A HUMAN BODY MODEL FOR DYNAMIC RESPONSE ANALYSIS OF AN INTEGRATED HUMAN-SEAT-CONTROLLER-HIGH SPEED MARINE CRAFT INTERACTION SYSTEM

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Abstract

Small boats are increasingly being operated at high speed in rough weather by organisations carrying out essential missions such as the military and rescue services. Crew and passengers on these boats are exposed to continuous vibration and impacts leading to reduced crew effectiveness, fatigue and the possibility of injury. In addition to this marine craft will soon fall under the jurisdiction of the European Union Directive 2002/44/EC on the protection of workers from vibration.

To assess the possibility of injury and mitigate it at the design stage of a vessel a design tool is needed to assess the vibration levels on / in the human body while the boat operates in dynamic environments. A review of current human body models is presented and a new human body model, which allows for estimates of muscle activity, is proposed. This model is supplemented by a numerical approach using finite element methods to assess the dynamic response of the integrated human – seat - controller - boat interaction system excited by wave loads or boat motions measured in full scale boat operation tests. The vibration control actuators are arranged between the seat and boat to reduce vibrations transmitted to the human body from the boat to obtain a comfortable ride condition.

1. Introduction

In recent years the problem of vibration exposure at sea has become substantially more important. There are two reasons for this, in many areas of the marine industry the use of high speed craft has increased; secondly, the impending European legislation on vibration at work (European Union Directive 2002) requires all boat operators to address the issue. The problem of vibrations at sea is complex, rough sea produces large amplitude motions in all six degrees of freedom (Lloyd 1998). The accelerations experienced by a small craft in rough seas can be severe. D'Arcy et al (2006) show accelerations of up to eight g (78.48 ms^{-s}) in moderate conditions. Ullman (2006) suggests values of 25 g (245.45 ms^{-2}) and mentioned that the most significant vibrations are not only in the vertical direction but also in lateral directions. When compared with vibration levels experienced in automobiles, agricultural machinery and most industrial settings these values are very high and complex, furthermore the European Directive on vibration exposure at work, Directive 2002/44/EC (European Union Directive 2002) will apply to all vessels by 2010 and sets vibration exposure limits.

The ultimate solution to excessive vibrations and impacts generated by rough weather is either to reduce speed or remain in port and these are the two solutions usually adopted by commercial

operators. Military and rescue operators may not have these two options available as missions may be time critical. In addition to this, crew of these vessels must often perform vital tasks after long rough transits. Evidence suggests that not only is there a high risk of injury (Ullman 2006) but also, reduced performance after a long transit on a high speed vessel. For many years the vessel's strength and performance were limiting factors, now it seems that human frailty is a significant limiter.

In order to assess a vessel from the point of view of human vibration, be it either an existing design or a new design, design tools are necessary to allow the vessel to be assessed easily, quickly and cheaply. The concept proposed in this paper is that of a global numerical model to model the integrated boat-seat-human interaction system. This model will allow the total system to be simulated and the parameters of any vibration isolation device to be optimised.

2. Literature Review on Human Models

In order to maximise the usefulness of the global model it is necessary to develop a detailed model of the human body. Simple models have been developed for many years to emulate the seat to head transmissibility or apparent mass of the human body, such as that developed by Suggs et al (1969), shown in Figure 1. This simple approach is not sufficient to assess the potential for injury. To that end advanced human body models were considered, those detailed below represent the state of the art in the human body modelling field. Detailed modelling of the human spine allows estimations of the spinal loads to be carried out.
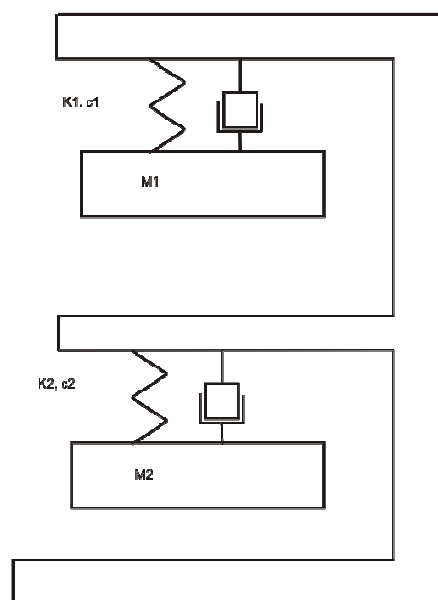

Figure 1 The simple model by Suggs et al (1969)

Pankoke et al (1998) developed an advanced model of a sitting man using Finite Element Modelling (FEM) techniques. The model focuses its detail on the lumbar spine region modelling the individual vertebrae and including the muscles of the lower back region as multiple springs. In order to reduce computational time the rest of the model is represented by rigid bodies with mass. The model was developed with three different postures, upright, relaxed (lorry driver) and slumped forward (crane operator). The model is also easily adjusted in both weight and height. The overall motion of the body model has been validated against experimental data and shows very good agreement with test data at frequencies up to about 7 Hz. Pankoke et al use the model to predict forces in the lumbar region of the spine.
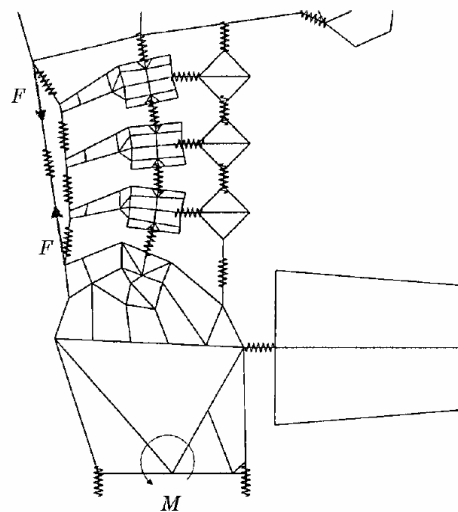

Figure 2 The FEA Model developed by Pankoke et al (1998)

Seidel et al(2001) used the finite element model developed by Pankoke et al (1998) to predict the loads in the spine during whole body vibration. They carried out further validation of the model against experimental data and a different model. The comparison shows that the model and the assumptions based it is based on are valid. As with other work on this type of model it is impossible to validate the internal forces within the spine.

Pankoke et al (2001) modified a highly detailed FEA model, similar to the model by Pankoke et al (1998) to produce a simpler model for force prediction in the lumbar region of the spine. The model represents vertebrae as rigid bodies connected by springs representing the inter-vertebrae disks. Muscles in the lumbar region of the spine are also represented by springs. As part of the simplification process the model properties have also been linearised to reduce the overall complexity. The model differs from Pankoke et al (1998) being three dimensional and representing the lumbar muscular structure in more detail, rather than grouping the muscles as single springs.

As with other spinal force prediction methods, it is impossible to directly verify the results of the model, however excellent results were obtained when using non-invasive methods. The model is only applied to vertical accelerations however unlike the majority of other models it is three dimensional and therefore could potentially be used for the six degree of freedom marine case.
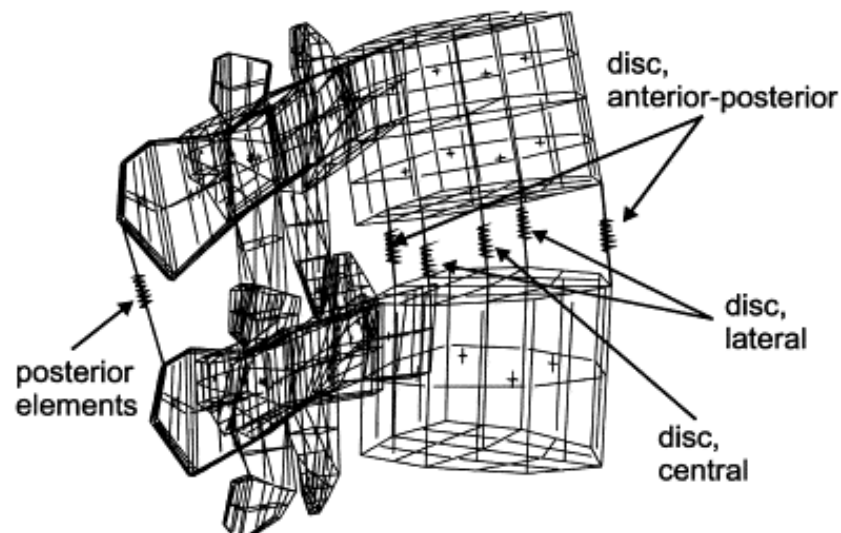

Figure 3 Pankoke et al(2001) reduced model representation of the lumbar spine
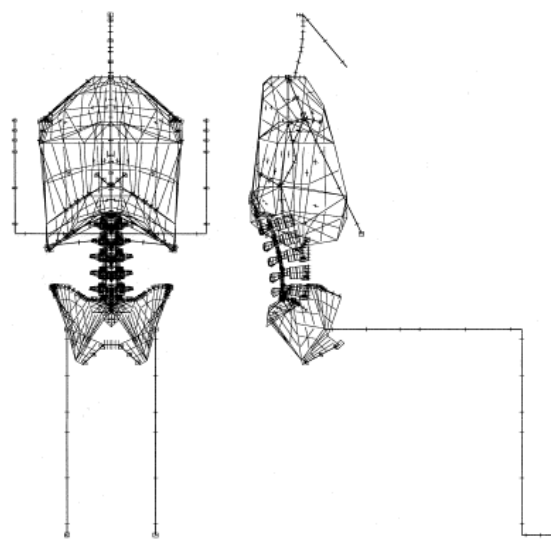

Figure 4 Complete Pankoke reduced model

Verver et al (2003) developed a model using numerical methods. Individual vertebrae are modelled as rigid bodies and are connected with joints, "in which translational and rotational stiffnesses are implemented" (Verver et al. 2003) The model is based on the MADYMO crash simulation model and includes the outer surface of the body modelled as a finite element mesh, connected to the internal structure of the body a unique feature among reviewed models. When compared to experimental data

this model achieved mixed results. When testing using a rigid seat, results for transmissibility to the head, first Vertebrae and Pelvis (Verver et al. 2003) compared poorly with experimental data from several subjects. Both magnitude and shape of the transfer function bear only tenuous resemblance to the experimental data. However when testing on a standard car seat, results where much improved. The model correctly predicts the seat to head resonance peak at about 3.5 Hz and while the predicted amplitude of motions is rather high this is in common with several other models, notably (Boileau and Rakheja 1998). The nature of the model allows axial and shear forces for the spine to be calculated. These data can be considered with some confidence due to the transmissibility results. The ability to measure intra-body forces is useful in minimizing fatigue in the human body. The model is unique in its use of a three dimensional geometry incorporating the outer surface of the body however some of the comparisons with experimental data are poor.
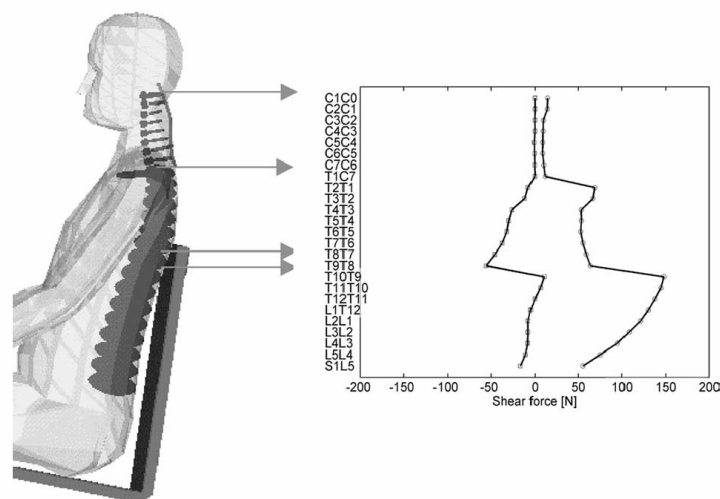

Figure.5 Spinal Shear Force Model by Verver et al (2003)

Having considered the current human body models it was decided to utilize an approach similar to that of Pankoke et al (1998) for our own biomechanical model. As stressed above, in the marine environment the experienced vibrations occur in all six degrees of freedom with no one degree being dominant therefore it is necessary to develop a six degree of freedom model.

3. An improved model

The new human body model proposed here is intended to allow the vibration seriousness to be assessed and vibration isolation seating to be designed. Compared to previous models, this model has the following features. A key feature, as mentioned above is detailed representation of the lumbar spine. By using a similar approach to Pankoke et al (1998) (2001) and modelling the muscles of the

back, it is possible to estimate the forces applied to the back and assess their severity and the effectiveness of vibration isolation.

- Three dimensional capabilities. The new model is a complete, three dimensional representation of the seated human being. This allows the complex six degree-of-freedom problem of a small boat at sea to be addressed.

- Modular capability. The modelling approach allows various aspects of the model to be improved over time. As shown in Figure 6, modelling has been concentrated in the lumbar spine area but the approach used allows the other areas to be updated and become increasingly detailed as work continues.

At present the human body has been divided into 4 distinct areas similar to those used by Pankoke et al (1998) and shown in Figure 6. For the initial global model, detailed modelling is restricted to region C the lumbar spine area.
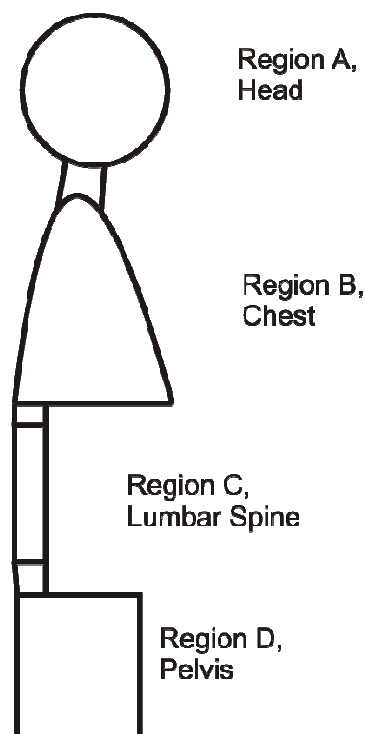

Figure 6 The four development regions of the human body

It is necessary to include a high level of detail in the lumbar region of the body and this is the prime focus of model development. Lumbar vertebrae are taken from the ANSYS Model developed by Grunendahl (2003) at Aachen University and simplified by removal of the cartilage of the inter-vertebral disks, to reduce the number of elements.
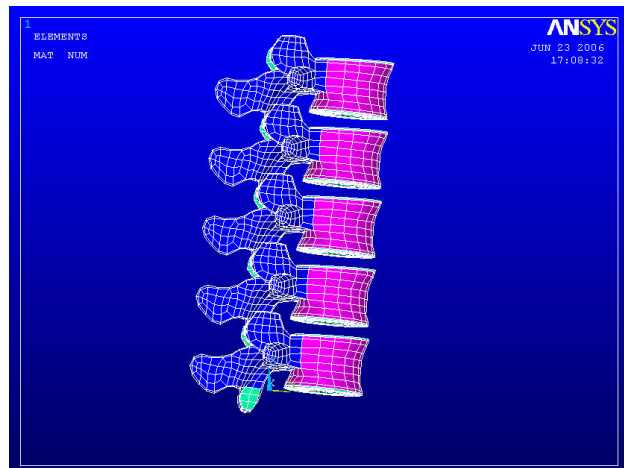
Figure 7 lumbar spine vertebrae

Regions A and B have been developed in simplified form from the NASA Anthropometry guidelines for a 50th percentile man, the pelvis geometry has been simplified from a freely available IGES file from 3D Doctor (3D Doctor 2006) to produce a simple body.

The key to this research is the detailed representation of the muscles of the lumbar spine, muscle position is taken from standard texts on human anatomy (Bloomfield et al. 1994; Marieb 2004). The muscles are modelled as linear springs, a method that has been used successfully by Pankoke et al (1998; 2001) and others(Prasad and King 1974; Belytschko and Privitzer 1983). Differing properties are used for different areas of muscle allowing the muscle properties to be easily adjusted.
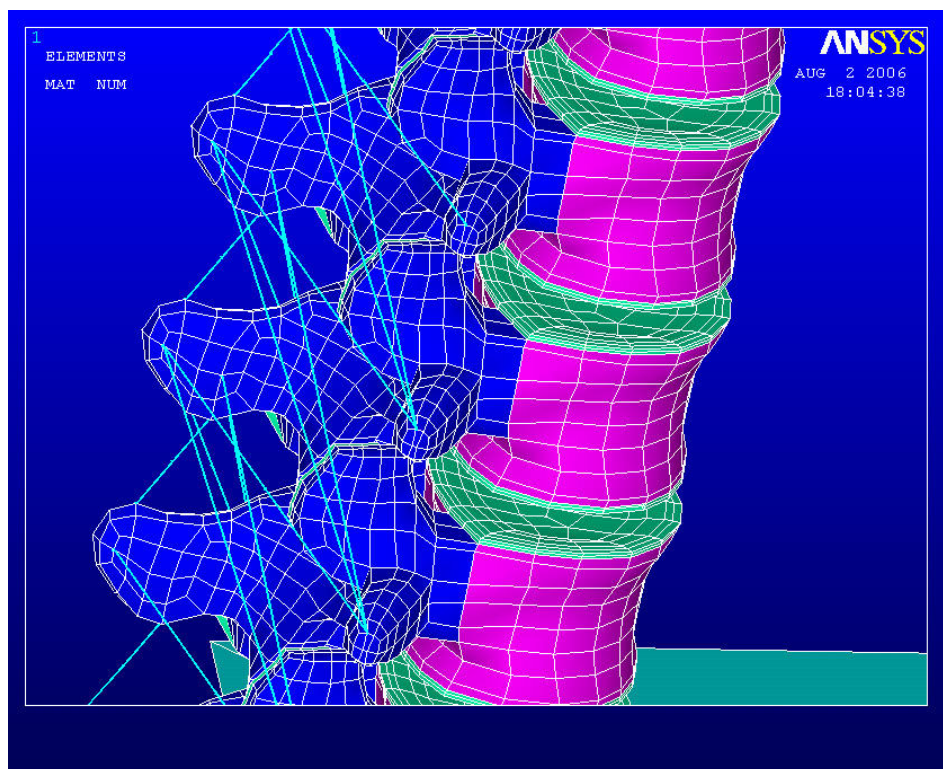

Figure 8 Deep spinal muscles of the lumbar spines

Figure 8 clearly shows the deepest muscles of the spine, these are modelled at the level of the individual vertebrae. The lumbar region is then developed, incorporating additional levels of muscular structure. This structure is partly shown in Figure 9. (some additional muscles removed for clarity)
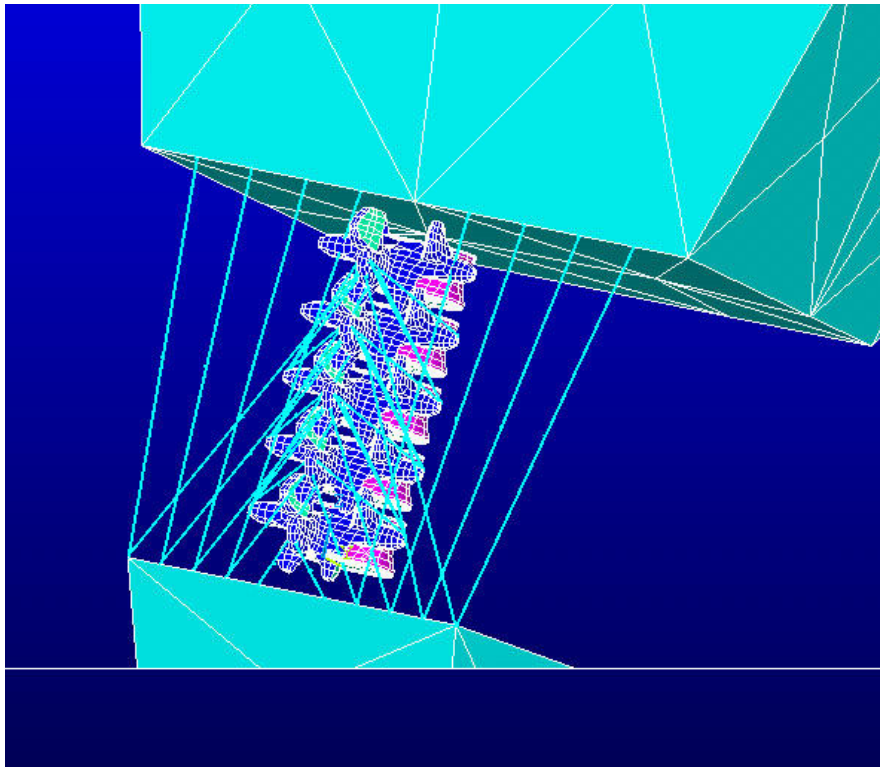

Figure 9 Multifidus and Illiocostalis lumborum representations

The model will allow the input of forces or displacements at the pelvis and output of motions of the head or chest and displacements, accelerations and forces on the lumbar spine. For this type of model it is notoriously difficult to obtain stiffness parameters for the materials used. For this model it is proposed that a combination of two techniques is used to identify mass, stiffness and damping parameters. The first is to utilize the published values and ranges to place the parameters within acceptable limits, having carried this out, published seat to head transmissibility data and apparent mass data can be used optimize the parameters.

4. Integrated modelling

The new human model discussed above takes its place as part of an integrated model. The aim of the modelling process is to create a model which can be used to optimise suspension seat parameters. This model will be a global, numerical model incorporating the vessel, seat and the human as shown in Figure 10. The input to this model is the six degree of freedom motion generated by the force of the sea on a vessel, the model then considers the interaction between the boat and the seat and the seat and the human. The model will then allow a designer or surveyor to input a vessel design and assess its vibration performance, results can then be used to develop suitable isolation systems for that particular vessel.
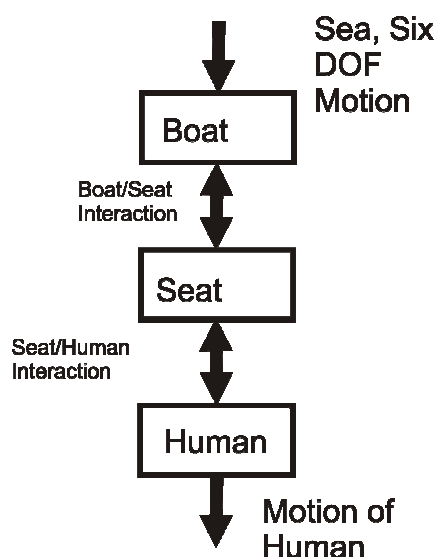
Figure 10 Model concept

In the final system the boat hull geometry will be added by the designer or surveyor of the particular hull. For the purposes of this model the hull is based on the geometry of an Atlantic 21 RNLI Lifeboat hullform, modelled in ANSYS from a DXF linesplan and automatically meshed using ANSYS. The Atlantic is typical of the type of vessel that this model will be used for and performance data are available for various aspects of the craft. Figure 11 shows the meshed model, generated using shell elements and a coarse level of detail. It is intended to model the vessel's structure more accurately, including plating and stiffeners to better represent the vibration behaviour of the boat.
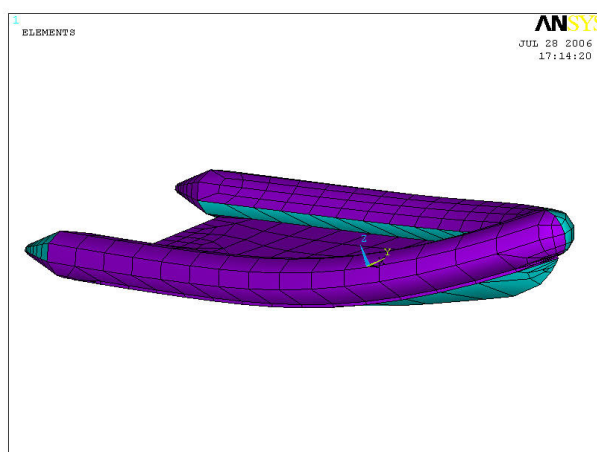

Figure 11 ANSYS Meshed Model of Atlantic 21

The vibration isolation seat will be inserted into this model between the vessel and the human body. Different types of seat can be inserted for different conditions.

This integrated model will allow the comparison of seat designs for a given boat and will allow the seat to head transmissibility to be determined, as well as forces within the body. The effect of altering the

stiffness and damping parameters of a suspension seat can be seen and seats can be judged on various criteria.

5. Validation

Model validation will be carried out using full scale tests with high speed vessels. It is not possible to measure forces within the bodies of the crew on these vessels, so as with the parameter identification process validation will be based on easily measurable quantities such as seat to head transmissibility. The difference between this and the parameter identification work is in the nature of the vibration experienced. By comparing model results with those for the real, intended use of the model its appropriateness for the task can be assessed. In addition to vibration measurements, crew heart rate and Oxygen use will also be measured, hopefully allowing some correlation with lumbar spine load data.

6. Conclusions

An improved human model incorporating into an integrated boat-controller-seat-human interaction system is proposed in this paper. The proposed model will be used to calculate the vibration levels on and in the human body transmitted from the boat excited by external forces from sea way. This three dimensional integrated model, after a further numerically and experimentally investigation, may provide a useful tool for assessing the performance of a vessel and its seat isolation system to allow optimisation seat designs to be considered during the design phase of creating a new high speed craft and to allow boat operators to better meet coming health and safety criteria.

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