Simulating 3D human postural stabilization in vibration and dynamic driving

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ABSTRACT

In future automated vehicles we will often engage in non-driving tasks and will not watch the road. This will affect postural stabilization and may elicit discomfort or even motion sickness in dynamic driving. Future vehicles shall accommodate this by properly designed seats and interiors whereas comfortable vehicle motion shall be achieved with smooth driving styles and well designed (active) suspensions. To support research and development in dynamic comfort, this paper presents validation of a multi-segment full body human model including visuo-vestibular and muscle spindle feedback for postural stabilization. Vibration transmission is evaluated using new tests with compliant automotive seats, applying 3D platform motion and evaluating 3D translation and rotation of pelvis, trunk and head. Dynamic driving is evaluated using a recently published "sickening drive" including a 0.2 Hz 4 m/s^2 slalom.
The model matches corridors of 3D human motion and reproduces vertical and fore-aft oscillations. Visuo-vestibular and muscle spindle feedback are shown to be essential in particular for head-neck stabilization. Active leg muscle control at the hips and knees is shown to be essential to stabilize the trunk in the high amplitude slalom condition but not in low amplitude horizontal vibrations. However, active leg muscle control can strongly affect 4-6 Hz vertical vibration transmission. Compared to the vibration tests, the dynamic driving tests show enlarged postural control gains to minimise head roll and pitch, and to align head yaw with the driving direction.
Human modelling can create the required insights to achieve breakthrough comfort enhancements while enabling efficient development for a wide range of driving conditions, body sizes and other factors. Hence, modelling human postural control can accelerate innovation of seats and vehicle motion control strategies for (automated) vehicles.

KEYWORDS

Comfort, Vibration, Biomechanics, Stabilization

Introduction

Automated cars provide opportunities for performing non-driving tasks such as reading books and looking at screens during the ride. Users will often take their eyes off the road hampering verticality perception and anticipation of vehicle motion. This will affect postural stabilization and may elicit discomfort and even cause more severe and/or frequent motion sickness [24]. The postural response of the human body to vehicle motion is of great value for studying human motion comfort [1, 2]. Deeper knowledge of postural stabilization and its relationship with motion comfort is particularly relevant for automated cars. Future (automated) vehicles shall accommodate these new requirements into the design of seats and interiors. Biomechanical modelling of the human body is

essential to reveal underlying mechanisms such as postural stabilization and models predicting human movements and comfort can support vehicle design.

Biomechanical models with different approaches have been developed and validated to study seat interaction. Multibody and/or finite element models have been used to study impact conditions in full 3D. Lumped approaches (incorporating mass, spring and damper elements generally in single axis motion) have been used to compute the forces on a seat, usually during vertical and less often during fore-aft motions [3-5]. Three-dimensional multibody models represent the human body with multiple segments [6-8] whereas finite element models capture soft tissue and seat deformation in more detail [9, 10]. Due to computational efficiency, multibody models are more common to investigate factors such as human weight, road class, and vehicle speed on human postural response in different directional motions [8]. Previous comfort oriented full body models focused mostly on the vertical [15] and fore-aft directions [16], but simulation of lateral movements is also essential. A recent multibody model captured combined lateral, vertical and roll vibrations, in terms of apparent mass but was not validated in terms of predicted head and trunk motion [11]. Inverse dynamic musculoskeletal models have been used to analyse factors such as joint forces and muscular activity [12-14]. However, inverse models have limitations to be used for designing seat and vehicle control strategies as they are not able to predict body motions and body response forces.

Besides the body response to seat vibration, on which many previous studies focused, head control strategies are essential for motion comfort. The perception of head motion by vestibular organs and vision plays a significant role in (dis)comfort and motion sickness [17]. The head control objectives are suggested to be partly conflicting as head motion can be controlled relative to trunk or space [1] dependent on motion conditions and task. Previously, an advanced neck model that included vestibulocollic reflex (VCR), the cervicocollic reflex (CCR), and neck muscle co-contraction was validated [18]. Visuo-vestibular and muscle spindle feedback mechanisms were shown to be essential in particular for head-neck stabilization.

In order to predict head motions in presence of seat vibrations and dynamic motions, 3D full body models that include these mechanisms are required. In the current study, a full body model has been validated during fore-aft, lateral, and vertical perturbations and slalom dynamic motion, and used to study effects of active leg stabilization.

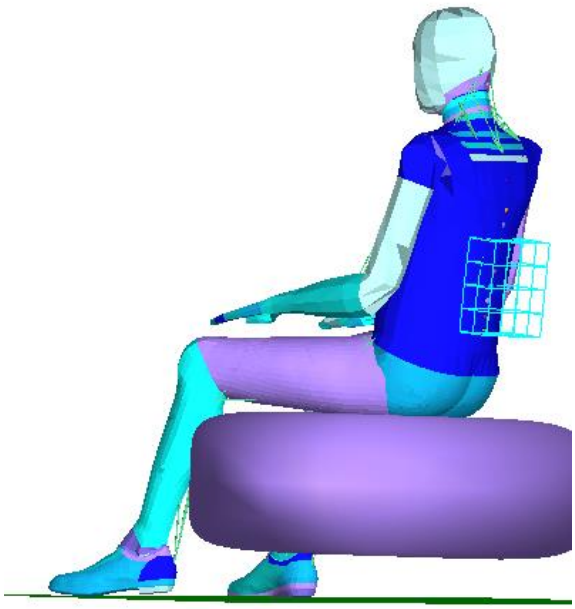

Figure 1 : Human model in vibration test on experimental seat with configurable backrest with foam block modelled using finite elements.

Methods

Model

The human active model (version 3.1), as distributed with MADYMO 7.8, was adopted using Matlab and Simulink for running simulations and post processing. The model was developed and validated primarily to simulate high severity crashes [19], and extended with postural stabilization for low severity conditions [20, 21]. The model includes active controllers to stabilize body segments, with feedback parameters specified for each body segment. These parameters manipulate the feedback gains of postural controllers. The head orientation can be controlled relative to a global coordinate reference system resulting in so called “head-in-space” control or alternatively relative to a local segment such as the

trunk resulting in “head-on-trunk” control. In this paper a head-on-trunk control strategy was used to control the head. Recorded motion was applied to the seat and floor which interact with the body through contact with feet, seat, and seat back. The model interacted with seat cushion and floor using multibody contact surfaces and gravity was simulated. Details were provided in our previous study [22]. In the current study, finite elements were used to model the compliant seat back (Figure 1).

Scenarios

The model has been validated in two scenarios,

1) Vibration: Motion platform tests with wideband noise signals, separately testing 3 seat motion directions, on compliant seats [23].
2) Slalom: Dynamic vehicle tests with slalom manoeuvres [24].

The motion platform tests allowed validation in the frequency domain across a range of 0.15-12 Hz. The vehicle tests allowed validation with a dominant lateral frequency of 0.2 Hz. In both experiments 3D full body motion (translational and rotational) was recorded with an XSENS motion suit. From both experiments we selected eyes open conditions.

The slalom experiment was primarily designed to induce motion sickness. Subjects were driven with slaloms of 3.5 m amplitude at a frequency of 0.2 Hz leading to peak lateral accelerations of 4 m/s^2 [24, 25] while seated in the middle of the rear bench of a Toyota Prius. Motion was simulated by importing accelerations of the vehicle in lateral (Y) and fore-aft (X) as well as the Yaw angle of the vehicle in space.

The vibration experiment was designed to investigate the effect of sitting posture and backrest height [23]. In this paper we simulated the preferred posture with middle back rest height condition with 0.3 m/s^2 rms acceleration. The frequency domain transmission from platform to body segment (head, trunk, and pelvis) acceleration was determined using a Hanning window with 15 segments (i.e., a window size of 24 seconds) with 50 percent overlap [23].

Results

Slalom Validation

Using the recommended neck postural activation gain of 1.0, model outcomes were fairly similar to experimental translational and rotational responses for head, trunk, and pelvis (Figure 2). Head roll fitted the measured data perfectly, while trunk and pelvis roll were overestimated by the model. Head yaw seemed to follow the measured yaw with a short delay. The model was also simulated without leg control activation, reflecting absence of reflexive stabilization at the hips and knees. The model without leg activation showed extensive roll particularly for head and trunk and eventually fell over.

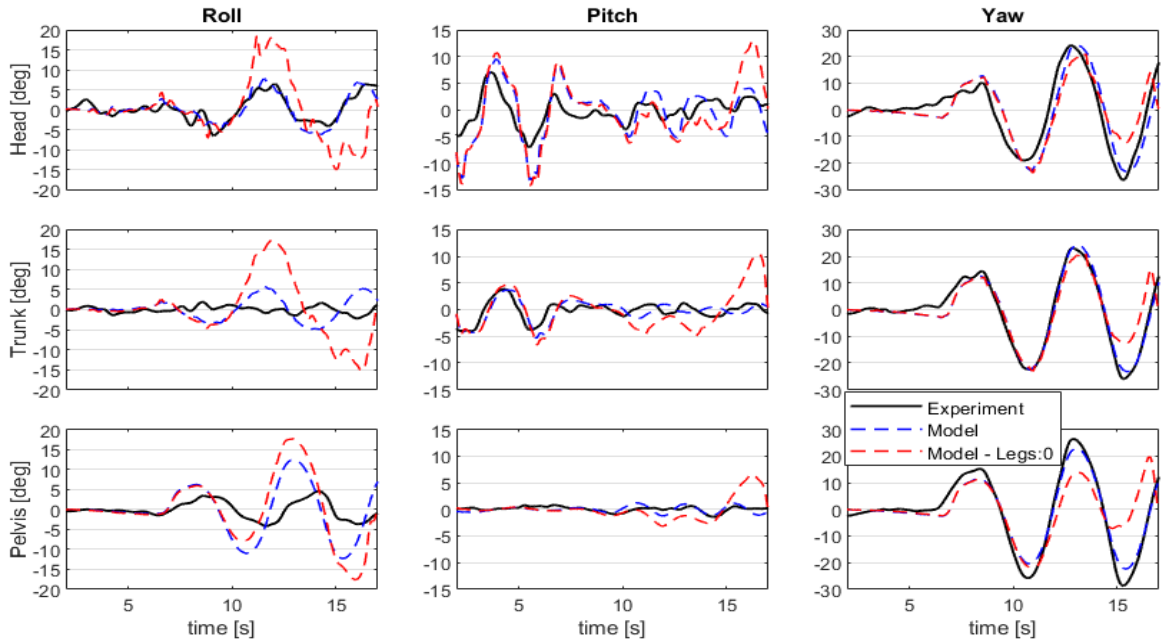

Figure 2 : Slalom. Model's prediction of head orientations (Blue Line for Model with legs activation set at 1, Red line leg activation set at zero) against the measured kinematics (Black line).

Vibration Validation

Frequency domain responses of body segments (head, trunk, and pelvis) were compared with the model for both translational and rotational body motion. A reduced neck activation gain of 0.2 was required to match the corridors of experimentally measured kinematics (Figure 3). Trunk responses to lateral perturbations from 2-4 Hz were underpredicted by the model. Rotational prediction of the model for head and pelvis closely matched the measured kinematics but trunk rotation was underestimated. Modelling without active leg controller strongly changed the vertical oscillations in all body segments, and slightly enlarged pelvis and trunk rotations during fore-aft and lateral perturbations.

Discussion

To our knowledge, this paper presents the first full body model validation for 3D head, trunk, and pelvis motion combining dynamic driving and vibrations in fore-aft, lateral, and vertical directions. Results showed that the slalom simulation (4 m/s^2 cornering) matched the measured data fairly well. The model also correctly predicted frequency domain responses with 0.3 m/s^2 perturbations.

Slalom simulations showed a good prediction of body segment rotations (Figure 2). Please note that body accelerations were also well predicted as presented in our previous work [22] for the first 45 seconds of the experiment, which includes one round of slalom, turn and part of the next round in the opposite direction. Trunk and pelvis yaw are well predicted, but the model's predicted head yaw is delayed compared to the measured head yaw. We attribute this delay to the fact that the subjects looked into the corner during the slalom.

In addition to the dynamic driving condition (slalom), the model responses to perturbations were tested in the frequency domain. Gain responses of body segments (head, trunk, and pelvis) well matched corridors of 3D measured motion. However, trunk rotational responses were underestimated by the model. Hence the spine of the model seems overly stiff. However we also found trunk rotations to be sensitive towards variations in the seat back model compliance and friction.

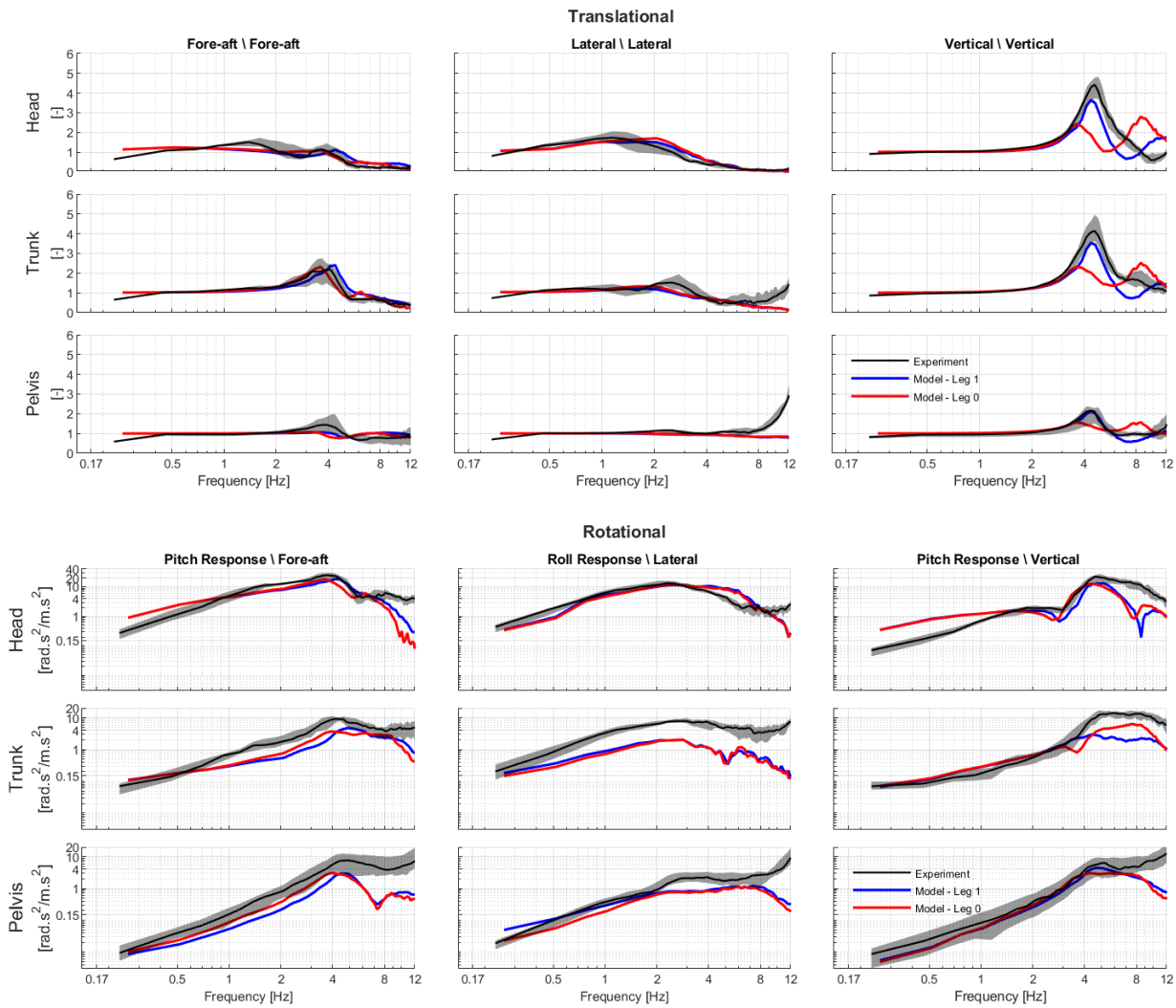

Figure 3 : Vibration. Model translational response (upper panel) and rotational response (lower panel) to platform perturbations in fore-aft (left), lateral (mid) and vertical (right) direction. Black lines represent the median of subject responses and dark shadows indicate 25th and 75th percentiles.

Modelling the slalom without active leg control resulted in excessive trunk and head roll (Figure 2) and the model eventually fell from the seat after two cycles of slalom. These results show the relevance of active leg control in lateral body stabilization in dynamic driving. However with low amplitude vibrations, active leg control hardly affected responses to fore-aft and lateral motion. This indicates the trunk to be mainly stabilized by the seat and the seat back in low amplitude loading. However vertical vibrations revealed a profound effect of leg control on 4-6 Hz oscillations. This may well relate to seat to upper leg interaction where leg control will stiffen the hips and thereby enlarge the contribution of seat to upper leg contact to vertical vibration transmission. We will further explore trunk stabilization including the role of the seat, seat back and active leg control in future studies.

The required neck activation control gain for a good fit with experimental data was much higher in the slalom (1.0) than the vibration scenario (0.2). It seems that postural stabilization is more active in intense dynamic manoeuvres. With advanced postural control models [18] we will further quantify the contribution of visual, vestibular and muscle spindle feedback in postural stabilization including adaptation to motion conditions.

There is room for improving the responses of head and trunk in the full body model. As a next step we aim to improve the model fit measuring and implementing seat characteristics. Further

experiments with advanced seats, while varying posture and perturbation type will refine seat modelling techniques and improve our understanding of postural stabilization of seated vehicle users.

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