the first thoracic vertebra (T1). Recorded T1 motion from volunteer rear-end sled experiments (Davidsson, 2001) is used to define the motion of T1 in the model. This T1 motion is defined with respect to the global coordinate system as shown in Figure 1 and is presented in the literature as *x*-acceleration, *z*-displacement and the rotation about *y*. Simulating a head-and-neck performance by specifying the motion of T1 is common practice in computational models, e.g. de Jager (1996) and van Lopik (2004).

RESULTS

In this section three results are presented. First, six anthropometric models have been predicted and their geometry and inertia properties are shown. Second, the average male model is subjected to a dynamic pulse applied at the first thoracic vertebra and the model's displacements are compared to experimental data. Third, the effects of anthropometric subject differences are investigated using different male models.

Table 1: Predicted anthropometric data based on input variables stature and weight

Parameter		**Male**			**Female**		
		Small	**Average**	**Large**	**Small**	**Average**	**Large**
Input (Gordon, 1989)	Stature [cm]	165	176	187	153	163	174
	Weight [kg]	61.9	78.0	98.3	49.6	61.4	76.9
Output	Head circumference [cm]	54.3	56.8	59.3	52.3	54.6	57.1
	Neck circumference [cm]	35.0	37.8	41.4	29.2	31.4	34.3
	Head weight [kg]	4.06	4.48	4.90	3.69	4.04	4.42
	Neck weight [kg]	1.04	1.22	1.44	0.68	0.8443	1.04
	Head moment of inertia [kg cm²]	179.0	223.7	268.4	158.6	187.4	219.0

For the first result; Table 1 shows anthropometric data for six models which represent the 5th, 50th and 95th percentile male and female subjects. The model's prediction for mass and moment of inertia have been verified against anthropometric data in the literature for each respective model/subject (Churchill, 1978; Linder, 2013; McConville, 1980; Moss, 2000; Robbins, 1983). The differences of these six models to the literature data is shown in Table A1 and A2 in the appendix.

For the second result; the 50th percentile male subject model has been dynamically tested and verified against published volunteer rear-end experiments published (Davidsson, 2001; Sato, 2014). The individual joint stiffness (c) and joint damping ($d1$ and $d2$) coefficients as shown in Table 2 have been derived based on published joint data of cadaver experiments (Jager 1996), but had to be scaled to adjust the model response to the experimental volunteer data. Therefore, this scaling is conducted because of the difference of in vivo and in vitro tissue properties.

Table 2: Stiffness and Damping Coefficients for rotational and translational motion

Rotational Stiffness					Rotational Damping	
Coefficient	C0-C1	C1-C2	C2-T1		Coefficient	
$c_{Flexion}$	400	80	50		$d1$	1.3
$c_{Extension}$	750	1500	900		$d2$	3

Figures 2 to 5 show the model responses compared to the individual volunteer responses in the JARI study. The individual volunteer responses are provided by van der Horst (2002). Figures 2 and 3 show head angle rotations with respect to the global coordinate system and the first thoracic vertebra (T1) respectively; Figures 4 and 5 show x- and z- displacements of the Occipital Condyle (OC) with respect to T1 respectively.

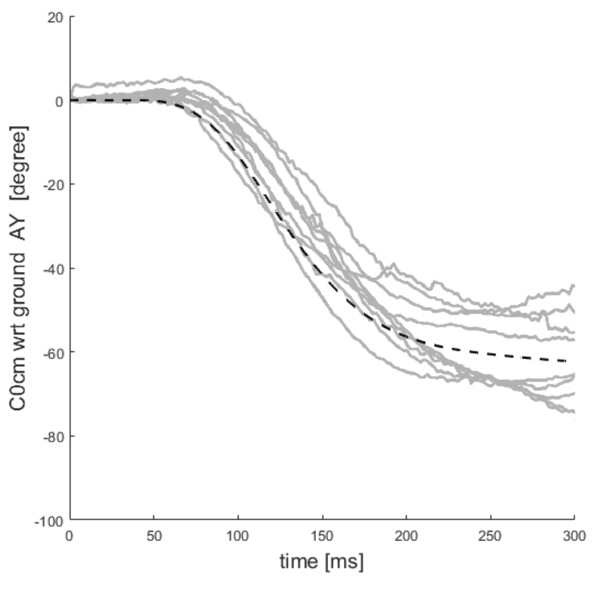

Figure 2: Head Angle with respect to the global coordinate system [°]; model versus volunteer responses by (van der Horst, 2002).

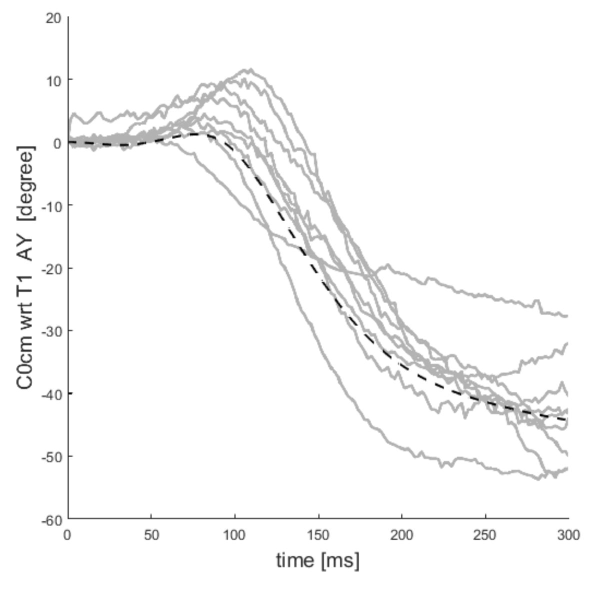

Figure 3: Head Angle with respect to T1 [°]; model versus volunteer responses by (van der Horst, 2002).

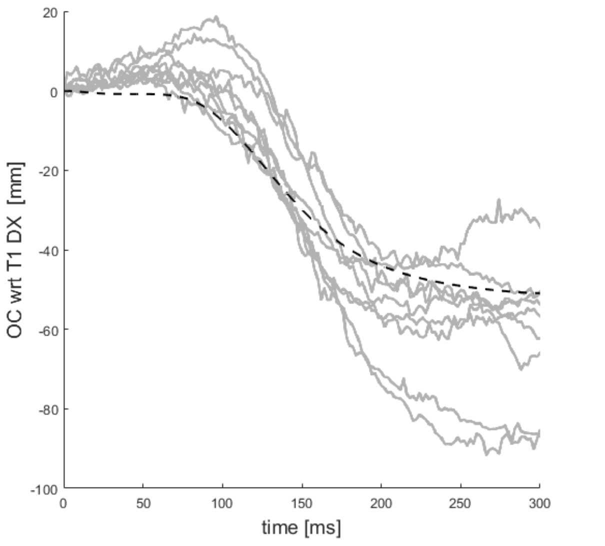

Figure 4: OC x-displacement with respect to T1 [mm]; model versus volunteer responses by (van der Horst, 2002).

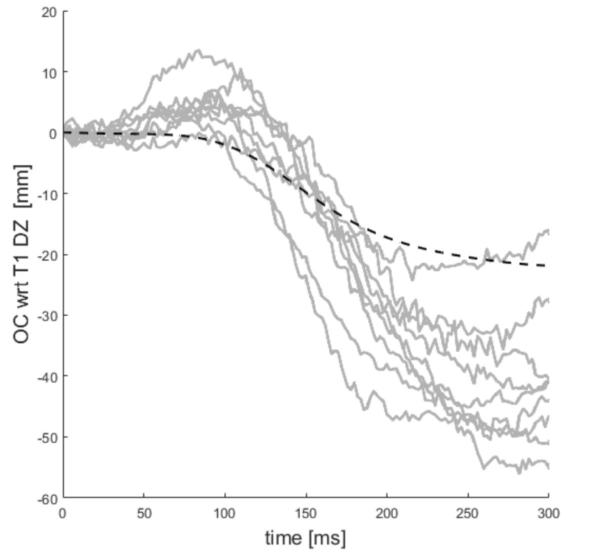

Figure 5: OC z-displacement with respect to T1 [mm]; model versus volunteer responses by (van der Horst, 2002).

For the third result; the dynamic effects of adjustments of anthropometric data (stature, weight and initial cervical curvature) on the head-and-neck response are being investigated based on the validated 50th percentile male model.

Altering the stature by keeping the BMI constant has little effect on the geometry of the model; however, the head inertia properties are affected. Therefore, increasing the stature affects the dynamic response of the model in terms of increasing head extension displacement and acceleration. Altering the weight has no effect on the geometry of the model, however, the neck circumference changes and so does the neck inertia properties. The moment of inertia of the neck has very little effect on the dynamic response of the model as the neck rotates only slightly during whiplash loading and also the moments of inertia of the neck segments are small compared to the moment of inertia of the head. The neck mass on the other hand affects the dynamic response, higher neck mass increases the intervertebral (segmental) rotations in the neck. Altering the initial curvature does not change the global head response considerably; however, the intervertebral (segmental) rotation of adjacent vertebrae is affected significantly.

DISCUSSION

The model's anthropometric predictions are within one standard deviation derived from literature data with the exception of the neck circumference (Table A3 in appendix). However, the only application of the neck circumference is to calculate the neck mass, and the calculated neck mass is within one standard deviation; therefore the prediction equation for the neck circumference was not altered. The anthropometric model has sufficient accuracy to predict subjects with different anthropometric data.

Figures 2 and 3 show a very good agreement for the head rotation for the 50^{th} percentile male model compared with the volunteer data, while Figures 4 and 5 shows marginal agreement to the OC-T1 x and z displacements. However, the OC-T1 z-displacements obtained in the volunteer experiments shows an elongation of the neck for the first 75ms, although in the literature it is commonly agreed that in the first 75ms there is a compression of the neck due to ‘ramping up’. Consequently it is doubtful how accurately the volunteer data of OC-T1 displacements actually are. The validation of the model is appropriate to investigate effect of anthropometric subject differences on the head and neck motion.

Anthropometric parameters have an influence on the global, segmental or a combination of global and segmental head-and-neck response of the model. This was tested for the same whiplash acceleration pulse applied at the first thoracic vertebra. Anthropometric subject differences of an individual have an effect on the head and neck, which therefore has an effect on the head and neck behavior during a crash and ultimately affects the whiplash injury risk for individuals.

CONCLUSIONS

The motivation of this research is to investigate how anthropomorphic subject parameters affect the risk of whiplash injuries. The parametric model can auto-predict geometry and inertia properties for any subject between the 5th and 95th percentile male and female subject based on mainstream anthropometric data.

This research provides the framework for a parametric computational model. The model predicts with sufficient accuracy head and neck motion while the required computational effort to configure the model and to run the simulation is far below a typical FE-model.

Currently the model is validated for the 50th percentile male subject; further validation will include female subjects which have been tested during the same study with comparable crash conditions. This will increase the model application range and the possible use in other research areas, e.g. other impact directions or impact sports-engineering.

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APPENDIX

Tables A1 and A2 summarize anthropometric data published by different researchers for small/average/large male and female subjects respectively. Different research groups used different methods on how the data was collected, which is one reason for the variations. In particular, the huge differences in neck weight arise probably due to the different segmentation of the neck with the head and with the torso. Table A3 shows the mean and standard deviation of designed model (Table 1) compared to literature data Tables A1 and A2.

Table A1: Literature data of anthropometric dimension and inertia properties for small/average/ large males. The percentage deviation from the model predictions (Table 1) are listed in brackets

Parameter	**Small male**		**Average male**			**Large male**	
	(Churchill, 1978)	(Moss, 2000)	(Churchill, 1978)	(McConville, 1980)	(Robbins, 1983)	(Churchill, 1978)	(Robbins, 1983)
Stature [cm]	167.2 1.3%	164.7 -0.2%	177.3 0.7%	177.5 0.9%	175.1 -0.5%	187.7 0.4%	186.4 -0.3%
Weight [kg]	63.6 2.7%		78.7 0.9%	77.3 -0.9%	76.6 -1.8%	95.6 -2.7%	102.6 4.4%
Head circumference [cm]	55.2 1.7%	53.6 -1.3%	57.5 1.3%	57.27 0.9%	57.06 0.5%	59.9 1.0%	
Neck circumference [cm]	35.4 1.3%		38.3 1.3%	37.67 -0.4%	38.82 2.7%	41.7 0.7%	
Head weight [kg]	4.4 8.4%		4.9 9.4%	4.337 -3.2%	4.137 -7.7%	5.4 10.2%	4.511 -7.9%
Neck weight [kg]	1.5 44.2%		1.7 39.3%	1.012 -17.0%	0.965 -20.9%	2.0 38.9%	1.168 -18.9%
Head moment of inertia [kg cm²]	150 -16.2%		187.2 -16.3%	232.888 4.1%	221.546 -1.0%	229.7 -14.4%	263.1 -2.0%

Table A2: Literature data of anthropometric dimension and inertia properties for small/average/ large females. Percentage deviation from the model predictions (Table 1) are listed in brackets

Parameter	**Small female**		**Average female**			**Large female**	
	(Churchill, 1978)	(Robbins, 1983)	(Churchill, 1978)	(Linder, 2013)	(Young, 1983)	(Churchill, 1978)	(Moss, 2000)
Stature [cm]	152.4 -0.4%	151.1 -1.2%	162.1 -0.6%	161.8 -0.7%	161.2 -1.1%	172.1 -1.1%	173.1 -0.5%
Weight [kg]	46.4 -6.5%	46.4 -6.5%	57.73 -6.0%	62.3 1.5%	63.9 4.1%	70.9 -7.8%	
Head circumference [cm]	52.3 0.0%		54.9 0.6%		54.78 0.4%	57.6 0.9%	57.1 0.1%
Neck circumference [cm]	31.1 6.3%		33.8 7.5%		32.86 4.5%	36.7 7.0%	
Head weight [kg]	3.9 5.7%	3.697 0.2%	4.2 4.0%	3.53 -12.6%		4.6 4.1%	
Neck weight [kg]	1.3 91.2%	0.601 -11.6%	1.4 65.8%			1.6 54.1%	
Head moment of inertia [kg cm²]		172.919 9.0%			169.917 -9.3%		

Table A3: Mean and standard deviation of model (Table 1) compared to literature data (Table A1 and A2) for all six subjects

Parameter	**Mean**	**SSD**
Stature [cm]	-0.2%	0.8%
Weight [kg]	-1.5%	4.4%
Head circumference [cm]	0.6%	0.8%
Neck circumference [cm]	3.4%	3.0%
Head weight [kg]	0.2%	7.8%
Neck weight [kg]	26.5%	40.5%
Head moment of inertia [kg cm²]	-5.8%	9.7%