

Digital Human Body Model for Occupant Monitoring System

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Abstract

Occupant monitoring systems have been developed and used for Autonomous Driving (AD) level 3+. These occupant monitoring systems have limitations in accuracy and measurement items. To compensate for this, a Digital Human Body Model (DHBM) based on the Modelica language is developed, and its features are introduced. Inverse Kinematics (IK) and Inverse Dynamics (ID) DHBMs are interlocked with the occupant monitoring system to increase measurement accuracy and calculate various information such as motion sickness and fatigue. However, simulation of occupant behavior prediction is impossible. Forward Dynamics (FD) DHBM is a model that implements the characteristics of the live human studied through experiments and can predict occupant behavior. However, parameter verification is necessary to trust the results of FD DHBM. It is developing real-time validation and parameter update algorithms for FD DHBM using occupant monitoring data, which are expected to be available in various fields such as comfort and safety.

Keywords: *Digital Human Body Model (DHBM), Occupant Monitoring, Autonomous Driving (AD), Active Safety System (ASS)*

1 Introduction

For autonomous driving level 3+, technology development and practical application of sensors, Advanced Driver-Assistance Systems (ADAS), and Active Safety Systems (ASS) are underway. ASS increases the pre-crash phase before impact and minimizes crash severity. Due to ASS, occupants have time to react, and physical characteristics such as sitting posture and muscle strength can affect their behavior. As a result, research on occupant behavior in driving and pre-crash phases has become necessary. Virtual simulation is needed to research various vehicle and occupant conditions effectively. However, Human Body Models such as the Global Human Body Model Consortium (GHBM) and Total Human Model for Safety (THUMS) for virtual simulation are specialized in crash simulation and injury prediction and validated for PostMortem Human Subjects (PMHS) -based in-crash (John J.

Combest 2018; Toyota Motor Corporation 2021). In addition, because it is an FE-based model, the CPU cost is high and difficult to simulate for the long term, making it unsuitable for long-term passenger behavior research.

The Occupant Model For Integrated Safety (OM4IS) consortium and several studies have conducted occupants' behavior studies based on volunteer experiments (Kirschibichler 2014; Huber 2015). OM4IS measured and analyzed occupant kinematics assuming the operation of the ASS. With the recent advances in posture detection technology, in-cabin occupant monitoring systems are installed in vehicles (e.g., Mobis DSM). In PC/mobile environments, machine learning-based human body monitoring systems (e.g., Google MediaPipe, Yolo v4) are being developed and are expected to be applied to actual vehicles in the future under Software Defined Vehicle (SDV) environments. Occupants' actual status and movement can be monitored and used for safety, comfort, etc. However, since the measured occupant movement is displacement-based data, the precision is relatively low, and it is impossible to predict the occupant behavior; a method to supplement this is necessary. Methods using mathematical filters (e.g., Kalman filters) can eliminate noise, but reflecting human characteristics and predicting behavior is still challenging. A Digital Human Body Model (DHBM) based on the Modelica language with low CPU cost and acausal characteristics was developed to supplement the occupant monitoring system.

Modelica language can build a multi-body system model and has acausal characteristics, which will be described later in Inverse Kinematics (IK), Inverse Dynamics (ID), and Forward dynamics (FD) models, which can be built based on a single basic model. It has the advantage of quickly conducting long-term simulations with low CPU costs. Moreover, since the Modelica language supports the Functional Mock-up Unit (FMU), it can conduct various simulations with other S/Ws that support the Functional Mock-up Interface (FMI). The control unit of the DHBM used the blocks module of Modelica (e.g., Continuous, nonlinear, table), and the human model part used the mechanic's modules such as multibody, rotational, and translational modules. It was conducted using Open-Modelica and ESI's SimulationX.

2 DHBM for Occupant Monitoring

In an environment where occupants are monitored, a DHBM for improving accuracy and calculating additional information has been created for more diverse use.

2.1 Base of DHBM

The basic DHBM consists of the pelvis as the root and is deployed to the end of each body (Head, Upper-, Lower-extremity). The body segments are set to rigid-body, and each segment contains body properties such as center of mass, mass, and inertia information. The body segments consist of the head, neck, trunk, upper arm (UA), forearm (FA), upper leg (UL), lower leg (LL), and foot. Depending on the occupant monitoring information or needs, the trunk shall be two (UT, LT) or three (UT, CT, LT). An articulated joint connects each segment, and each joint except the elbow (1D) is composed by connecting three 1D revolute joints in series. In the case of the lower extremity, the joints are fixed as necessary to prevent movement. Properties of body segments and joint positions are based on values corresponding to the GHBM AM 50th %tile or the subject's body dimensions. These values are fixed before the analysis begins.

2.2 Seat-Human Interaction & Seat Belt

In situations where lateral acceleration occurs, such as evasive lane change, seat cushions, and bags affect human body behavior. Conversely, in emergency braking situations, the effect of the seat back is eliminated, and the seat cushion and seat belt affect occupant movement. A seat-human interaction module and a seat belt module were developed to describe this.

For seat back-human interaction, contact force was calculated using an elastic-gap block. For seat cushion-human interaction, contact force was calculated using a foam characteristic table and kinematics between the cushion and lower body and applied to the lower body.

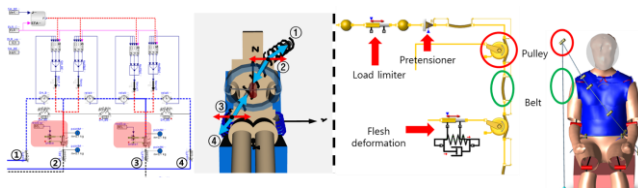


Figure 1. Seat belt model in Open-Modelica (left), and in SimulationX (right)

The seat belt was composed of three parts and four contact points, and the belt loosening amount was measured with a dummy spring, as shown in Figure 1. Based on this, the belt tension force was calculated, and the belt tension force was applied to the trunk. In the lateral direction of the belt, lateral friction force was applied to the DHBM using a sliding part. In SimulationX, seat belts were

implemented using a belt, belt preset, and pulley block, as shown in Figure 1.

2.3 Inverse Kinematics (IK) of DHBM

The occupant monitoring information used in this study is the 3D position of the main landmarks and joints of the human body and includes a certain level of error. If IK analysis is performed using each position as an input, the length of each segment is continuously changed due to errors included in the input. This conflicts with the segment length of the dummy set in a rigid body, making normal IK simulation impossible. To solve this problem, a spring-damper connects each input point and the corresponding point of the human model to function as a buffer. The angle of each joint can be calculated through the IK DHBM, and acceleration that is difficult to calculate mathematically other than displacement and angle, it is possible to calculate angular velocity. However, the active torque of each joint cannot be calculated through the IK DHBM.

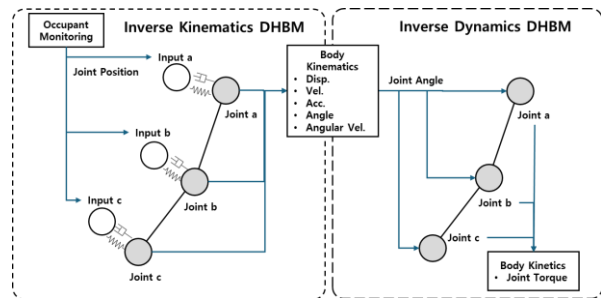


Figure 2. Conceptual Diagram of IK, ID DHBM

2.4 Inverse Dynamics (ID) of DHBM

To obtain the DHBM's kinetic information, an ID DHBM was constructed using the IK model's joint angle as the input. Each joint's kinetic information (joint torque) can be calculated using the acausal characteristics to satisfy the input kinematic (joint angle). This is the same as the occupant monitoring results. All kinematic and kinetic information can be obtained.

3 DHBM for Simulation

IK, ID DHBM can describe and analyze the behavior of passengers based on the measured (or under measurement) monitoring information, but it is impossible to predict the behavior of occupants. The FD DHBM, including the characteristics of a living human, can predict the occupant's behavior according to the vehicle's movement. Live humans exhibit different behaviors from the Anthropomorphic Test Device (ATD) or PMHS under the same external force conditions (Beeman 2012). This is due to the characteristics of live humans, and its typical characteristics include muscle contraction (co-contraction) and awareness (Kirschbichler 2014). Various

characteristics of the human body needed for calculating occupant behavior and their application are as follows:

3.1 Active Joint Torque

The live human generates muscle force through the contraction and relaxation of various muscles, which is applied as a torque to rotate the body segment. Among the methods of modeling muscle contraction in the human body, calculating muscle contraction and muscle force according to the activation level by modeling all muscles is also used. This requires an excessive amount of computation. To speed up computation, the concept of active joint torque (equivalent torque applied to each joint) was introduced without calculating the contraction force of each muscle. The active joint torque actuator was configured based on the PID closed-loop control, and the change in the joint angle (or body segment angle) compared to the reference was set as an error. And the torque to be applied to each joint was set as an output. Choi (2016) verified an active elbow model reflecting active joint torque and co-contraction.

3.2 Co-contraction

Beeman (2012) conducted low-speed sled tests on ATD, PMHS, and human volunteers. The volunteer showed behavior between the PMHS and the ATD and differences in behavior according to the co-contraction level. It showed more similar behavior to ATD in the braced condition (high level of co-contraction) than in the relaxed condition (low level of co-contraction). As the co-contraction level increases, the human joint stiff and behaves like a rigid body. It is applied to a human model by damping torque, and an example is shown in Figure 3.

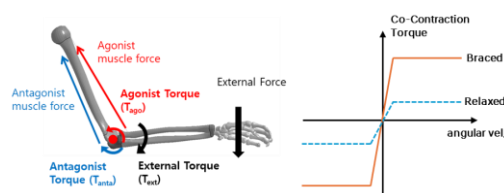


Figure 3. An overview of co-contraction (left), an example of co-contraction torque applied to the model (right)

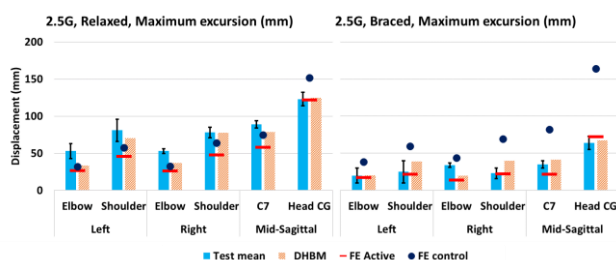


Figure 4. Validation result of low-speed sled test

A low-speed sled test confirmed DHBMs that reflect co-contraction (Beeman 2012). Compared to the results of the same validation of the GHBM FE active model

(Devane 2019), both relaxed and braced conditions showed high similarity except for the shoulder at the braced condition, as shown in Figure 4.

3.3 Awareness

OM4IS measures the behavior of passengers according to their awareness of evasive single-lane change and emergency braking situations assuming an autonomous driving situation. In the unaware condition (low level of awareness), in which passengers do not know the situation, they showed large behavior with a neural delay time longer than the informed condition (high level of awareness) in which all situations are known. The higher the awareness level, the shorter the neural delay time, so the torque is rapidly actuated, and the amount of excursion decreases. In the DHBM, awareness was reflected by not applying the active joint torque calculated during the neural delay time to the torque actuator (Han 2019).

3.4 Response Strategy

Vehicle occupants have two strategies: driver behavior and passenger behavior. In the case of the driver, to perform driving, the driver moves with a strategy of fixing the head position as much as possible and adjusting the gaze in the direction of progress. On the other hand, the passenger has a strategy of resisting the body more passively without considering the head position (Zikovitz 1999). For passengers, the same strategy as the driver can be taken, which can be viewed as a characteristic according to inter- and intra-subject variations. To reflect this, DHBM's PID control error used both the weighted joint and segment angles (Son 2023).

3.5 Forward Dynamics (FD) DHBM

The validation of critical parameters is necessary for the DHBM to describe occupants' behavior. The main parameters are PID gains, co-contraction, awareness level, and strategy ratio. The optimization technique can find parameters that show the same behavior as the subject test data. Using the OM4IS evasive lane change results, optimization targeting each subject's behavior and overall average behavior was conducted and reviewed (Han 2019). By applying floor input (or pelvis input) to the validated model and simulating it, the behavior of the human body according to a given vehicle movement can be predicted. Through this, it is possible to predict the occupants' behavior and use the result to optimize vehicle control. However, in the case of live humans, since inter- and intra-subject variations exist, the accuracy of the simulation may decrease as it deviates from the validation condition.

4 Use Case

IK DHBM can improve the accuracy of body kinematic information in occupant monitoring systems and calculate more information. For example, head translational acc., rotational vel. can be calculated, and motion sickness can

be calculated using models such as Motion Sickness Incidence (MSI).

ID DHBM is used to calculate kinetic information using occupant kinematic information. Active joint torques, the simulation results of ID DHBM, can be viewed as the energy needed to maintain posture. The regression equation obtained through the volunteer experiment can be converted into the Metabolic Equivalent of Task (MET) and kCal units, and the muscle fatigue of passengers caused by maintaining posture while driving can be checked.

FD DHBM uses vehicle movement to predict occupant kinematics and kinetics. Since occupant monitoring information is not needed, it is possible to simulate occupant behavior according to vehicle kinematics quickly. For example, it is possible to decide which ASS strategy is more dangerous to passengers under various conditions.

5 Conclusion

This paper introduces the types and characteristics of passenger monitoring systems and available Modelica language-based DHBMs. In addition, it presents the main characteristics of the human body found through ATD, PHMS, and live-human subject experiments and how to implement them in FD DHBM. The main characteristics of DHBM are as follows.

1. The main characteristics of the human body include active joint torque, co-contraction, awareness, and response strategy. These characteristics must be reflected in the human model to express the human body's behavior well in DHBM.
2. DHBMs using the Modelica language have a lower CPU time than FE models, can be simulated for a long time, and can be linked to the occupant monitoring system. It also supports FMU with FMI, enabling co-simulation with various programs.
3. The IK and ID HBMs enhance the accuracy of occupant monitoring information and calculate the kinematics and kinetics of occupants to enable quantitative evaluation, such as motion sickness and muscle fatigue. However, they have a disadvantage in using already measured (or being measured) information, and it is impossible to simulate behavior prediction.
4. FD HBM has the advantage of implementing co-contraction, awareness, and individual size, which are characteristics of the human body, so that occupant kinematics and kinetics can be calculated and predictive simulations can be performed. However, the validation of the model parameter is required, and the reliability of the FD HBM is

guaranteed only for the conditions under which the model parameter validation is performed.

The currently developed DHBM based on the Modelica language has the advantage of quantitatively analyzing and utilizing occupant behavior and is being reviewed for use in more diverse fields. To improve the limitations of the FD model, an algorithm for periodic validation and parameter updates is being developed using the IK model or occupant monitoring information. It is expected that this will increase the accuracy of predicting passenger behavior.

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