
Article

Simulating 3D human postural stabilization in vibration and dynamic driving

Mojtaba Mirakhorlo¹, Nick Klufft^{1,2}, Raj Desai¹, Marko Cvetković¹, Tugrul Irmak¹, Barys Shyrokau¹, Riender Happee^{1,*}

¹ Delft University of Technology, the Netherlands

² Vrije Universiteit Amsterdam, the Netherlands

* Correspondence: r.happee@tudelft.nl

Featured Application: motion comfort of automated driving and other transportation modes

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. Dynamic driving is evaluated using a “sickening drive” including a 0.2 Hz 4 m/s² slalom. Vibration transmission is evaluated with compliant automotive seats, applying 3D platform motion and evaluating 3D translation and rotation of pelvis, trunk and head. The model matches human motion in dynamic driving and reproduces fore-aft, lateral and vertical 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 minimize trunk and 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, Modelling

1. Introduction

Automated vehicles 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 [1]. The postural response of the human body to vehicle motion is of great value for studying human motion comfort. Deeper knowledge of postural stabilization and its relationship with motion comfort is particularly relevant for motion planning and active suspension control. Future (automated) vehicles shall accommodate these new requirements into the design of seats and interiors. Biomechanical modelling of the human body can reveal underlying mechanisms such as postural stabilization and models predicting human movements and comfort can support vehicle design.

Biomechanical models with various 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 [2-4]. Three-dimensional multibody models represent the human body with multiple segments [5-7] whereas finite element models capture soft tissue and seat deformation in more detail [8, 9]. Due to computational efficiency, multibody models are more common to investigate effects of factors such as human weight, road class, and vehicle speed on human postural response in different motion directions [7]. Previous comfort oriented full body models focused mostly on the vertical [10] and fore-aft [2] directions, 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 [10, 12, 13]. 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 [14]. The head control objectives are suggested to be partly conflicting as head motion can be controlled relative to trunk or space 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 [15, 16]. 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, lumbar and neck stabilization.

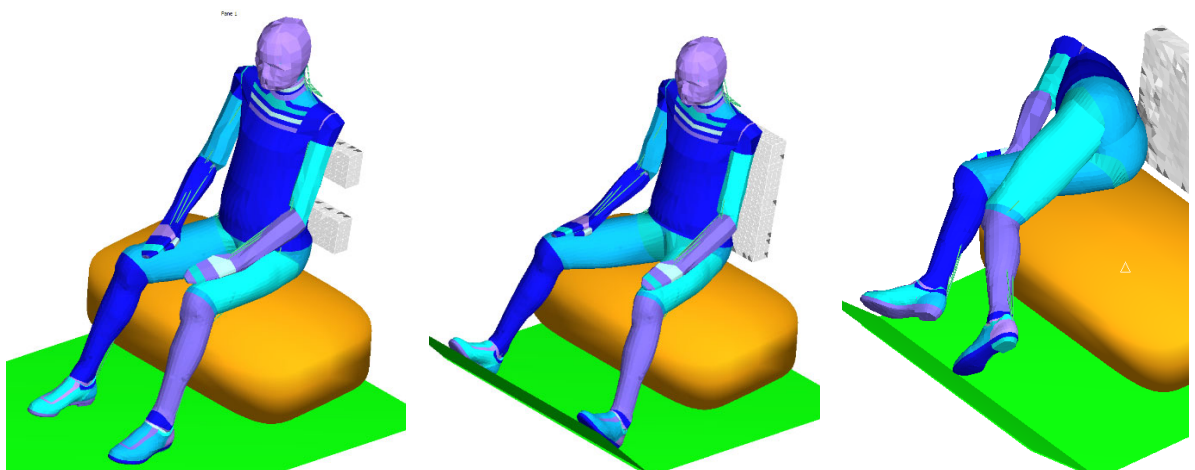


Figure 1 : Human model in vibration test on experimental seat with configurable backrest with 2 foam blocks modelled using finite elements (left) and on the rear bench of a Prius vehicle in the slalom test (mid) and falling without leg control in the slalom (right).

2. Materials and Methods

2.1. Human Model

The human active model (version 3.3), as distributed with MADYMO 2022, was adopted using Matlab and Simulink for running simulations and post processing. The model was developed and validated primarily to simulate high severity crashes [17], and extended with postural stabilization for low severity conditions [18, 19]. It represents a mid-size male adult of 75 kg, 1.76 m standing height, and 0.92 m erect sitting height. The model includes active controllers to stabilize body segments, with adjustable 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 founded on visual and vestibular motion perception or alternatively relative to a local segment such as the trunk resulting in “head-on-trunk” control associated with muscle spindle feedback. Feedback can also be selected to be relative to another body such as the vehicle, representing head orientation in vehicle control. The suitability of these alternative control strategies to capture head postural control is described in the results and discussion section.

Recorded vehicle or seat motion was applied to the seat and floor which interact with the body through contact with feet, seat cushion, 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 [20]. In the current study, finite elements were used to model the compliant seat back (Figure 1).

2.2. Scenarios

The model has been validated in two scenarios, being

1. Slalom: Vehicle tests with slalom manoeuvres [1].
2. Vibration: Motion platform tests with wideband noise signals, separately testing 3 seat translational motion directions on compliant seats [21].

In both experiments human 3D full body motion (translational and rotational) was recorded with an XSENS motion suit. From both experiments we selected eyes open conditions with visual perception of the vehicle interior and the world in the slalom (windows not blocked) and the vehicle interior and the lab in the vibration tests.

The slalom experiment was primarily designed to induce motion sickness. Subjects were driven with slaloms of 3.5 m amplitude at a frequency around 0.2 Hz leading to peak lateral accelerations of 4 m/s² while seated in the middle of the rear bench of a Toyota Prius [1]. 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 [21]. In this paper we simulated the erect posture with high back rest condition with 0.3 m/s² rms platform acceleration. Motion was simulated applying the measured platform 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 [21].

The postural control gains for neck, spine, and hips were optimized fitting the experimental data whereas arm and knee control parameters were adapted accordingly. Control gains were separately fitted for the slalom and for the fore-aft vibration. For lateral and vertical vibration we present results using parameters fitted for the fore-aft vibration.

3. Results

3.1. Slalom Validation

High postural feedback gains were needed to stabilize the trunk and to obtain realistic head motions in the slalom (Figure 2). Lower postural gains resulted in excessive trunk and head rotation and eventually the body simply rolled and fell (Figure 1 - right). Without active leg control the body rolled and fell even earlier. Hip and knee joint feedback

control helped to reduce pelvis roll and pitch, spine control reduced trunk rotation and neck control reduced head rotation. In addition to such a reactive postural stabilisation we implemented a constant hip and knee extension activity pushing the trunk into the seat back and pushing the thighs into the seat. This pushing activity reduced trunk pitch and strongly reduced trunk roll (Figure 2). The reduced trunk roll can be attributed to the effect of seat back friction being more effective due to pushing.

With high postural control gains and pushing legs, head roll fitted the measured data well, while trunk and pelvis roll were overestimated by the model. Head yaw followed the measured yaw with a short delay. As described in the introduction three head-neck control strategies were compared. As expected, head in space control yielded an unrealistic low yaw motion where the controller tried to minimise yaw while the vehicle was turning. Good results were found with head on trunk control (Figure 2) while very similar results were found with head in car control. Thus our current results cannot discriminate the realism of the latter two control strategies. Results for acceleration show a good fit with high postural gains (Figure 3) and are not very sensitive to postural control gains and leg pushing.

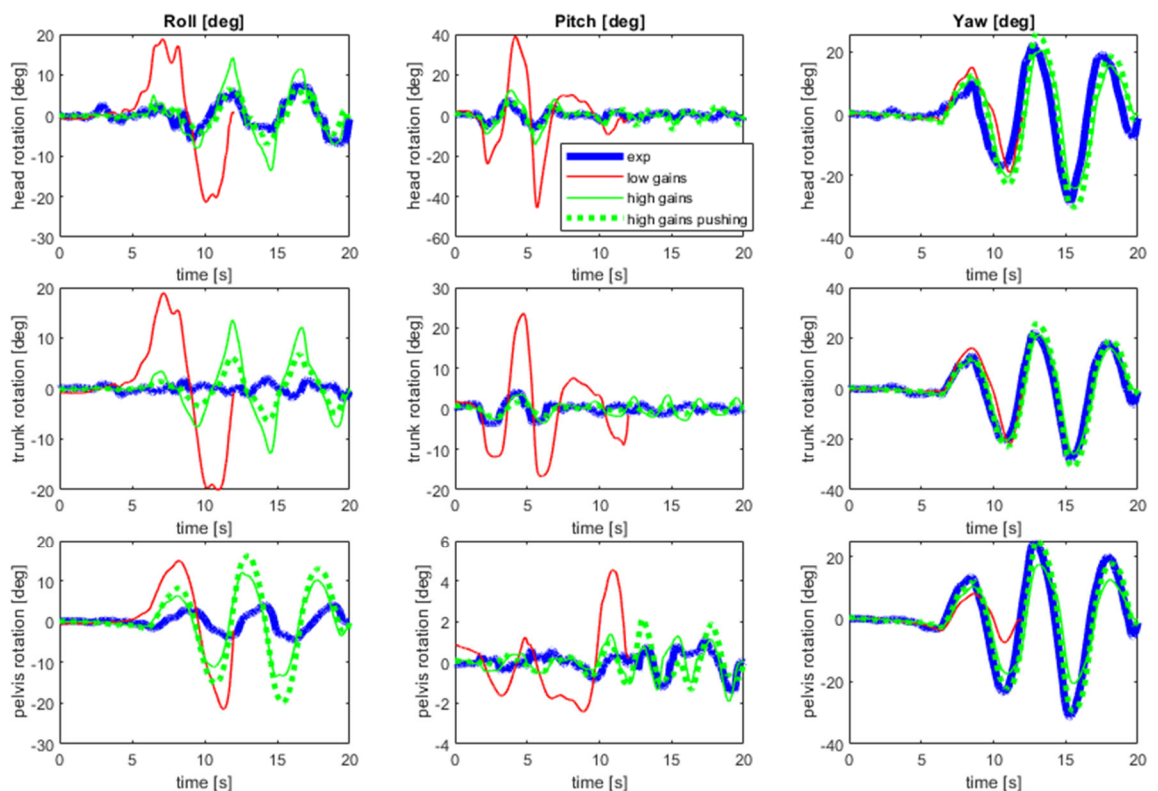


Figure 2 : Slalom validation for body **rotation**. Model prediction of head (upper), trunk (mid) and pelvis (lower) orientations. blue line: experimental; dotted green line: best model fit with high postural gains and with hips and knees pushing the body into the seat back; solid green line: high gains but not pushing; red line: lower postural gains fitted towards the vibration experiment.

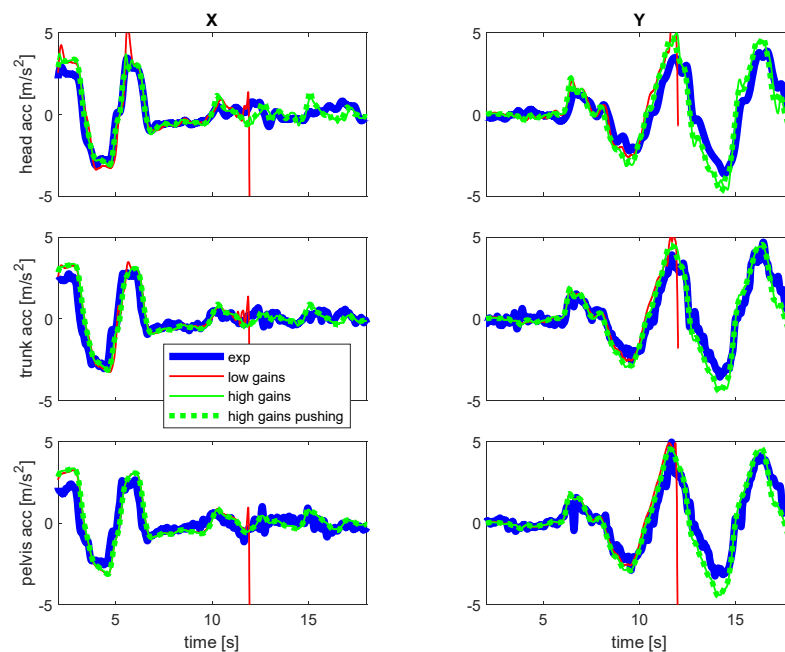


Figure 3 : Slalom validation for body **acceleration**. blue line: experimental; dotted green line: best model fit with high postural gains and with hips and knees pushing the body into the seat back; solid green line: high gains but not pushing; red line: lower postural gains fitted towards the vibration experiment.

3.2. Vibration Validation

Frequency domain responses of body segments (head, trunk, and pelvis) were validated for both translational and rotational body segment motion in fore-aft (Figure 4), lateral (Figure 5) and vertical (Figure 6) vibrations. Reduced neck and spine postural control gains were found to optimally predict head and trunk rotation. Hip and knee control gains were set at minimal levels such that they hardly affected the frequency domain results but prevented lateral drift of the knees. Arm control gains were set at zero level in line with the applied instruction to relax the arms with hands resting on the thighs.

The best fit parameters with low postural gains (green lines) provided a much better fit as compared to the high gains fitted towards the slalom data (red & red dotted lines). Translational responses closely matched the 5 Hz oscillation in vertical vibration in pelvis, trunk and head and matched the lateral response well for the head while underestimating trunk translation. In fore-aft vibration, the 4-5 Hz peak was well reproduced for the trunk but underestimated for the head. Rotational responses for head and trunk matched the measured kinematics but pelvis rotation was strongly underestimated.

The high postural control gains fitted towards the slalom provided unrealistic low rotations of head and trunk and increased the peak frequency and amplitude of vertical vibrations. This effect is even stronger with high postural control gains and legs pushing the body into the seat back and the thighs into the seat. This shows that while active leg stabilization is not essential to stabilize body roll and pitch with low motion amplitudes the legs can strongly affect vertical vibration transmission. Increasing the arm postural control gains from zero to 0.5 notably affected trunk acceleration and rotation in fore-aft and vertical vibration (not shown). This can be explained by the resulting stiffening of the shoulder complex coupling the arm inertia to the trunk.

These results were obtained using a head orientation in space control strategy, and were slightly more realistic as when using head on trunk control. As the seat and cabin were not rotating in space, the head in car control strategy would be equivalent to head in space, and was therefore not evaluated.

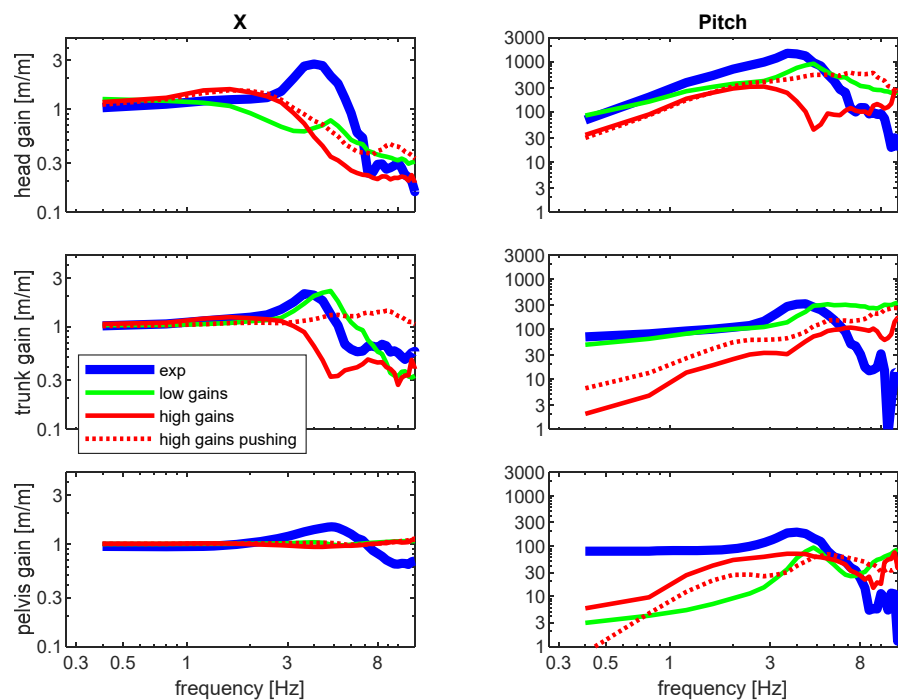


Figure 4 : Fore-aft vibration validation. Model prediction of head (upper), trunk (mid) and pelvis (lower) in translation (left) and pitch rotation (right). blue line: experimental; solid green line: best model with low postural gains; red dotted line: high gains fitted towards the slalom but not pushing; red solid line: high gains and with hips and knees pushing the body into the seat back.

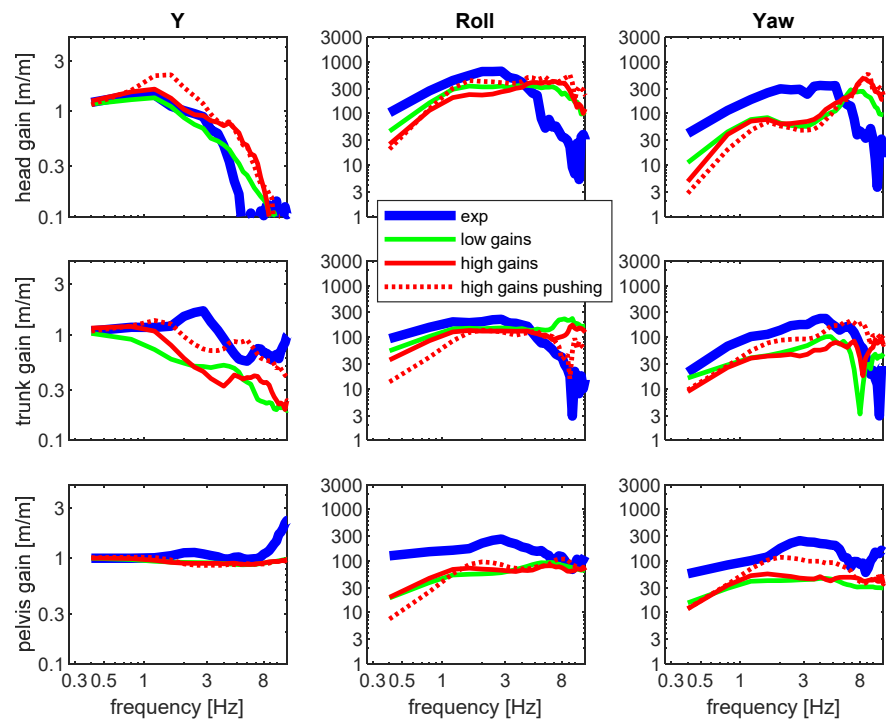


Figure 5 : Lateral vibration validation. Model prediction of head (upper), trunk (mid) and pelvis (lower) in translation (left) and roll & yaw rotation (mid & right). blue line: experimental; solid green line: best model with low postural gains; red dotted line: high gains fitted towards the slalom but not pushing; red solid line: high gains and with hips and knees pushing the body into the seat back.

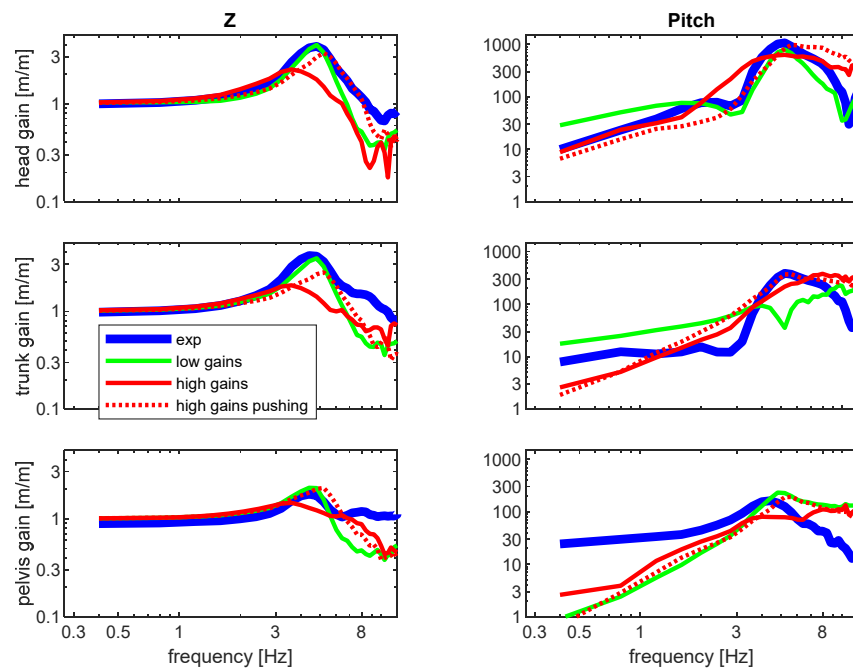


Figure 6 : Vertical vibration validation. Model prediction of head (upper), trunk (mid) and pelvis (lower) in vertical translation (left) and pitch rotation (right). blue line: experimental; solid green line: best model with low postural gains; red dotted line: high gains fitted towards the slalom but not pushing; red solid line: high gains and with hips and knees pushing the body into the seat back.

4. 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) and accelerations (Figure 3). 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 3D measured motion. However, pelvis rotational responses were underestimated by the model.

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 (Figure 1 - right). 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 strong effect of leg control on 4-6 Hz oscillations, when leg control gains were enlarged, and the effect of legs pushing into the seat was simulated. Leg control stiffens the hips and thereby enlarges the contribution of seat to thigh contact to vertical vibration transmission.

The required neck and spine control gains for a good fit with experimental data were much higher in the slalom as compared to the vibration scenario. 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 model responses in particular for the pelvis. 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.

Author Contributions: For research articles with several authors, a short paragraph specifying their individual contributions must be provided. The following statements should be used “Conceptualization, X.X. and Y.Y.; methodology, X.X.; software, X.X.; validation, X.X., Y.Y. and Z.Z.; formal analysis, X.X.; investigation, X.X.; resources, X.X.; data curation, X.X.; writing—original draft preparation, X.X.; writing—review and editing, X.X.; visualization, X.X.; supervision, X.X.; project administration, X.X.; funding acquisition, Y.Y. All authors have read and agreed to the published version of the manuscript.” Please turn to the [CRediT taxonomy](#) for the term explanation. Authorship must be limited to those who have contributed substantially to the work reported.

Funding: This research was funded by Toyota Motor Corporation.

References

- [1] T. Irmak, D. M. Pool, and R. Happee, “Objective and subjective responses to motion sickness: the group and the individual,” *Experimental Brain Research*, vol. 239, no. 2, pp. 515-531, 2021.
- [2] E. Kim, M. Fard, and K. Kato, “A seated human model for predicting the coupled human-seat transmissibility exposed to fore-aft whole-body vibration,” *Applied Ergonomics*, vol. 84, pp. 102929, 2020.
- [3] N. Nawayseh, and M. J. Griffin, “A model of the vertical apparent mass and the fore-and-aft cross-axis apparent mass of the human body during vertical whole-body vibration,” *Journal of Sound and Vibration*, vol. 319, no. 1-2, pp. 719-730, 2009.
- [4] Y. Cho, and Y.-S. Yoon, “Biomechanical model of human on seat with backrest for evaluating ride quality,” *International Journal of Industrial Ergonomics*, vol. 27, no. 5, pp. 331-345, 2001.
- [5] T. Teng, F. Chang, and C. Peng, “Analysis of human body response to vibration using multi-body dynamics method,” *Proceedings of the Institution of Mechanical Engineers, Part K: Journal of Multi-body Dynamics*, vol. 220, no. 3, pp. 191-202, 2006.
- [6] R. Desai, A. Guha, and P. Seshu, “Multibody biomechanical modelling of human body response to direct and cross axis vibration,” *Procedia computer science*, vol. 133, pp. 494-501, 2018.
- [7] N. Mohajer, H. Abdi, S. Nahavandi, and K. Nelson, “Directional and sectional ride comfort estimation using an integrated human biomechanical-seat foam model,” *Journal of Sound and Vibration*, vol. 403, pp. 38-58, 2017.
- [8] A. Siefert, S. Pankoke, and H.-P. Wölfel, “Virtual optimisation of car passenger seats: Simulation of static and dynamic effects on drivers’ seating comfort,” *International Journal of Industrial Ergonomics*, vol. 38, no. 5-6, pp. 410-424, 2008.
- [9] C. Y. Tang, W. Chan, and C. P. Tsui, “Finite element analysis of contact pressures between seat cushion and human buttock-thigh tissue,” *Engineering*, vol. 2, no. 09, pp. 720, 2010.
- [10] M. Verver, J. van Hoof, C. Oomens, N. Van De Wouw, and J. S. Wismans, “Estimation of spinal loading in vertical vibrations by numerical simulation,” *Clinical biomechanics*, vol. 18, no. 9, pp. 800-811, 2003.
- [11] J. Wu, and Y. Qiu, “Modelling of seated human body exposed to combined vertical, lateral and roll vibrations,” *Journal of Sound and Vibration*, pp. 115509, 2020.
- [12] M. Notomi, and J. Rasmussen, “Musculoskeletal computational analysis of the influence of car-seat design/adjustment on fatigue-induced driving.” 2011 Fourth International Conference on Modeling, Simulation and Applied Optimization, 2011, pp. 1-6, doi: 10.1109/ICMSAO.2011.5775600.

-
- [13] X. Wang, L. Savonnet, I. Theodorakos, G. Beurier, and S. Duprey, "Biomechanical human models for seating discomfort assessment," *DHM and Posturography*, pp. 643-656: Elsevier, 2019.
- [14] G. Bertolini, and D. Straumann, "Moving in a moving world: a review on vestibular motion sickness," *Frontiers in neurology*, vol. 7, pp. 14, 2016.
- [15] R. Happee, E. de Bruijn, P. A. Forbes, P. van Drunen, J. H. van Dieën, and F. C. T. van der Helm, "Neck postural stabilization, motion comfort, and impact simulation," *DHM and Posturography*, pp. 243-260: Elsevier, 2019.
- [16] R. Happee, E. de Bruijn, P. A. Forbes, and F. C. van der Helm, "Dynamic head-neck stabilization and modulation with perturbation bandwidth investigated using a multisegment neuromuscular model," *Journal of biomechanics*, vol. 58, pp. 203-211, 2017.
- [17] R. Happee, M. Hoofman, A. Van den Kroonenberg, P. Morsink, and J. Wismans, "A mathematical human body model for frontal and rearward seated automotive impact loading," *SAE transactions*, pp. 2720-2734, 1998.
- [18] R. Meijer, E. Van Hassel, J. Broos, H. Elrofai, L. Van Rooij, and P. Van Hooijdonk, "Development of a multi-body human model that predicts active and passive human behaviour." IRCOBI Conference 2012..
- [19] M. Meijer, J. Broos, H. Elrofai, E. de Bruijn, P. Forbes, and R. Happee, "Modelling of bracing in a multi-body active human model." IRCOBI Conference 2013.
- [20] M. Mirakhorlo, D. Tugrul Irmak, and R. Happee, "Simulating lateral postural stabilisation in dynamic cornering." in 8. VDI-Fachtagung Humanschwingungen Vibrations- und Schwingungseinwirkungen auf den Menschen. VDI: Würzburg, Germany
- [21] M. Mirakhorlo, N. Kluft, B. Shyrokau, and R. Happee, "Effects of seat back height and posture on 3D motion transmission to pelvis, trunk and head," *Under revision*.