Multi-directional modal analysis of the head-neck system and model evaluation

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ABSTRACT

This study details an original evaluation method for head-neck system models for side and oblique impact scenarios with small impact energies. In the literature, human neck models are often validated against corridors established in the time domain (inter alia [1] and [2]). This method is of limited precision for the characterization of multi degree-of-freedom systems for impact simulation purpose. Each validation corridor is linked to one specific impact scenario only: the models' biofidelity depends strongly on the scenario. In order to gain a more proper identification we suggest completing a validation with the presented approach. It is based in the frequency domain and deals with modal parameters of volunteers and models. Methodology and three evaluations of head-neck models are detailed. There will be no discussion about time domain methods given but we state clearly the importance of time domain validation.

Results of the study are the similarity of the modal characteristics of the tested subjects, the demonstration of linear behaviour for small impact energies and the data of the evaluation of the three models. To the authors knowledge it is the first study that provides experimental and numerical modal analysis techniques in order to validate the lateral and rotational characteristics of head-neck models.
Keywords: Biofidelity, Neck, Side Impact Dummy, Validation

THIS WORK IS IN CONTINUITY WITH THE VALIDATIONS OF HEAD-NECK models performed by Willinger et al. 2005 [3] and Meyer et al. 2005 [4]. These earlier studies were restricted to the sagittal plane. In the present study, a principal motivation is to open the research field to lateral neck loading conditions with application to lateral or oblique impact in car accidents as well as for out-of-position investigation.

METHODOLOGY

The first step of the study is the realisation of two types of modal analyses: lateral (Figure 1a) and rotational excitation (Figure 1b) are used in order to extract the lateral and rotational modal behaviour of the volunteers' head-neck system. Receiving the proposal of Ono et al. 1997 [5], in the first test arrangement head and cervical spine are excited by loading the head with a force of maximum 150 N (over 50 ms) that is applied laterally to the head. The rotational stimulation has been carried out by using an original pivot-mounted chair that is decelerated abruptly by driving against a rigid barrier.

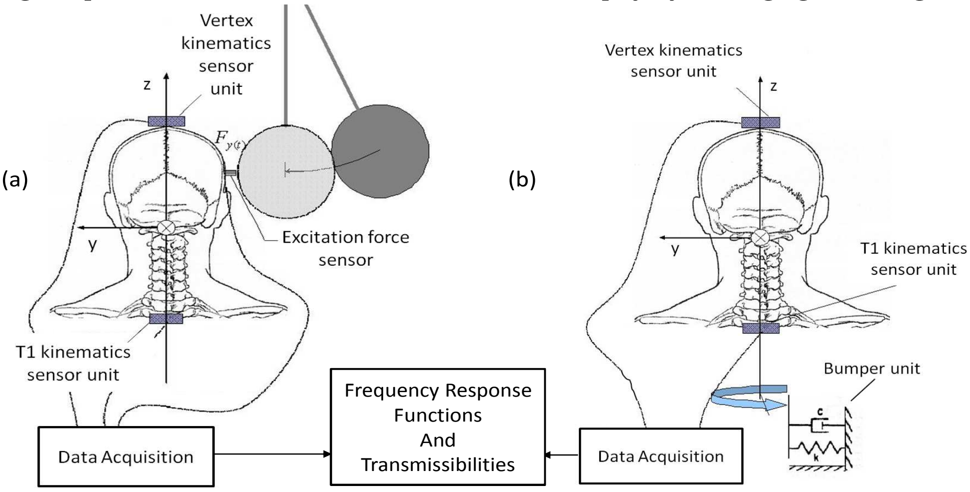

Figure 1- Experimental modal tests scheme under lateral (a) and rotational (b) stimulations

The volunteers were not tensed in both test schemes. The rotational test serves to the verification of the eigenfrequency of the rotational mode. The measured volunteer data (n =10, male) permits the calculation of transfer functions in terms of apparent mass [6]. This analysis leads to the mechanical identification of the volunteers' head-neck system by modal parameters as eigenfrequency, modal damping and modal deformation. They are determined in this case by exploiting modulus, phase response and real and imaginary part of each of the complex transfer functions. After this experimental neck characterization step, a numerical analysis is carried out on existing models. A soft impact scenario is performed with the Strasbourg University Head-Neck FE model (SUHN), developed in 2005 [4] and two MADYMO multibody models: “Hybrid III” [7], as SID is based on the Hybrid III head-neck section [8] and “EuroSID II” [9]. As within the experiment, a virtual mass impacts the head model laterally with a force varying from 70 to 90 N and a duration of 50-60 ms. The calculated dynamic contact force and the kinematic responses of vertex, head-neck and neck-thorax junctions in terms of linear acceleration and angular rate serve as base for the numerical modal analysis. This identifies the modal parameters of the considered model. In a final step the comparison of these numerical transfer functions, modal parameters with the test-based modal data shows the biofidelity of the lateral and rotational characteristic of the specific model.

RESULTS

The three natural modes that have been identified are characteristic for the lateral kinematics of the human head-neck section. They are the “inclination” mode, the “axial rotation” mode coupled to the previous one and the “lateral retraction” mode (lateral “S” shape curvature [10]). [10] describes the functional, anatomical coupling of head’s rotation and inclination for quasi-static motions. The results of the modal analysis affirm this by identifying the effect of modal coupling. This effect is elementary for the understanding of the lateral kinematics of the head-neck system. The natural frequencies, mode shape vectors and modal damping of the identified modes are listed in Table 1.

Table 1. Overall results of the experimental modal analysis, mean values incl. stand. dev.; n=10, male

Mode	Natural Frequency [Hz]	Modal Damping	Mode Shape Vector Vertex	Head-neck
Inclination (1st lat. mode)	1.51± 0.47	0.48± 0.08	[0.46± 0.27	0.55± 0.11]
Axial rotation (1st rot. mode)	2.93± 0.53	*(only: transmissibility)*	*(only: transmissibility)*	
Lateral retraction (2nd lat. mode)	7.95± 1.88	0.28± 0.09	[-0.48± 0.25	0.34± 0.09]

These three modes are extracted from the transfer function. The results from the rotational tests confirm those from the lateral tests and so are not detailed by additional graphs. The characteristic of the imaginary part of the transfer function shows the modal shapes belonging to the different modes, as illustrated for one volunteer in Figure 2. Maxima and Minima represent the values of the mode shape vectors [6]. The coherency function is for all tests between 0.8 and 1 from 0 to 20 Hz, which means approximately linear behaviour.

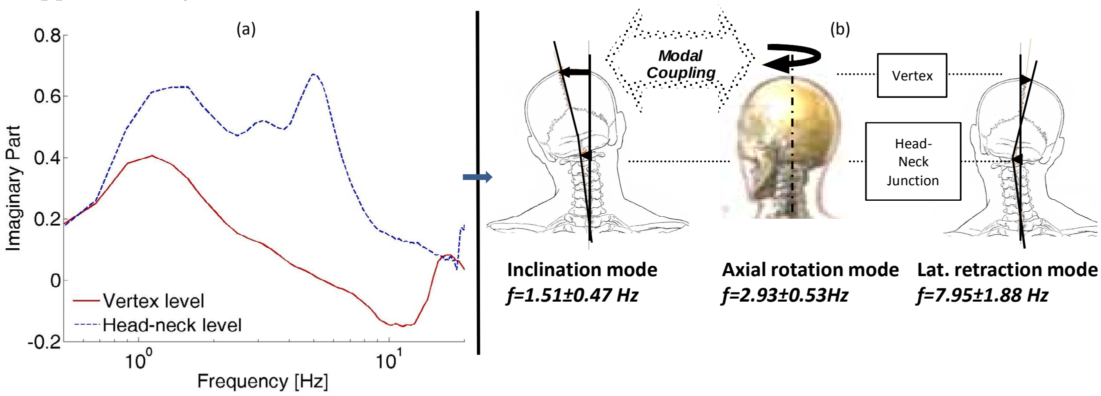

Figure 2- Imaginary Part of the transfer function (a) and the mode shapes associated (b)

The graph shown in Figure 3 represents the experimental data with mean value and related standard deviation for all volunteers against model data. In the upper part, the characteristics of the modal mass with its minima at the natural frequencies can be observed. The lower part of the graphs shows the averaged phase response at head-neck junction. For the analysis we chose the band from 0 to 15 Hz. This is because low order modes lead to large deflections. The knowledge of these modes lead to a better comprehension of the lesion mechanisms. This is of prior interest when we regard trauma mechanics.

For the essential evaluation the results of the numerical and experimental analyses are superimposed. The evaluation of the SUHN FE model (see Figure 3) shows that the resonance frequency of the inclination mode lies at *2.11 Hz*, which is about 40 % higher than the mean of the resonance frequencies for male volunteers (*f=1.51±0.47 Hz*). Even if this is at the limit of the corridor drawn by the standard deviation range it is an important point, that the FE model shows the coupling between the first lateral mode and the first rotational mode with a frequency of *f=2.05 Hz*.

Within the volunteers group the ratio between the two resonance frequencies of these modes is in the mean 1.9 . For the model this value is 1.1 . Furthermore the model represents basically the modal shapes given by the analysis of the in-vivo test data. For the second mode (lateral retraction) there is a deviation of 12 % for the FEM model relative to the averaged subject data. The result of the evaluation is that the lateral and rotational modal characteristic of the FE model is similar to the one derived from the volunteer test data. This is remarkable, regarding the complexity of the model compared to the two less complex multibody models.

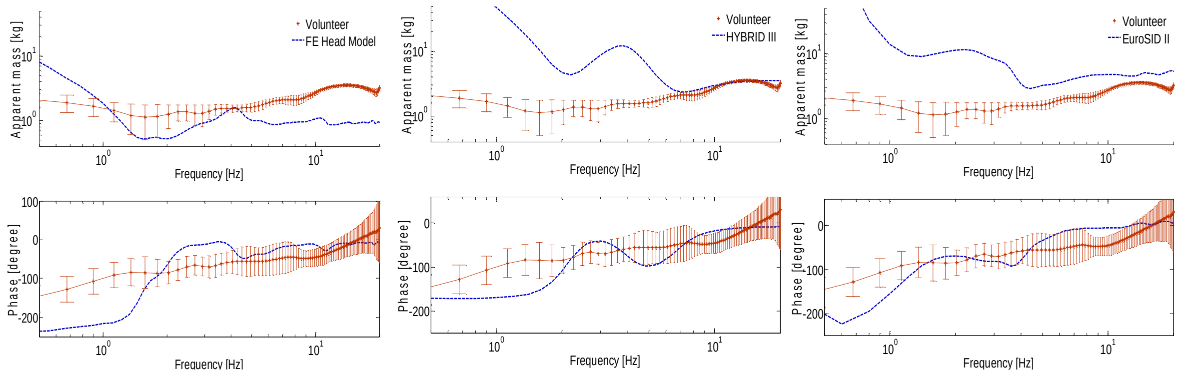

Figure 3- Superimposition of transfer functions in terms of apparent mas at head-neck level against experimental data for SUHN FE model, HYBRID III model and EuroSID II model

The analysis of the HYBRID III Madymo model outputs a first resonance frequency (*f=2.2 Hz*, inclination mode) (Figure 3). A lateral retraction mode is out of range (*32.8 Hz*) but in contrast to the volunteers lateral retraction mode, another inclination mode with *f=7.1 Hz* can be obseved. The first of these two inclination modes is part of an upper thoracic spine and cervical spine comprehending lateral mode being excitated by the impact on the head. As there is a nodal point near the neck-torso joint, the effected numerical correction consisting in subtracting the torso acceleration field from the head acceleration field (in the time domain) before addressing the modal analysis can't mask this mode. The coupling effect between the inclination and the rotational mode isn't clearly visible in the transfer function. A rotational mode observed at *f=1.91 Hz* is again comprising the upper thorax.

The EuroSID II model (Figure 3) shows a similar modal characteristic as the one of the HYBRID III model. This model also shows two inclination modes at *f=1.21 Hz* (combined with a rotational mode at *f= 0.44 Hz*) and *f=4.15 Hz*. The first of these two is not comparable with the first order mode found for male volunteers (*f=1.51± 0.47 Hz*): again (cp.: HYBRID III) it's a natural mode shape that covers the upper thorax of the dummy as well as his head-neck section. The second mode then is soonest qualified to be compared with the inclination mode found for the volunteers. Here the ratio between the resonance frequencies amounts ~ 2.75. So the eigenfrequency is far out of the range of the calculated standard deviation. The first lateral retraction mode appears at 26.20 Hz. This means that the upper neck articulations of the dummy are too stiff regarding inclination. The evaluation of the HYBRID III model and the EUROSID II model causes the conclusion that there is a quantifiable lack of biofidelity of the lateral and the rotational characteristic for both models. It can firstly be quantified by the calculated modal parameters.

DISCUSSION

Although the examined FE model shows closely the same characteristic, the performed evaluation demonstrates that there are still differences to be considered. The dummies show insufficient modal characteristics. For their use in WAD investigations more sensitive models that represent in detail the three modes "inclination", "axial rotation" and "lateral retraction" should be used.

It has to be examined in further studies, if a physical dummy that combines the illustrated modal behaviour for small displacements and biofidelic kinematics for the nonlinear domain is technically feasible.

For detailing the method it has been sufficient to deal with numerical models. But the application of the shown evaluation method in the domain of physical dummies is in our opinion of high priority.

It is plausible that there are higher orders for the rotational modes, but they show with their frequencies superior to 15 Hz relative small displacements.

One could wonder if this kind of “small-displacement” evaluation method is really necessary to do. In consideration of the fact that we proved linear behavior as the coherency function for all tested volunteers varies between 0.8 and 1 in the band from 0 to 15 Hz, models showing the illustrated modal characteristic can do a good job in low velocity impacts. On the other hand a more sensitive model, compared for example to Hybrid III, ensures a biofidelic motion initialization. This has an effect on the time response, shown by Meyer 2004 [11]. In all cases we recommend a combination of frequency domain and time domain based validation.

A limitation is that with 10 volunteers only a small population has been seen. Another one is the fact of remaining in the linear domain.

CONCLUSIONS

The proposed strategy details original multidirectional neck testing methods in the field of experimental modal analysis, three numerical modal analysis of three existing head-neck system models and the evaluation of these in terms of lateral and rotational modal parameters. The performed in-vivo tests lead to the identification of frequency response functions whereby the volunteers showed similar characteristics. The averaged modal parameters that have been found serve to the superposition of these with the computed transfer functions of existing head-neck system models. It has been shown that the two dummy models investigated (Hybrid III, EuroSID II) differ in terms of lateral and rotational modal characteristics from the tested population. This has been quantified by giving deviations of the eigenfrequencies in percentages. The SUHN FE model showed a comparatively biofidelic response.

This study presents an original method for the evaluation of numerical multidirectional human head-neck models also applicable to physical models. The method helps to make validations independent of impact scenarios. It describes system identification techniques in the context of biomechanics and accidentology. The shown analysis techniques are intended to be used for the evaluation of mathematical and physical models.

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