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Parametric Model for Simulating Occupant Responses During Pre-Crash Vehicle Maneuvers

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16. Abstract

The objective of the study was to develop and demonstrate an efficient tool to accurately predict occupant pre-crash kinematics in response to different types of vehicle pre-crash maneuvers. A literature review demonstrated that crash avoidance maneuvers can be divided into three categories: braking, steering, and a combination of braking and steering, with braking being the most common maneuver. An efficient and parametric active finite element (FE) human model for pre-crash maneuvers is not currently available. Previous subject testing showed consistently high variability of occupant responses in evasive maneuver events, which may be due to large variations in posture-maintenance tactics. An efficient active FE human model was then developed by simplifying the midsize male global human body model consortium (GHBMC) simplified model, i.e., GHBMC-M50-OS v1.8.4 (called GHBMCsi) and adding proportional-integral-derivative (PID) controllers to the joints to simulate active muscle effects. By adjusting the PID coefficients, the new-model can be used to account for a range of muscle activation levels and can match the large range of occupant kinematics in braking and turn-and-brake maneuvers. Twelve models were also generated by morphing the midsize male model into male and female occupants with a wide range of age, stature, and body shape. The morphed models have also shown the capability to cover the range of kinematics in pre-crash maneuver events based on subject testing results with given sets of occupant characteristics (i.e., age and body mass index). Finally, a mesh morphing tool was developed to use the result of a pre-crash occupant kinematics simulation to position the GHBMCsi for crash simulations.

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Introduction

The current design process for vehicle safety systems is strongly influenced by crash tests defined in Federal Motor Vehicle Safety Standards (FMVSS), the U.S. New Car Assessment Program (NCAP) administered by the National Highway Traffic Safety Administration, as well as the consumer information program conducted by the Insurance Institute for Highway Safety (IIHS). Most crash tests and restraint system optimizations are performed using anthropomorphic test devices (ATDs) that are "in-position," i.e., seated nominally, with only a few tests that evaluate protection for "out-of-position" scenarios. However, field data analyses have shown that approximately 40-50 percent of crashes are preceded by some sort of vehicle maneuver related to the crash event, such as braking or steering (Ejima et al., 2009; Stockman, 2016). Studies with volunteers have shown that pre-crash vehicle motions may cause occupants to move out of their initial positions, potentially into postures in which the occupant protection systems will be less effective in crashes.

Abrupt vehicle maneuvers prior to crashes may become more common as crash avoidance technologies become standard equipment on many vehicles in the coming decade. Automated emergency braking (AEB) for frontal crash avoidance is already available on many new vehicle models. Manufacturers and suppliers have also demonstrated systems that are capable of automated steering maneuvers to avoid crashes. Although these technologies are intended to avoid crashes or mitigate crash severity, unexpected abrupt vehicle motions may force vehicle occupants into a position that is very different from the seating positions defined in the vehicle crash tests. When the maneuvers are successful in avoiding the crash, occupants are likely to be unharmed. If a crash occurs despite the crash avoidance intervention, changes in occupant posture and position that result from the maneuvers may have a strong influence on the performance of the crash protection systems during a crash.

A few previous modeling studies (Adam & Untaroiu, 2011; Bose et al., 2010; Untaroiu & Adam, 2012) have demonstrated that occupant pre-crash posture has significant effects on occupant injury risks in frontal crashes. Hu et al. (2015a) used field data, naturalistic driving data and computational simulations to demonstrate that passive safety systems that can adapt to occupant pre-crash posture have the potential to further reduce occupant injury risks in frontal crashes. More recently, NHTSA sponsored a study to examine how alternative starting postures affected crash injury predictions obtained using ATDs. The Advanced Adaptive Restraints Systems program, sponsored by NHTSA, demonstrated the potential to improve occupant protection in pure-frontal and oblique-frontal crashes by tailoring the restraint system performance to the occupant's characteristics and position. In addition to nominal, in-position tests with small-female, midsize-male, and large-male ATDs, tests and simulations were conducted in three "out-of-position" conditions created by leaning the ATD forward, inboard, or outboard. In each case, the ATD head was shifted by about 100 to 150 mm from the nominal position by inclining the torso. Leaning generally increased the injury risk predicted from ATD responses, with inboard leaning in oblique conditions being particularly challenging for the restraint system.

Understanding the changes in occupant posture and position using computational models is a valuable step to enhance occupant protection. However, the motions of occupants in a pre-crash maneuver can be complex and may vary by occupant characteristics, such as age, sex, stature, and body weight. Pre-crash maneuvers may last several seconds at relatively low accelerations (compared with a small fraction of a second at high accelerations for a typical crash), and consequently muscle activations can have an important effect on occupant movements. Finite element (FE) human or ATD models are typically used to simulate occupant kinematics in crash events with durations of 50-150 ms. However, it is computationally intractable to use existing FE human models to simulate such long-duration events. Efficient models to predict occupant motions during pre-crash maneuvers and associated simulation methods are needed. Moreover, to ensure the accuracy of such models, validation needs to be conducted against volunteer testing on occupant responses during pre-crash maneuvers. Ideally, such testing data should provide occupant responses with different levels of muscle activations, under varied pre-crash maneuvers and with a large sample size to cover a diverse population with a wide range of size, shape, and age.

Research Objectives

The objective of this study was to develop and demonstrate an efficient tool to accurately predict occupant pre-crash kinematics in response to different types of vehicle pre-crash maneuvers. The results of pre-crash simulations can then be used to posture the midsize male GHBMCsi[1] FE model for subsequent crash simulations. The tool should include the effects of muscle activation and be adaptable to simulate occupants with a wide range of age, body size and shape. The following tasks have been performed:

- Task 1. Conduct a literature review to summarize: 1) existing/future crash avoidance maneuvers, 2) current/future methodologies of simulating occupant kinematics in crash avoidance maneuvers, and 3) current/future methodologies of data collection to characterize occupant kinematics under different crash avoidance maneuvers.
- Task 2. Develop and demonstrate an efficient tool to accurately predict occupant pre-crash kinematics in response to different types of vehicle pre-crash maneuvers. This tool should be adaptable to muscle activation for a range of occupant sizes and age.
- Task 3. Develop a tool that can position the GHBMCsi for crash simulations using the result of the pre-crash occupant kinematics simulation.

[1] An efficient active FE human model was developed by simplifying the midsize male global human body model consortium (GHBMC) simplified model, i.e., GHBMC-M50-OS v1.8.4 (called GHBMCsi) and adding proportional-integral-derivative (PID) controllers to the joints to simulate active muscle effects.

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Task 1: Literature Review

Literature Review on Crash Avoidance Maneuvers

The intended goals of this portion of the literature review were to identify (1) what types of crash avoidance maneuvers are observed, (2) the relative incidence of each type of maneuver, (3) the effectiveness of those maneuvers in preventing crashes, and (4) the range of vehicle kinematics (e.g., deceleration and rotation rate) during those maneuvers.

Previous Research

An early study by Adams (1994) reviewed 11 publications on driver strategies on crash avoidance maneuvers. Among the 11 studies, 5 of them used motor vehicle crash avoidance maneuvers data, two of them reported driving simulator results, and four of them were field testing studies with human volunteers. Adams's study found that although drivers' response to near-crash situations varied substantially from study to study, in general, braking is more likely than steering, but steering (steering alone or steering combined with braking) may be associated with higher crash avoidance rate than braking alone. Factors that may affect the choice of maneuver were also discussed in Adams's study, such as vehicle speed and reduction in reaction time.

Ejima et al. (2009) reported the rates of evasive maneuvers in different crash types based on data from the Institute for Traffic Research and Data Analysis in Japan (1993-2004). The results showed that around 50 percent of the drivers made evasive maneuvers in all frontal crash types; and among those drivers who conducted maneuvers, braking alone is the most common, followed by braking combined with steering, and steering alone. Interestingly, this study also reported that the chest injury rate was higher with evasive maneuvers, which justified the significance of developing and validating models for estimating occupant kinematics during crash avoidance maneuvers. Although it was not reported in Ejima's study, the authors also found that the injury rate for the head and face was lower with evasive maneuvers based on a personal communication with the first author.

Three consecutive studies conducted by Kaplan and Prato (2012a, b, c) presented attempted crash avoidance maneuvers and the relation of those maneuvers to the crash severity based on an analysis of NASS-GES crash data. Most drivers failed to act when facing critical events, and among the drivers who acted, the choice of crash avoidance maneuvers varied greatly depending on the nature of the critical pre-crash event. Interestingly, steering alone or steering combined with braking were associated with a higher crash severity, which is contrary to the conclusions from the earlier study by Adams (1994). Note that studies based on crash data may under-estimate the rate of crash avoidance maneuvers by overlooking the cases with successful crash prevention by evasive maneuvers. If certain types of maneuvers are more effective (say, steering alone versus braking alone), they will be underrepresented in these analyses of crash data. However, the current effort is focused on the situation in which a crash *does* occur, so the crash-based analyses are the most relevant.

Dozza (2013) analyzed naturalistic driving data from 100 cars. The most common crash avoidance maneuver was braking only (66%), followed by steering only (25%), and a combination of braking and steering (9%).

Using the data from National Motor Vehicle Crash Causation Survey (NMVCCS), Stockman (2016) reported that approximately 40 percent of the drivers made avoidance maneuvers prior to crash. The most common crash avoidance maneuvers was braking only (~45%), followed by a combination of braking and steering (~30%), and steering only (~20%).

Scanlon et al. (2015) conducted a study using the data from event data recorders (EDRs) available in the NASS-CDS database to investigate the frequency, timing, and kinematics of driver evasive maneuvers prior to intersection crashes. Drivers attempted crash avoidance maneuvers in four-fifths of intersection crashes, which is much higher than has been reported in other studies considering all crashes. Median evasive braking time was found to be 0.5 to 1.5 s prior to crash, and the median initial evasive steering time was found to occur 0.5 to 0.9 s prior to crash. The median evasive braking deceleration was 0.58 g, and the median of the maximum evasive vehicle yaw rates was 8.2 °/s. Using a similar method, the same group (Riexinger and Gabler, 2018) conducted a study on driver maneuvers in road departure crashes. In these crashes, steering was the most common evasive action, followed by braking. The average deceleration of the evasive braking was 0.41 g.

More recently, Powelleit and Vollrath (2019) conducted a driving simulator study with 131 subjects to a professional driver's choice of crash avoidance maneuver and the driver's response time. Several interesting findings were presented. The drivers' choices were influenced by scenario characteristics, such as braking distance and room for evasive steering. Braking was found to be more frequent with lower speed limits, while steering was more common at higher speed limits. Drivers' responses were faster in urban setting than in the rural or highway settings. Response times increased by 100 to 200 ms when responding to vehicle braking in front of the case vehicle when compared to obstacles.

Summary

Through the reviews of various types of studies (field crash data, naturalistic driving data, simulator data, survey data, etc.), the following were observed:

- The crash avoidance maneuvers are generally divided into three categories: braking, steering, and a combination of braking and steering.
- Almost all the reviewed studies found that braking is the most common crash avoidance maneuver, followed by steering with braking, and steering only. Although some early studies have estimated higher success rate of steering than braking in avoiding crashes, recent studies have shown that steering may also be associated with higher crash severity.
- Braking periods for crash avoidance maneuvers are generally less than 1.5 s, and the braking levels are between 0.4 and 0.6 g, consistent with other literature that shows that drivers routinely brake sub-optimally even in emergency situations. Current AEB systems are typically capable of braking at approximately 1 g, i.e., near the functional limit.

Modeling Methodologies to Estimate Occupant Kinematics in Crash Avoidance Maneuvers

Because human motions in response to abrupt vehicle motions are modulated by muscle activity, models of this behavior must consider the effects of muscle activation. In the literature, several modeling methodologies have been proposed for this purpose. These methods can be divided into two main categories: open-loop control, where muscle activation functions are defined prior to simulation, and closed-loop control, where muscle activities are regulated based on simulated sensory information feedback from the current state of the model, such as occupant posture and position. A literature review by Östh et al. (2015b) summarized a majority of the human models with active muscle control existing at that time. Therefore, in this section we only briefly mentioned the studies before 2015 and instead focus on newer studies and how previous methods are relevant to simulating whole-body occupant kinematics in pre-crash maneuvers in an efficient manner.

Previous Research

MADYMO (mathematical dynamic models) human models with active muscle control: MADYMO human models are typically multibody-based human models using rigid bodies linked by joints, springs, and dampers to simulate dynamic responses of the human body. Because of the multibody nature of MADYMO models, they are generally very efficient and suitable for simulating long-duration pre-crash maneuvers. A variety of active muscle control methodologies have been applied to MADYMO human models, such as 1D muscles with both open-loop and closed-loop controls (Meijer et al., 2013a; Meijer et al., 2013b; Meijer et al., 2008; Meijer et al., 2012), and torque actuators with closed-loop controls (Cappon et al., 2007). MADYMO active human models have also been applied to a wide range of dynamic conditions, including pre-crash braking (van Rooij, 2011), elbow flexion (Budziszewski et al., 2008), frontal, lateral, and rear impacts (Meijer et al., 2012), as well as rollover crashes (Cappon et al., 2007). However, this prior work has focused primarily on active muscle effects on occupant kinematics and injuries during crashes rather than motions induced by vehicle maneuvers.

FE human models with open-loop active muscle control: The early stage of FE human models with active muscle forces started at the component level with open-loop controls. Examples include studies on cervical spine (Brolin et al., 2005; Brolin et al., 2008; Chancey et al., 2003; Dibb et al., 2013) and lower extremities (Chang et al., 2008; Chang et al., 2009). In recent years whole-body FE active human models, such as an active total human model for safety (THUMS), known as THUMS version 5 (Iwamoto & Nakahira, 2015; Iwamoto et al., 2015), became available for simulating active muscle forces through open-loop controls. In all these studies, 1D Hill-type muscle elements were used to simulate both passive and active muscle forces. A muscle activation time-history profile can be used to control the activation of each muscle. Previous studies have used maximum muscle activation at a specified time in a simulation to represent the effect of reflexive muscle response (Brolin et al., 2005). By adding simultaneous activation of all muscles, it simulates a startle response to mechanical, acoustic, and/or visual stimulations. The open loop approach is suitable for simulating impact conditions with short duration, but not for longer duration, such as those presented in the pre-crash maneuvers. Another method to estimate muscle activation profile is through optimization of static posture-maintaining activities. For example, Chancey et al. (2003) developed an FE cervical spine model with detailed muscles and investigated the effects of active muscle forces on neck tensile loading. Both minimal and maximal active muscle forces were determined by optimizing the muscle forces to stabilize initial head-neck posture. These muscle activation profiles were used in several other studies (Bose & Crandall, 2008; Bose et al., 2010; Brolin et al., 2008). However, it is difficult to maintain posture stabilization through optimizations in open-loop control because certain posture errors are inevitably associated with the initial posture, which have to be allowed in the optimization process. For instance, Chancey et al. (2003) defined posture maintenance as less than 5° rotation or 10 mm translation of the head over 100 ms period. In contrast, the active THUMS model used an optimization process called reinforcement learning with tabulated muscle control functions to account for joint angles and velocities in dynamic events (Iwamoto and Nakahira, 2015; Iwamoto et al., 2012). This method improved the active muscle force prediction by considering human motor control with respect to stretch and rate of change of muscle lengths derived from joint angles and velocities. However, many time-consuming simulations are required to generate the dynamic activity tables.

FE human models with closed-loop active muscle control: Starting from 2012, several studies conducted by Chalmers University researchers at SAFER have used closed-loop muscle activation with FE human models. The SAFER active human model used THUMS version 3 as the baseline model but implemented multiple PID controllers to activate 1D Hill-type muscle elements using joint angles as the feedback. The controller model for an example using an arm FE model is illustrated in Figure 1. Thus far, the SAFER active human model has included closed-loop controls for the upper extremities (Östh et al., 2012b), cervical and lumbar spines (Östh et al., 2012a), and lower extremities (Östh et al., 2014). The model has been applied to elbow impulse load and posture maintenance, autonomous braking, and driver maximal emergency braking conditions.

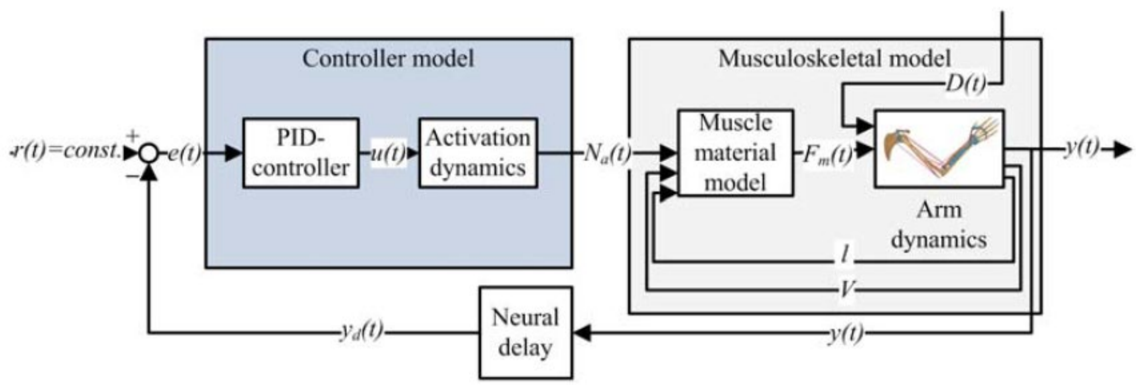


Figure 1. Illustration of the muscle controller model (Östh et al., 2012b)

Recent development of active FE human models: For the past 2 years, closed-loop proportional-integral-differential (PID) controllers have become the norm for active muscle control in FE human models. For example, the active ViVA OpenHBM (Kleinbach et al., 2018), representing a midsize female, was developed for whiplash injury prediction in rear-end vehicle crashes. In the active ViVA model, Hill-type muscle forces and joint torques are controlled by the PID controllers available in Ls-Dyna. This model has only been validated against a small set of rear impact test data, but is the first active FE human model representing an occupant other than the midsize male. Closed-loop PID controllers were also reported in THUMS version 6 models representing small female, midsize male, and large male occupants (Kato et al., 2018). Two PID controllers were used for each muscle so that the joint posture and muscle force could be controlled separately (Figure 2). This was the first time that active FE human models representing three sizes of occupants was reported. The THUMS version 6 models are highly complex and were developed mainly for predicting injuries in crashes. Thus, their simulation times may be very long for pre-crash maneuver simulations.

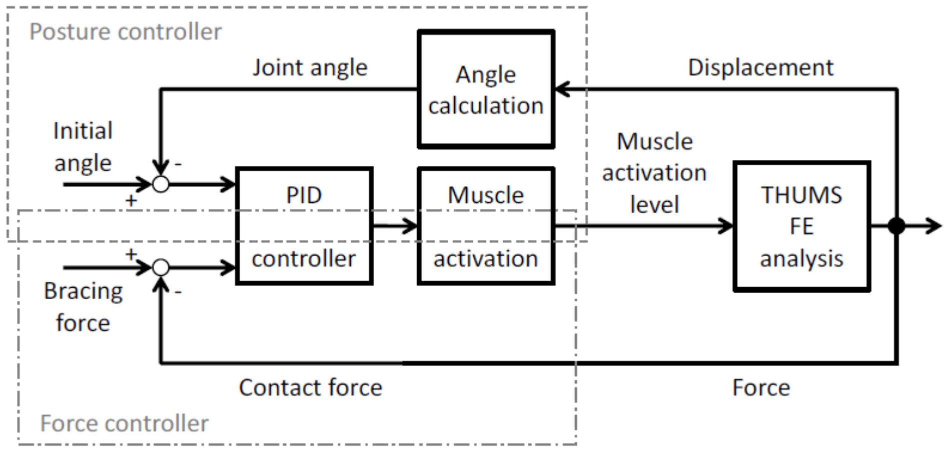


Figure 2. Muscle activation controller for THUMS version 6 (Kato et al., 2018)

Recent applications of active human models: In the past 2 years, an increasing number of studies have applied active human models for pre-crash simulations and integrated active and passive safety designs. For example, Satio et al. (2016) used the SAFER active human model to evaluate the pre-pretensioner effects on occupant protection with activation of AEB and followed by a frontal crash. Similarly, Östmann and Jakobsson (2016) also used the SAFER active human model to evaluate the occupant injury risks with variety of brake pulses and activation of an electrical reversible seatbelt retractor. Yamada et al. (2016) conducted simulations with the THUMS version 5 model to investigate the performance of an emergency locking retractor during crashes with and without AEB. More recently, Matsuda et al. (2018) conducted simulations of occupant posture changes due to evasive maneuvers. This is likely the first time that a combination of braking and steering event was simulated with an active FE human model. Another unique aspect of this study is that THUMS version 5 (a relatively efficient active human model) was used for pre-crash maneuver simulations, while the model-predicted posture changes were input into the THUMS version 4 (a more detailed model without active muscles) to simulate crash events. Using a more efficient model for pre-crash simulations significantly reduced the overall simulation time.

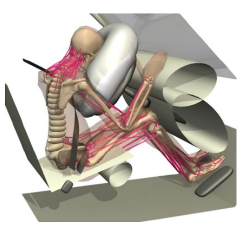
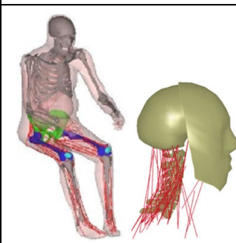
Limitations of the previous methods: A summary of previous modeling technologies related to pre-crash maneuvers is shown in Table 1. There are several limitations associated with each method.

1) **Efficiency:** In the past, FE active human models focused on predicting injury outcomes with muscle activation during crashes. Pre-crash maneuvers generally take a long time to run with FE human models. Although MADYMO models are efficient to simulate events with longer durations, the characteristics of the MAYDMO active human model are generally encrypted, which leaves very limited freedom for modification. Considering the pre-crash events are 10 to 15 times longer than the crash events, more efficient active FE human models are needed.
2) **Occupant characteristics:** Almost all previous active FE human models represent a midsize male. The recent development of ViVA and THUMS version 6 models extend the coverage of occupants with different sizes. However, age, body shape and other occupant variations were not considered in those models. Occupant pre-crash kinematics may vary significantly with respect to different occupant characteristics. Therefore, active

FE human models representing a diverse population are needed. The recent development of mesh morphing technology and parametric FE human modeling (Hwang et al., 2016b; Hwang et al., 2016a; Zhang et al., 2017a; Zhang et al., 2017b) will enable the development of active FE human models for a diverse population.

3) **Validation:** Due to relatively small amount of subject testing data available from studies of pre-crash maneuvers, validation of previous models was typically limited to frontal braking events or lateral steering/deceleration events.
4) **Linkage to GHBMC model:** A majority of the previous active FE human models used certain version of the THUMS model as the baseline model. Due to geometry differences between THUMS and GHBMC model, it would be difficult to use simulation results from those models to accurately re-position GHBMC for crash simulations. Since university researchers and industry engineers are increasingly using GHBMC models, it is apparent that a human model based on GHBMC geometry is needed.

Table 1. Summary of previous modeling technologies related to pre-crash maneuvers

Model	**MADYMO Active Human Model**	**THUMS Active Human Model**	**SAFER Active Human Model**	**Other Active Human Models**
References	(Cappon et al., 2007; Meijer et al., 2013a; Meijer et al., 2013b; Meijer et al., 2012; van Rooij, 2011; van Rooij et al., 2013)	(Iwamoto and Nakahira, 2014; Iwamoto et al., 2009; Iwamoto et al., 2012; Iwamoto et al., 2011; Kato et al., 2018; Sugiyama et al., 2007; Yamada et al., 2016)	(Östh et al., 2015a; Östh et al., 2012a; Östh et al., 2012b; Östh et al., 2014; Östh et al., 2013; Östmann and Jakobsson, 2016; Saito et al., 2016)	(Brolin et al., 2005; Brolin et al., 2008; Chancey et al., 2003; Chang et al., 2008; Chang et al., 2009; Dibb et al., 2013)
Figure				
Software	MADYMO	FE Ls-Dyna	FE Ls-Dyna	FE Ls-Dyna
Body Region	Whole-body	Whole-body	Whole-body	Cervical spine and lower extremities
Muscle Control	Open-loop & Closed-loop (PID)	Open-loop (ver. 5) Closed-loop (ver. 6)	Closed-loop (PID)	Open-loop
Efficiency	High	Low	Low	Low
Occupant	Mid-size male	Mid-size male Small female Large male	Mid-size male	Mid-size male
Pre-crash Simulations	AEB	Pedal braking, AEB Braking+steering	AEB	None

Summary

The previous studies support the following conclusions regarding active human modeling for estimating occupant kinematics during vehicle maneuvers.

Active muscle force control: Closed-loop PID control has become a standard method for simulating active muscle forces because PID controllers are readily available in Ls-Dyna, the FE software most commonly used for crash simulations with FE human models. Although new methods for active muscle control may be developed in the future, the current method for using PID controller in Ls-Dyna has been proved to be reliable and easy to use. Specifically, the SAFER and THUMS models have shown encouraging results with the PID controllers.

Efficient and parametric human models: Although the active FE human models have advanced significantly in the past few years, they are typically computationally expensive. Given the fact that the period of pre-crash vehicle maneuvers can be 15 times longer than a crash event, a much more efficient active FE human model is needed. Furthermore, current active FE human models do not represent occupants with a wide range of body size, shape, and age. Parametric active FE human models representing a diverse population are needed.

Model validation: Although existing active human models have undergone some sort of validation against subject testing in pre-crash maneuvers, they are limited in that they match only the mean responses of occupants in such events. Due to the small sample size of most previous subject testing, the human response variations cannot be properly accounted in the models. Moreover, the pre-crash maneuver conditions used for model validation are also limited primarily to braking events.

Linkage to GHBMC: The pre-crash maneuvers and the crash events are very different in terms of the duration and acceleration level. Therefore, instead of simulating together, it is intuitive to simulate those two types of events sequentially using two models with different levels of detail and focus. The relatively efficient-to-simulate THUMS version 5 model has been used for pre-crash simulations, and the predicted results were used to position the more detailed THUMS version 4 model for crash simulations. However, an active GHBMC model is not yet available.

Subject Testing to Characterize Occupant Kinematics Under Crash Avoidance Maneuvers

To support active human model development and application, the focus of previous subject testing in this area has been on the kinematics and muscle responses of human volunteers.

Previous Research

Several previous studies have gathered data on occupant responses to abrupt vehicle maneuvers. Morris and Cross (2005) conducted a test-track study to investigate the motions of 49 “unaware” front-seat passengers during hard braking, lane changes, and other maneuvers. The testing employed subterfuge and distraction to reduce the participants’ awareness of the purpose of the testing. Video was recorded of participants’ reactions to maneuvers that began with the participants in various prescribed starting postures. Quantitative analysis of motions was not provided, but the authors reported a strong influence of lower-extremity bracing availability based on pre-maneuver posture.

Ejima et al. (2009) examined muscle activity and associated kinematics in low-speed frontal impacts on a sled. Five young men were tested on a rigid seat with their hands on a steering wheel. Hault-Dubrulle (2011) conducted a driving simulator study to examine responses to an impending collision. The authors documented bracing behaviors prior to simulated crashes, with the occupants pushing against the steering wheel. These behaviors are not possible for passengers and may be unlikely for drivers using automated steering systems.

Bohmann et al. (2011) examined the responses of child passengers to vehicle maneuvers. The data demonstrated the strong influence of bracing with the feet on postural control. Schöneburg et al. (2011) summarized passenger response data from a midsize male volunteer in hard braking. The level of awareness of the occupant was not reported.

Carlsson and Davidsson (2011) examined the responses of 17 men and women to hard braking as drivers and passengers. All were aware of the purpose of the study and had optical targets applied to their heads and chests. Forward excursions for passengers were similar for both automated and driver-initiated braking. The locking of the seatbelt approximately 500 ms into the event appeared to be the primary factor limiting torso and head movement. Peak head excursions were larger for women than for men at the same stature, but the range of responses was more than 100 percent of the mean.

Östh et al. (2013) and Ólafsdóttir et al. (2013) reported a large study of occupant responses to automated braking events of approximately 1.1g for both drivers and passengers, respectively. The bracing behaviors reduced excursions for drivers, and a seatbelt equipped with a reversible pre-tensioner reduced excursions for both drivers and passengers. The study participants were aware of the purpose of the testing and were instrumented for motion tracking and electromyography. The 11 men and 9 women in the passenger trials were tested first in the driver seat. The data showed a large amount of variability in excursions due to braking. The range of peak head excursions was about 200 percent of the mean value.

Kirchbichler et al. (2014) measured front passenger motions in a range of braking and lane-change maneuvers with 51 men and 6 women. The vehicle was equipped with a passive optical motion capture system and participants wore a specially designed suit with markers. The first test series was conducted with a flat rigid seat and a lap belt only. The second series included a more realistic seat. Some trials are described as “unaware” in the sense that the participants were not explicitly warned that the maneuver was about to begin. However, the overall level of test preparation was high, so that the initial state of the participant may have been quite different from a typical vehicle passenger.

Huber et al. (2015) presented additional data from the Kirchbichler et al. test series, focusing on data from 19 men and 6 women in braking and lane-change-with-braking maneuvers. The data collection methods and limitations were the same as those presented by Kirchbichler the previous year. The data demonstrate a large amount of variability between people, such that the range ±1SD spans more than 50 percent of the mean forward excursion for hard braking events. For head angle change, 2 SD is greater than the mean change from the starting posture.

The UMTRI Study

In 2017 a research group at UMTRI conducted the largest study to date of occupant responses to abrupt vehicle maneuvers (Reed et al., 2018). The primary goals of the study were to (1) assess the differences in response between aware and unaware passengers by comparing the first exposure with subsequent exposures, and (2) gather data from a large, diverse sample that would enable the assessment of the effects of passenger characteristics on outcomes.

A total of 87 men and women with a wide range of body size and ages from 18 to 70 were recruited from the local community. Informed consent was obtained with a protocol that emphasized subjective assessment of vehicle ride, obfuscating the primary objective. Standard anthropometric data were obtained from each participant and whole-body 3D surface data was captured using UMTRI's VITUS laser scanner. In-vehicle testing was conducted at Mcity, a University of Michigan test facility adjacent to UMTRI. Participants sat in the right front passenger seat of a 2015 Toyota Avalon with the seat positioned full rearward and wore the safety belt in a prescribed, optimal position.

The vehicle had an inertial measurement unit to record vehicle accelerations and a novel motion-capture system developed at UMTRI that uses a single Microsoft Kinect version 2 sensor to obtain 3D motion data (Figure 3). The Kinect V2 uses a time-of-flight laser system to obtain a fast, accurate depth field that is converted via a calibration to a dense 3D point cloud. The calibrated system has head tracking accuracy comparable to optical motion capture systems but requires no markers on the subject or manual post-processing. A 3D scan of the participant's head obtained prior to testing is fit to the 3D data from the sensor to obtain position and orientation. Root-mean-square-error values relative to benchmark video tracking are between 1.5 and 3 mm depending on the distance to the sensor. UMTRI presented this methodology at the NHTSA biomechanics workshop (November 2017) and a paper on the calibration was presented at an SAE Congress in 2018.

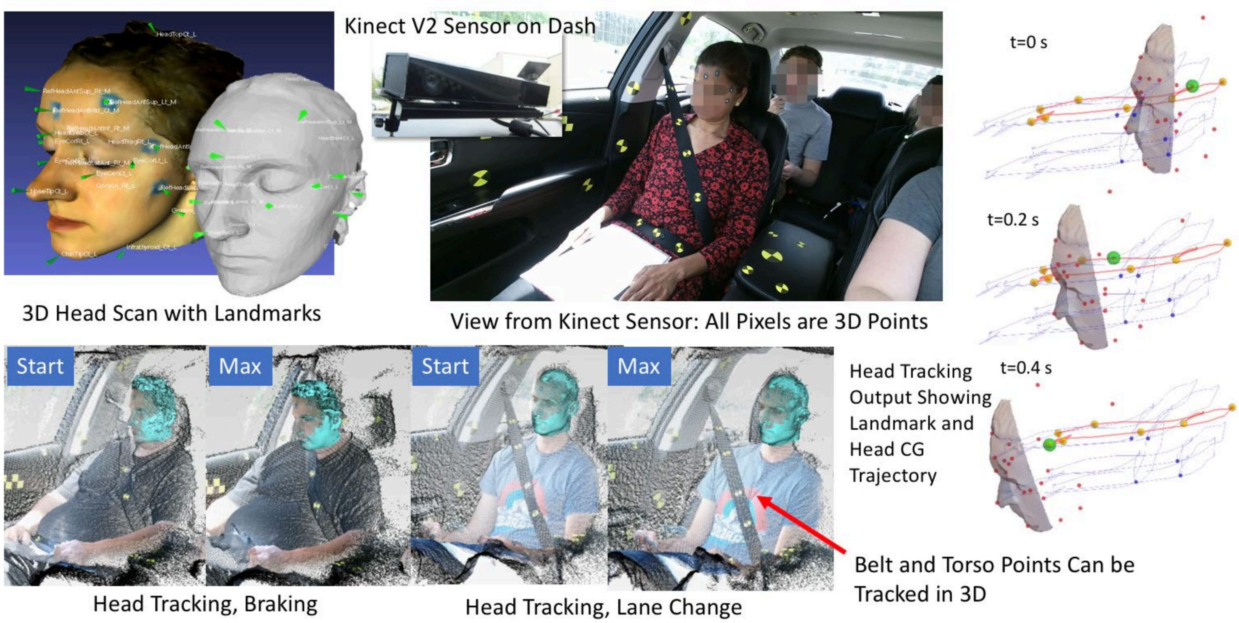


Figure 3. In-vehicle automated posture tracking using UMTRI's Kinect-based system

Prior to testing, a 3D head scan is obtained using a handheld scanner in about one minute. Landmarks are manually picked on the scan to enable estimation of head CG location. In the vehicle a software system uses the Kinect sensor to record 3D data and video at 30 Hz. Using an automated method the head scan was fit to the subject's dynamic data, obtaining an accurate 3D representation of head position and orientation over time. The 3D coordinates of any point in the scene over time can also be tracked, such as points on the belt or torso, relative to the subject or vehicle.

After several minutes on the course, during which time they answered oral and written questions concerning the vehicle ride and handling, the participants were subjected to a 1-g, maximal braking event from 35 mph. The ride continued for about 5 minutes, during which a rapid rightward lane change, a sharp right turn with braking to a stop, and a second linear hard braking event were conducted. Head excursion data from the four abrupt vehicle maneuvers were analyzed.

Consistent with previous studies with smaller samples, the variance in head excursions across subjects was a large percentage of the mean excursions. The mean (sd) of maximal head CG excursions in braking, lane-change, and turn-and-brake events were 160 (50) mm, 118 (40) mm, and 131 (35) mm, respectively. Forward head excursions in the first, "unaware" braking event were significantly larger than in the second, but the difference (18 mm) was small relative to the standard deviation across subjects.

Head excursions were found to be only moderately related to passenger attributes. Forward head excursion in braking was significantly related to age and body mass index ($p<0.01$), but these factors accounted for only about 20 percent of variance. Participant stature was significantly related to lateral excursion in the lane-change and turn-and-brake trials ($p<0.01$) but accounted for only about 5 percent of the variance. No other participant attributes were important predictors. Men and women did not exhibit different responses after accounting for body size.

The data were analyzed to develop statistical models of the participant kinematics. For example, Figure 4 shows kinematic corridors for forward head excursion in 1-g braking and lateral head excursion in a rightward lane-change. The individual subject curves show the large variability in subject response to vehicle motions that are very similar.

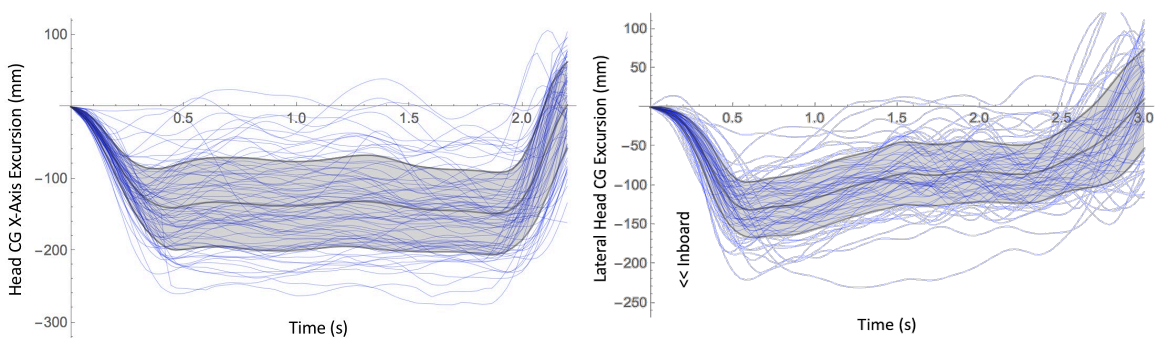


Figure 4. Corridors (mean±sd) for forward head excursion in 1-g braking (left) and lateral head excursion in turn-and-brake (right).

Individual trial data are shown in light lines.

The conclusions from this UMTRI study include:

1. Head motions in the vehicle maneuvers studied are largely under the control of the passengers; head motion relative to the torso and head angle changes are minimal.
2. The variance in head excursion is large. The range of fore-aft head CG excursions in braking, for example, extends from zero to 280 mm.

3. Kinematic responses in the conditions studied are only modestly related to passenger attributes, such as age and body mass index; instead, passenger behaviors largely determined the responses.
4. The initial, "unaware" braking trial produced significantly higher excursions, but the difference was less than half of the within-condition population standard deviation.
5. The console adjacent to the passenger provided support during lateral accelerations and probably reduced excursions.

A related study was conducted by Ohio State University, Children's Hospital of Philadelphia, and the University of Virginia. A test track study was conducted with 12 children and the same number of adults. Participants were seated in the rear seat of a sedan and subjected to a range of vehicle maneuvers. A marker-based optical motion capture system was used to track head and torso motions, and muscle activity was monitored using surface electromyography. The first results were published September 2018 at the IRCOBI conference. Graci et al. (2018) reported kinematics and EMG data for a constant-radius right turn sustained at approximately 0.5g lateral acceleration for 30 seconds. Data from 9 adults and 5 children age 9 to 12 were reported. During the initial, transient phase of the maneuver, children had smaller lateral head excursions than adults, even after simple scaling for sitting height. However, head excursions during the steady-state portion of the experiment were not significantly different between subject groups.

Holt et al. (2018) presented preliminary results from a lateral study of volunteer kinematics during exposure to lateral oscillations. Head and torso excursions from 19 adults were recorded using an optical motion capture system during a series of lateral oscillations peaking at approximately 0.7 g. Voluntary bracing and a motorized pre-tensioning seat belt reduced lateral excursions, but deployable seat bolsters did not. The greatest excursions were observed during the first cycle of the test apparatus.

UMTRI communicated with colleagues at Volvo who ran similar tests in 2016. They used optical methods to measure passenger responses to a range of vehicle maneuvers on a test track, using a vehicle driven by a robot. Twenty-five adults participated as drivers and passengers. Muscle activity was recorded at 19 anatomical locations. The effects of a motorized pre-tensioner were quantified, as was the case in the earlier work by both Östh et al. and Ólafsdottír et al., which included some of the same collaborators from Sweden. These data are being used for the tuning and validation of the SAFER active human body model (Östmann & Jakobsson, 2016).

Ghaffari et al. (2018) presented the first findings from this effort, focusing on male passenger kinematics in lane-change maneuvers with and without braking. Head and torso excursions were measured for nine men using an optical camera system. Lateral and fore-aft excursions were like those observed in previous studies with similar lane-change or braking exposures (e.g., Ólafsdóttir et al. 2013, Reed et al. 2018), and similar standard deviations were observed. As in the previous work, the motorized seat belt reduced excursions significantly.

Summary

The previous studies support the following observations and conclusions concerning occupant kinematics during abrupt vehicle maneuvers.

Responses are highly variable: All previous studies have shown that the standard deviation of head excursion in braking or lane change events is at least 50 percent of the mean value.

Responses are volitional: One contributor to the relatively high variability is that the responses are due to posture-maintenance tactics adopted by the individual, and these can vary widely. For example, in the UMTRI study, many participants looked up from the questionnaire taped to their thighs when the braking event began and then looked back down. The inertial forces producing the excursions are relatively small, well within typical activities of daily living. The ~1 g acceleration on the head during abrupt braking, for example, is like the neck force encountered when a person bends over from the waist.

Pre-tensioning (motorized) seat belts reduce excursions: Several in-vehicle studies and at least one lab study have shown that removing slack and pre-tensioning the seat belt tends to reduce excursions. However, considerable variance in responses remains. This finding is consistent with the observation that most passengers tend to "ride" the locked belt during braking, with the torso substantially engaged by the belt. With less belt slack, the torso and head excursions are reduced.

Summary Based on the Literature Review

We conducted literature reviews on (1) crash avoidance maneuvers, (2) modeling methodologies to estimate occupant kinematics in crash avoidance maneuvers, and (3) subject testing methodologies to characterize occupant kinematics under crash avoidance maneuvers. Crash avoidance maneuvers are generally divided into three categories: braking, steering, and a combination of braking and steering, with braking being the most common maneuver in the field. The ranges of braking period and level were also found to be consistent to a majority of the subject testing conditions. Through the modeling review we found significant progress in developing and validating active FE human models for estimating occupant pre-crash responses due to evasive maneuvers has been published in the recent years, but an efficient, parametric, and/or GHBMC-based active human model is not currently available. The subject testing review showed consistently high variability of occupant responses in evasive maneuver events, which may be due to large variations in posture-maintenance tactics adopted by the individual. The potential muscle forces are high compared with the inertial effects, so the occupant can control their responses easily in the maneuver events. More subject tests are needed to further investigate the occupant kinematics with a wider range of initial conditions and vehicle motions.

Task 2: Active Human Model Development and Validation

Process Overview

Figure 5 shows the overall process for developing and validating the active human model to predict occupant kinematics during pre-crash vehicle maneuvers. The model development process involved three steps. First, the GHBMCsi model was simplified to increase computational efficiency, and the resultant model was called GHBMCsi-pre. Second, closed-loop muscle activation controls through PID controllers were included into the GHBMCsi-pre model. Last, the active GHBMCsi-pre model was parameterized through mesh morphing methods previously developed at UMTRI to account for occupant size, shape, and age variations.

The model validation process also involved three steps. First, pre-crash maneuver simulations were run with the GHMBCsi and GHBMCsi-pre models without muscle activation. The models were tuned so that the responses were just above the upper bounds of volunteer excursions. This established the baseline settings for the GHBMCsi-pre model. Second, PID controllers for muscle activation were applied to the GHBMCsi-pre model so that it could match the full range of subject testing results with midsize males. Third, an entire set of morphed GHBMCsi-pre models were tuned to match pre-crash kinematics for a wide range of subjects of different sizes, shapes, and ages.

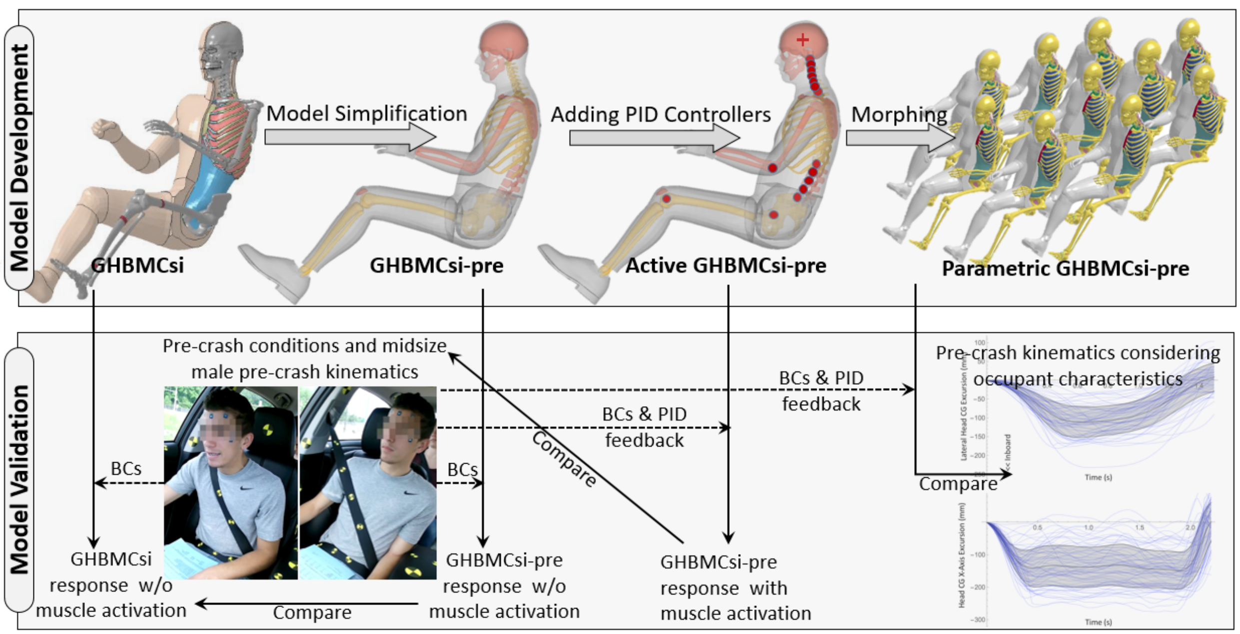


Figure 5. Overall process for developing and validating the active GHBMCsi-pre models

Because the GHBMCsi-pre model is a highly simplified version from GHBMCsi, we first compared the responses of GHBMCsi model in the pre-crash maneuver conditions to those from subject testing. Then the GHBMCsi-pre model was tuned to be over the upper bound of the occupant kinematics corridor to represent a subject without muscle activation. The main kinematic target was occupant maximal head excursion, and the parameters that were controlled in this process are the scaling factors of joint stiffness in the GHBMCsi-pre model and contact characteristics between the human model and the seatbelt. Since both GHBMCsi and GHBMCsi-pre models were used in the same conditions, the computational times needed for each simulation can be compared to ensure the efficiency of the GHBMCsi-pre model.

After the passive response of the GHBMCsi-pre model was tuned, the GHBMCsi-pre model with PID controls representing muscle activation was run in the braking and turn-and-brake conditions. Based on the subject-testing data, a midsize male responses corridor was developed to be matched by the active GHBMCsi-pre model. Once the active GHBMCsi-pre model was validated, parametric GHBMCsi-pre models representing occupants with a wide range of age, size, and shape were developed and tuned to match the subject testing corridors considering the age, size, and shape effects.

CORrelation and analysis (CORA) was used to quantitatively evaluate the quality of model validation. CORA scores were calculated for the head excursion time histories between the tests and some of the simulations. A CORA score of 1.0 represents a perfect match between the test and simulation, while CORA score of 0.0 represents no correlation between the test and simulation results. More details about model evaluation can be found in previous UMTRI work (Hu et al., 2015b). Based on our experience, the CORA score may be affected by the shape and number of peaks in the response curves, but an average CORA score higher than 0.7 can generally be considered as good.

GHBMCsi-Pre Without Active Muscles

GHBMCsi Model Simplification

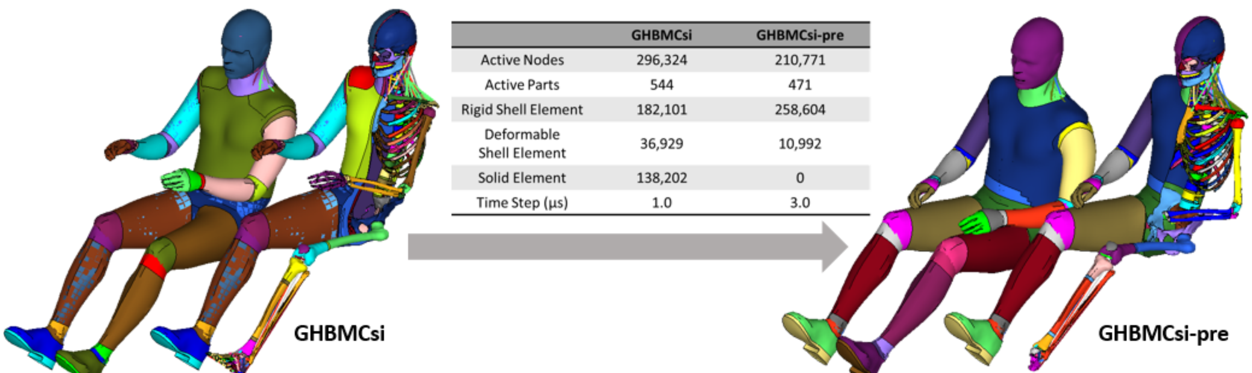
One of the limitations of current active FE human models is that they have primarily been developed to study the effects of muscle activation on occupant injury outcomes during the crash rather than pre-crash kinematics. As a result, the active FE human models are typically too expensive computationally to simulate longer duration pre-crash maneuvers. The better option lies in a more simplified FE human model that shares the same geometry and joint configuration as the GHBMCsi. Therefore, in this study, we built an active human model by further simplifying the GHBMCsi model; the resulted model is called GHBMCsi-pre, which stands for GHBMCsi pre-crash model.

Because injury assessment is not the focus for pre-crash simulations, we simplified the GHBMCsi model into a multi-body-based model with rigid bodies and joints, but with the same major bone and external body surface geometry as the GHBMCsi. By doing so, the GHBMCsi-pre will run faster and the results can also be directly applied to reposition the GHBMCsi for crash simulations. Modifications of the GHBMCsi model included the following.

- Removed all the soft tissue solid elements (e.g., internal organs, muscles, and flesh components)
- Changed ribs to rigid and removed all the solid bone elements
- Removed all the elements representing bones in hands and feet and rigidized surface elements of the hands and feet
- Rigidized external body surface mesh in the head, arms, and legs by attaching them onto the corresponding bone parts
- Re-structured the external body surface mesh in the neck and torso to link them to corresponding skeleton structures

- Assigned proper mass and inertia to rigid parts to maintain the weight distribution of the human body
- Adjusted joint stiffness to simulate a person with minimal/limited active muscle, i.e., the upper bound of the kinematics corridor based on the subject testing

As shown in Figure 6, with the above changes, the number of deformable elements was reduced by 90 percent, the time step was increased by 2 times, and the total computational time for simulations was reduced by about 80 percent from the GHBMCsi model. The resulted GHBMCsi-pre model is still an FE human model that runs in Ls-Dyna (LSTC). However, it only has rigid shell elements, 1D muscle/beam elements, joints, springs, and dampers. The benefit of developing GHBMCsi-pre model is that it kept the same joint configuration and skeleton/body geometry of the GHBMCsi, but it is more computationally efficient than the original GHBMCsi. In particular, the CPU time needed to run a pre-crash maneuver simulation using the GHBMCsi-pre model is less than 20 percent of the time needed to run the GHBMCsi model under the same condition.



	GHBMCsi	GHBMCsi-pre
Active Nodes	296,324	210,771
Active Parts	544	471
Rigid Shell Element	182,101	258,604
Deformable Shell Element	36,929	10,992
Solid Element	138,202	0
Time Step (μs)	1.0	3.0

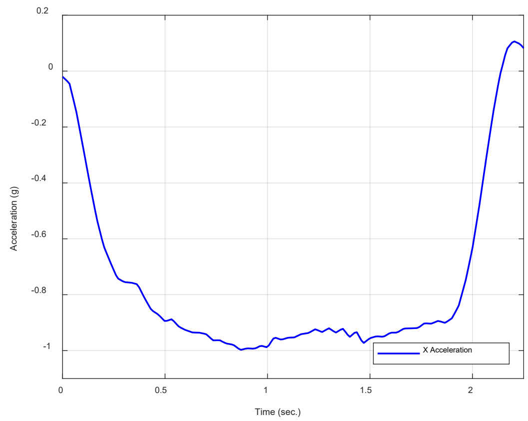
Figure 6. Simplification from GHBMCsi to GHBMCsi-pre

Simulation Setup in Braking and Turn-and-Brake Events

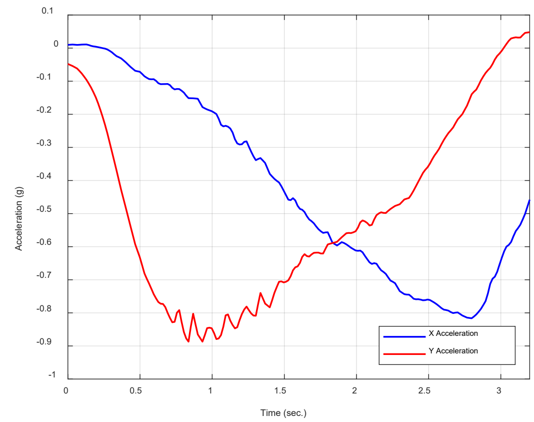
In this study, we chose two pre-crash maneuver conditions, abrupt braking, and turn-and-brake events, for model validation. These two conditions were chosen for two reasons. First, these are the two testing conditions used in the UMTRI subject-testing, which had the largest sample size in the literature regarding pre-crash maneuver induced occupant motion. In those tests, the vehicle 3D motion histories, seatbelt location, and vehicle interior geometry have been well quantified, which can be directly used to define boundary conditions in simulations. Second, these two conditions include the most widely used crash avoidance maneuvers and cover both frontal and lateral motions of the vehicle. As majority of the previous active human modeling studies only focused on braking conditions, the addition of turn-and-brake condition can extend the capability of active human models. Figure 7 a) and b) show the average deceleration profiles in the abrupt braking and turn-and-brake tests conducted at UMTRI. The vehicle kinematics are very consistent in the tests, in which 1 g deceleration was reached in the braking test and the lateral g-level in turn-and-brake test is around 0.9 g. The X (forward) and Y (inboard) decelerations in the abrupt braking and turn-and-brake tests were applied to the model to estimate occupant pre-crash kinematics. At the same time, a 1-g gravity was applied to the human body as well.

In this study, a simplified controlled-response seat FE model as shown in Figure 7c) was used to represent the Toyota Avalon seat that was used in the subject testing. This semi-rigid seat was based on the seat designed to mimic the behavior of real seats by (Uriot et al., 2015). This seat has a seat pan plate that rotates and is controlled by two sets of springs that results in a two-slope angular stiffness. A second anti-submarining plate is controlled by two springs for a single slope angular stiffness. The stiffness values of the springs were chosen to represent the behavior of a previously physically tested OEM seat. The seat stiffness is modelled as torsion springs with the front seat moment/rotation relationships reported in (Uriot et al., 2015). In this study, the anti-submarining plate was aligned at the same angle as the seat pan to allow occupant lower extremity forward motion in abrupt braking events, while slight lateral curvature was also added into the seat pan to better simulate the occupant lateral motions in the turn-and-braking events.

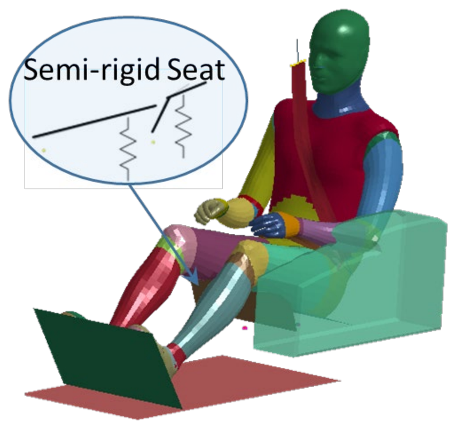
A generic seatbelt model with a shoulder retractor was used for all the simulations with anchorage locations set up to match the test data. One of the challenges of occupant pre-crash simulations is to accurately simulate the seatbelt webbing payout before retractor locking. We conducted video analysis to estimate the actual range of webbing payout in some of the UMTRI subject testing and found that the range of retractor webbing spool-out before locking is from 20 to 40 mm (as shown in Figure 7d). As a result, in this study we set the retractor webbing spool-out as 30 mm in the seatbelt retractor model.



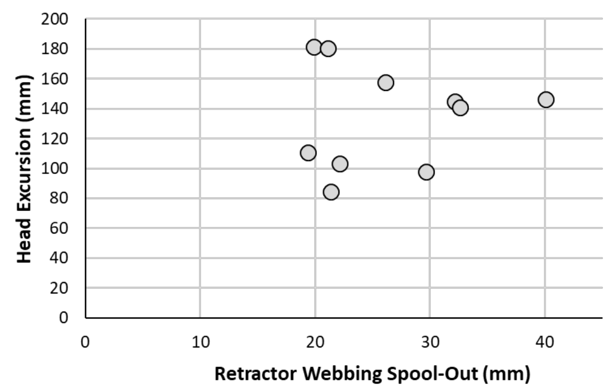
a) Abrupt braking



b) Turn-and-brake



c) Generic seat and seatbelt models with GHBMCsi



d) Retractor webbing spool-out

Figure 7. Vehicle kinematics in UMTRI pre-crash maneuver tests and model setup

GHBMCsi and GHBMCsi-Pre Responses in Braking Events

Figure 8 and Figure 9 show the response comparison between the GHBMCsi and GHBMCsi-pre models under abrupt braking condition, and how their responses compared to the subject testing head excursion corridor. Both models are without any active muscle forces, thus they should both sustain higher excursions than the testing corridor. However, the GHBMCsi model clearly under-estimated the head forward excursions, while the GHBMCsi-pre model was tuned to be much more compliant and the predicted head excursion is over the upper bound of the testing corridor. Because the GHBMCsi model was originally developed for high-speed impact simulations, and most of the biological soft tissues are rate dependent, it is not surprising that the GHBMCsi under-estimated the head excursion in a 1-g braking condition. For the GHBMCsi-pre model, the joint stiffness in the lumbar spine and cervical spine regions was softened, so the head excursion is in a reasonable range under the abrupt braking condition.

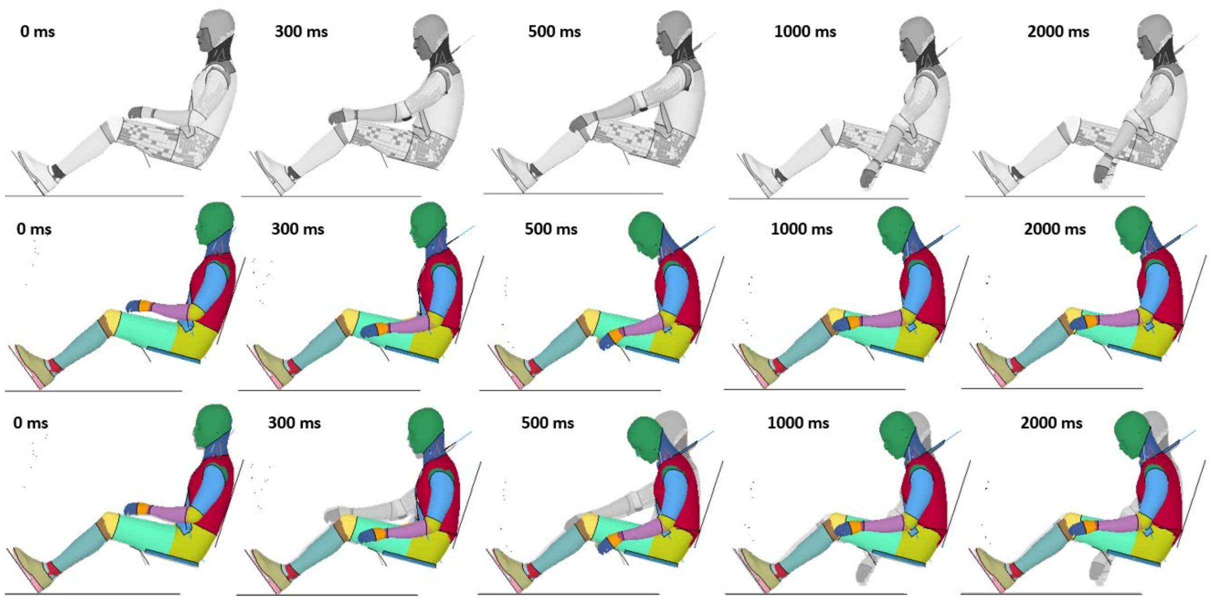


Figure 8. GHBMCsi (grey) and GHBMCsi-pre (color) kinematics in abrupt braking condition

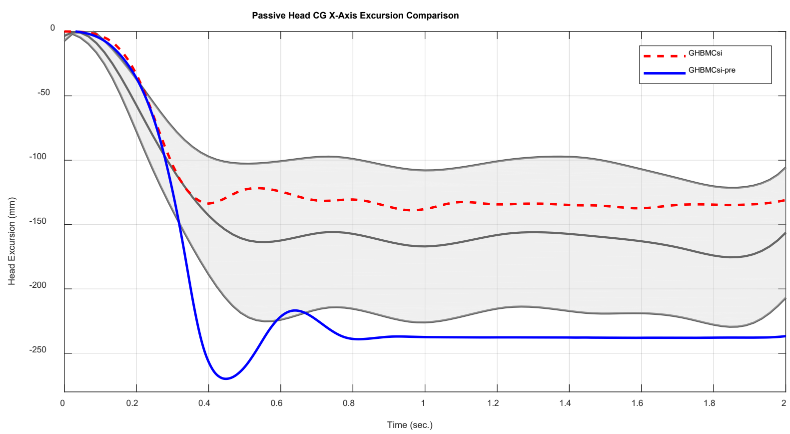


Figure 9. GHBMCsi and GHBMCsi-pre head forward excursions in abrupt braking condition with minimal simulated muscle activation ("passive").
Note: Black curves and grey area represent subject testing corridor.

GHBMCsi and GHBMC-Pre Responses in Turning and Braking Events

Figure 10 and Figure 11 show the response comparison between the GHBMCsi and GHBMCsi-pre models under turn-and-brake condition. Like the results in braking condition, GHBMCsi model slightly under-estimated the lateral excursions, but sustained higher forward head excursion than the testing corridor. At the same time, we tuned the GHBMCsi-pre model to be over the upper bounds of the testing corridors for both lateral and forward head excursions to simulate occupants without active muscles.

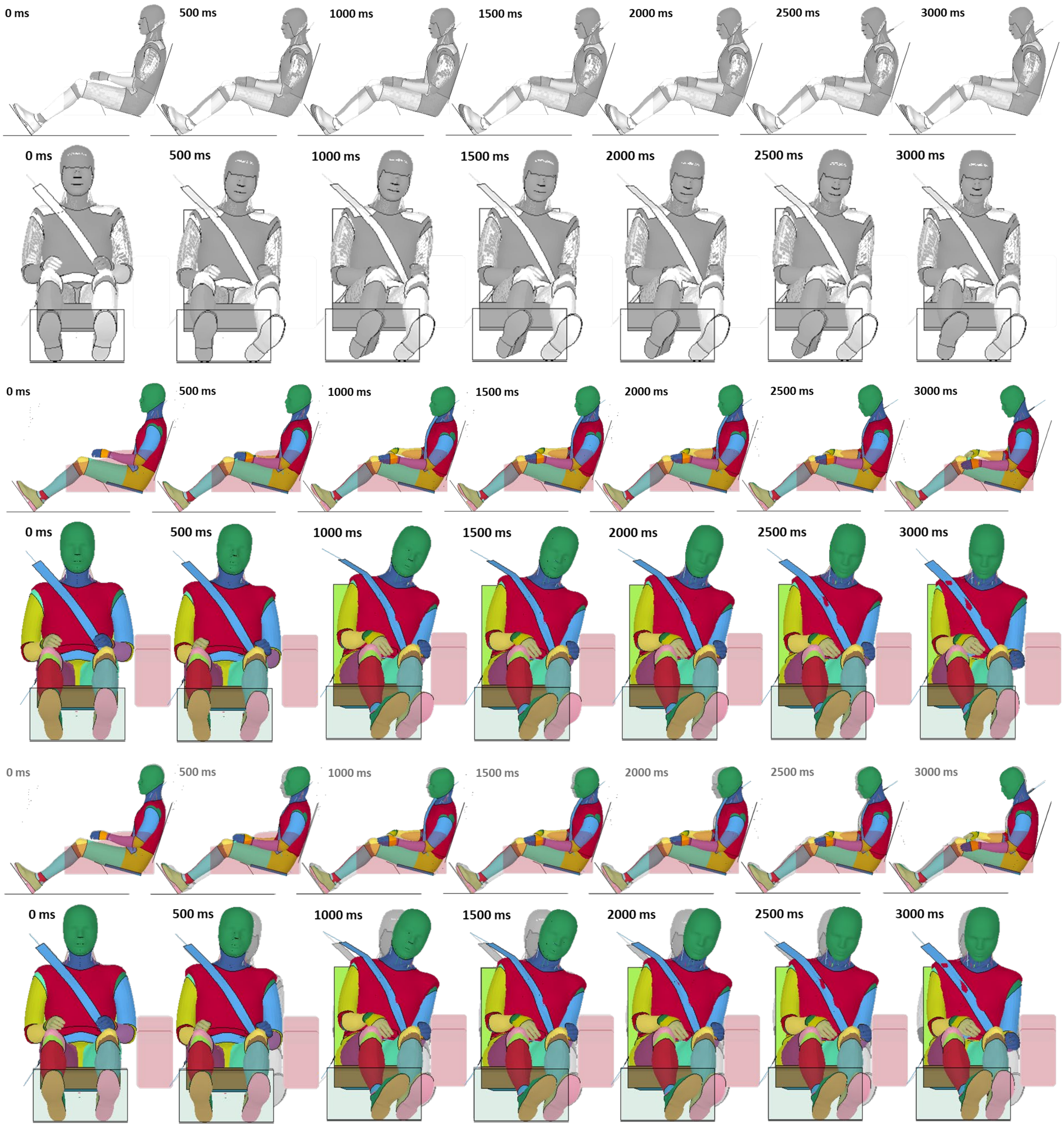


Figure 10. GHBMCsi (grey) and GHBMCsi-pre (color) kinematics in turn-and-brake condition

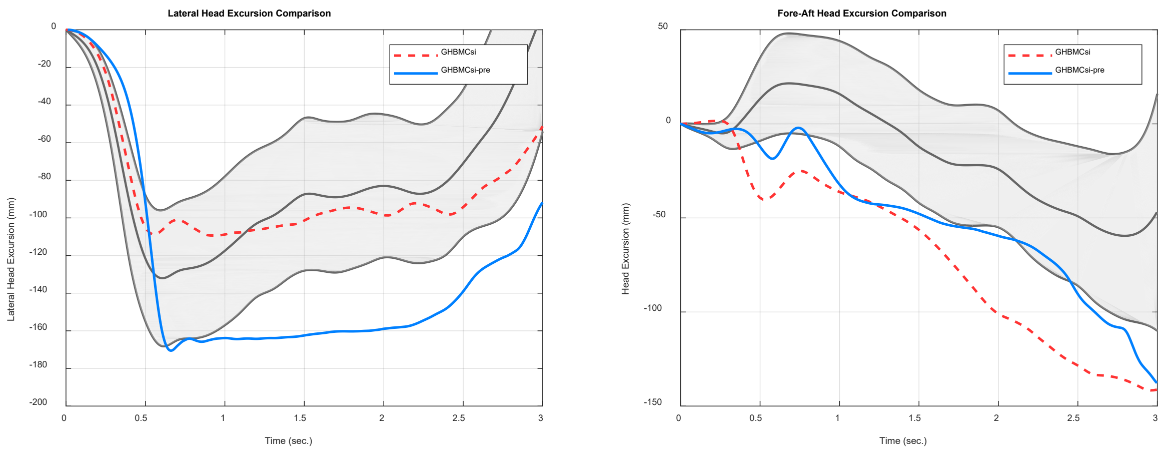


Figure 11. GHBMCsi and GHBMCsi-pre head excursions in turn-and-brake condition with minimal simulated muscle activation ("passive").
Note: Black curves and grey area represent subject testing corridor.

Active GHBMCsi-Pre Model

Closed-Loop Control for Muscle Activation

In this study we used closed-loop control for muscle activation for several reasons. First, open-loop control requires optimizations to achieve reasonable model accuracy, which is too time-consuming for FE models and results in brittle solutions that are not generalizable across test conditions. Second, closed-loop control is more consistent with the human reflex arc and neuromuscular control system and is far superior to open-loop control in terms of simulating muscle activations. Third, closed-loop active muscle or postural control has been successfully used by SAFER active human model and THUMS version 6 with impressive results (Kato et al., 2018; Östh et al., 2015a; Östh et al., 2014; Östmann & Jakobsson, 2016).

More specifically, in this study, the closed-loop control was implemented using a widely used controller design approach based on integrated proportional, integral, and derivative (PID) controllers. The PID controller is defined as:

$$u(t) = k_p \cdot e(t) + k_i \cdot \int_0^t e(\tau)d\tau + k_d \cdot \frac{de(t)}{dt} \qquad (1)$$

where *u(t)* is the overall control function, determined by k_p, k_i, and k_d, all non-negative coefficients for the proportional, integral, and derivative terms of the error function, respectively. The error function *e(t)* can be expressed as

$$e(t) = r(t) - y(t) \qquad (2)$$

where *y(t) is* the current state of the system and *r(t) is* the reference. That is, the controller monitors a target value based on a set of variables and chooses an appropriate set of responses.

When PID feedback control is applied to model human postural responses, the proportional and derivative feedback can model the effects of muscle spindle and vestibular reflexive stabilization, while the integrative controller removes any steady state error due to constant loads such as gravity.

Because the GHBMCsi-pre is a rigid-body-based model with joints but not actual muscles, in this study we used PID feedback control with joint torque actuators to mimic active muscle forces. By using this method, we do not need to add all the detailed geometry of muscles throughout the body of the GHBMCsi-pre model. Since the goal of this model is to predict pre-crash maneuver-induced occupant kinematics, not muscle forces or injury outcomes, this arrangement is the easiest and the most efficient way to develop the active GHBMCsi-pre.

PID controller software is widely available in the control system toolboxes of numerical programs, such as MATLAB/Simulink, Scilab, etc. Ls-Dyna can be linked with those programs to use PID controller for muscle activation simulations. Andersson (2013) demonstrated that Ls-Dyna standard keywords, including PIDCTL and DELAY through *DEFINE_CURVE_FUNCTION, can be directly used as PID controllers.[2] The results between MATLAB PID controller and LS-Dyna standard keywords are consistent. Therefore, to reduce the complexity of the active GHBMCsi-pre model, we used Ls-Dyna alone for active joint control.

The overview of neuromuscular feedback control loop to be used for the active GHBMCsi-pre model is shown in Figure 12, which is like the SAFER active human model (Östh et al., 2015a, 2012b, 2014, 2013). However, in this study, we used accumulated joint angular velocity instead of joint angle as the PID control target. As a result, the proportion, integral, and derivative terms of the PID controller are corresponding to the joint angular velocity, joint angle, and joint angular acceleration. In the literature, the PID control targets are typically displacement or angle. If such targets are used, the goal of the PID control is to keep the body stationary in the pre-crash maneuvers. However, based on the UMTRI subject testing we found that subjects are capable of fully controlling their motion during the pre-crash maneuver events, and the variations of head excursions are mainly due to behavior rather than capability. In other words, if any subject wants to keep the head stationary during a braking event, he/she is certainly capable of doing so, after overcoming lags due to neuromuscular delays. Therefore, instead of controlling the displacement or the joint angle, in this study we proposed a new algorithm of controlling the angular velocity. By doing so, we hypothesized that occupants are trying to minimize the joint angular velocities during pre-crash maneuver events, consistent with the observation that occupants tolerate some movement and do not immediately act to return to their starting posture.

Therefore, *u(t)* is calculated based on Equation 1, in which r(t) and y(t) are the original and current accumulated joint angular velocities. Through Ls-Dyna joint moment actuators, joint moments were added to the GHBMCsi-pre model, and the occupant excursions were estimated by the model, which resulted in a new *u(t)* for the next time step.

As shown in Figure 12 and Table 2, a total of 7 cervical spine joints and 6 lumbar spine joints were included into two separate pairs (in X and Y angular directions) of PID controllers; while nonlinear joint stiffness values were assigned to the hip, knee, ankle, and elbow joints to simulate active muscle effects in pre-crash maneuver conditions. Within each PID controller, the sums of the joint angular velocities were calculated as the control target in each time step, and the PID-controller-estimated joint torque was then evenly distributed back into each joint. A neural delay

[2] Andersson, S. (2013). *Active muscle control in human body model simulations: Implementation of a feedback control algorithm with standard keywords in LS-DYNA*. [Master of science thesis, Division of Vehicle Safety, Department of Applied Mechanics]. Chalmers University of Technology, Gothenburg, Sweden.

of 20 ms was assigned for the cervical joints and a neural delay of 25 ms was assigned for the lumbar spine joints based on a study by (Östh et al., 2012a).

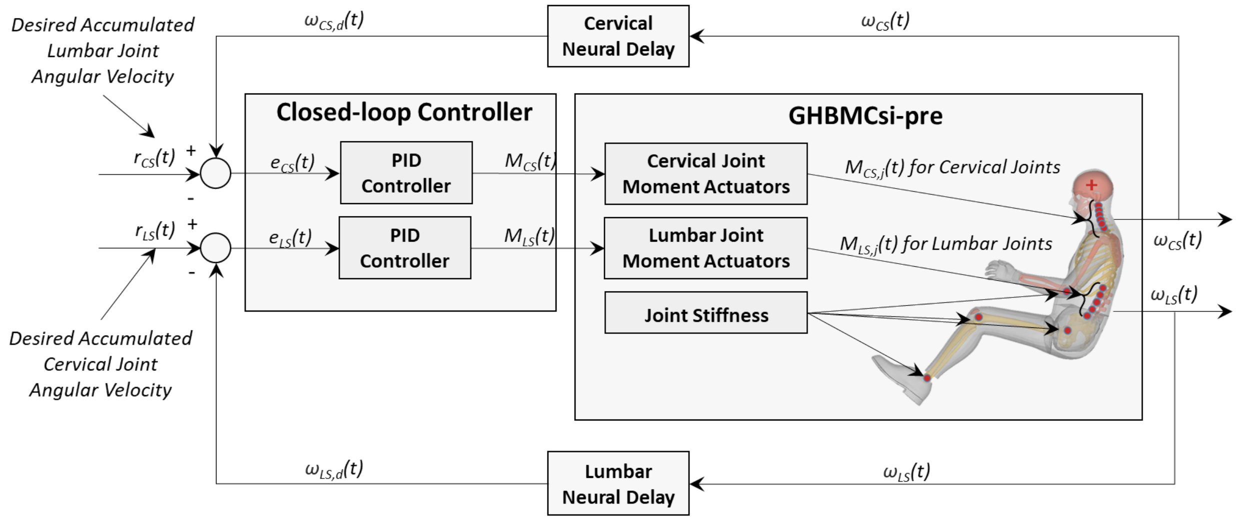
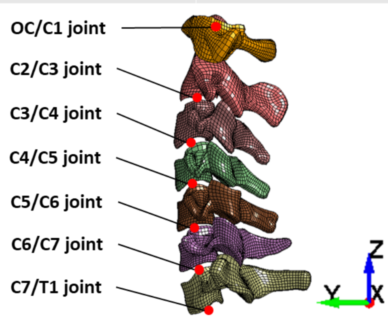
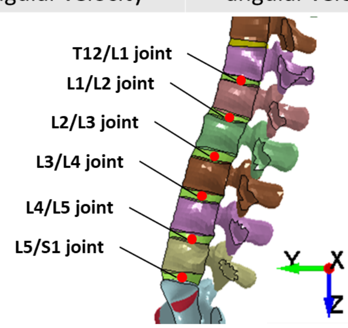


Figure 12. Illustration of neuromuscular feedback control in the active GHBMCsi-pre

Table 2. Configurations for all active PID controllers

PID Controller	Cervical Spine		Lumbar Spine	
	C-Spine PID-X	C-Spine PID-Y	L-Spine PID-X	L-Spine PID-Y
PID Control Axis	X-Axis Rotation (Fore-Aft)	Y-Axis Rotation (Lateral)	X-Axis Rotation (Fore-Aft)	Y-Axis Rotation (Lateral)
PID Control Signal	Sum of all cervical joints' x-axis angular velocity	Sum of all cervical joints' y-axis angular velocity	Sum of all lumbar joints' x-axis angular velocity	Sum of all lumbar joints' y-axis angular velocity
PID Joint Controller Setup Illustration				

Active GHBMCsi-Pre Responses in Braking Events

Figure 13 and Figure 14 show head forward excursions of the active GHBMCsi-pre model with different levels of PID controls in the abrupt braking condition. We first set k_i and k_p as 1.0 and 2.0 in the lumbar spine PID controller, and set k_i and k_p as 0.02 and 1.5 in the cervical spine PID controller. Then we uniformly scaled the PID coefficients up by 5, 10, 20, 30, and 40 times. By setting the PID coefficients to these values, the forward head excursions of the active GHBMCsi-pre model covered the full range of the subject testing corridor in the abrupt braking condition. A CORA rating of 0.708 was achieved with the PID coefficients set at five times the baseline values. We also found that the lumbar spine PID controller has much more significant effects on the head excursion than the cervical spine PID controller, because the subjects tended to maintain fairly constant neck angles.

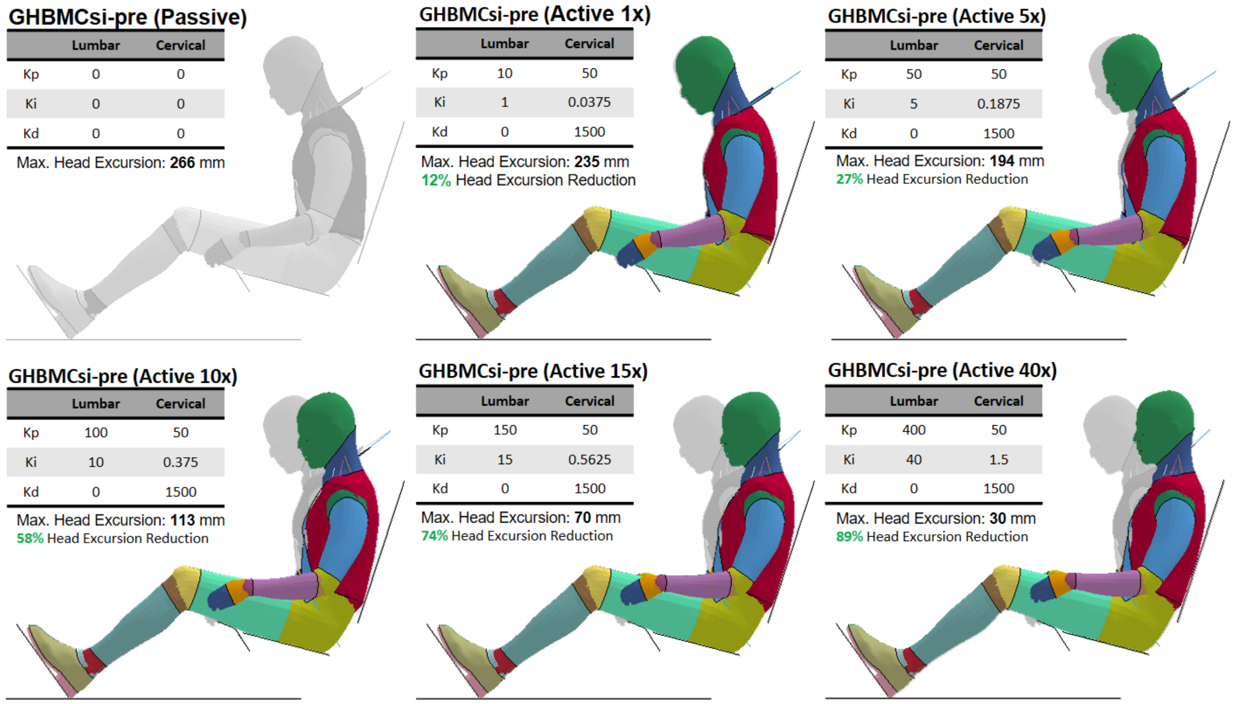


Figure 13. Maximal head forward excursion comparison between GHBMCsi-pre (grey) and active GHBMCsi-pre under different levels of PID controls (color) in abrupt braking condition

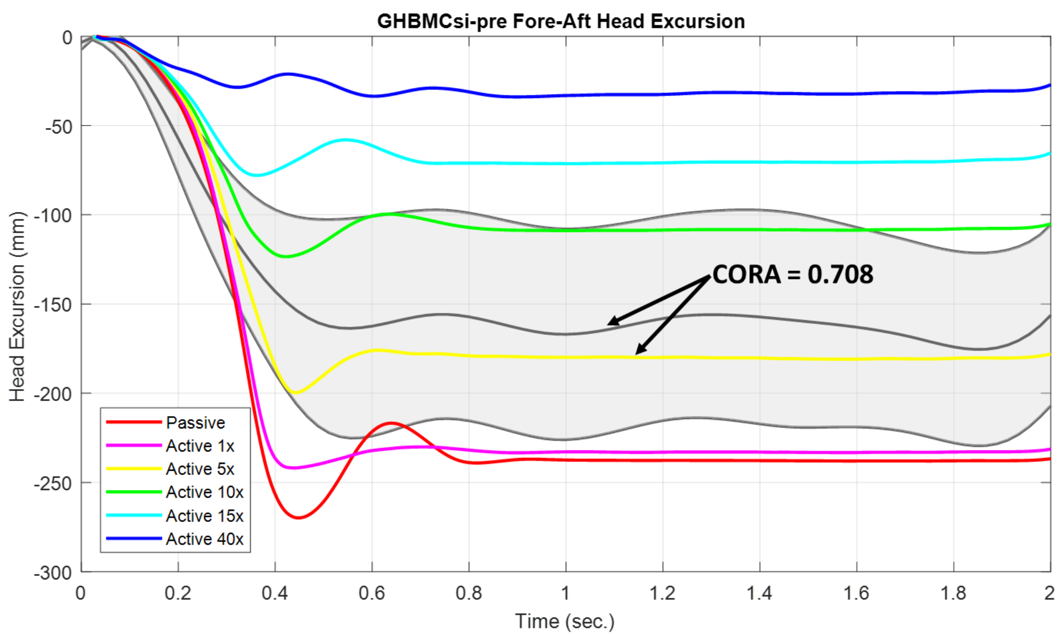


Figure 14. Head forward excursion time histories from active GHBMCsi-pre under different levels of PID controls in abrupt braking condition

Active GHBMC-Pre Responses in Turning and Braking Events

Figure 15 and Figure 16 show head lateral and forward excursions of the active GHBMCsi-pre model with different levels of PID controls. The full set/range of PID coefficients are shown in Table 3. By controlling the PID coefficients in these ranges, the forward and lateral head excursions of the active GHBMCsi-pre covered the full range of the subject testing corridor in the turn-and-brake condition. There is a small backward head motion at the beginning of the event shown in the subject testing corridor, which is due to seat back deformation by centrifugal force generated by the turn event. The model did not show that small backward head motion, because a rigid seat back was used in the simulations. Other than that, the active GHBMCsi-pre models can well cover the range of subject responses in the turn-and-brake condition. A CORA rating of 0.772 for the lateral head excursion and 0.622 for the forward head excursion were acheived with the PID coefficients set at 10 and 15 times the baseline values, respectively. The lower CORA rating for the forward head exursion is mainly due to the small backward head motion at the beginning of the testing.

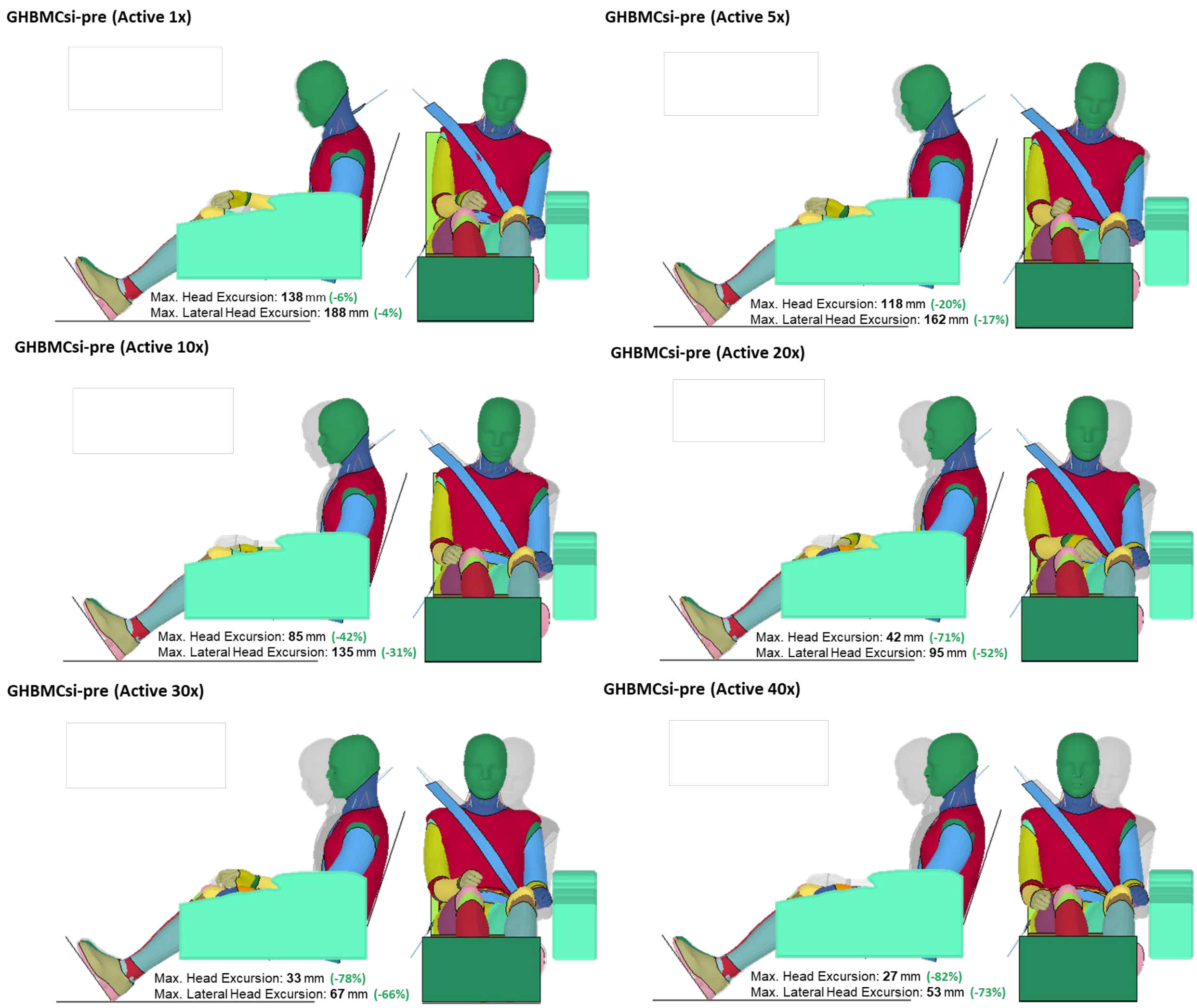


Figure 15. Maximal head lateral excursion comparison between GHBMCsi-pre (grey) and active GHBMCsi-pre under different levels of PID controls (color) in turn-and-brake condition

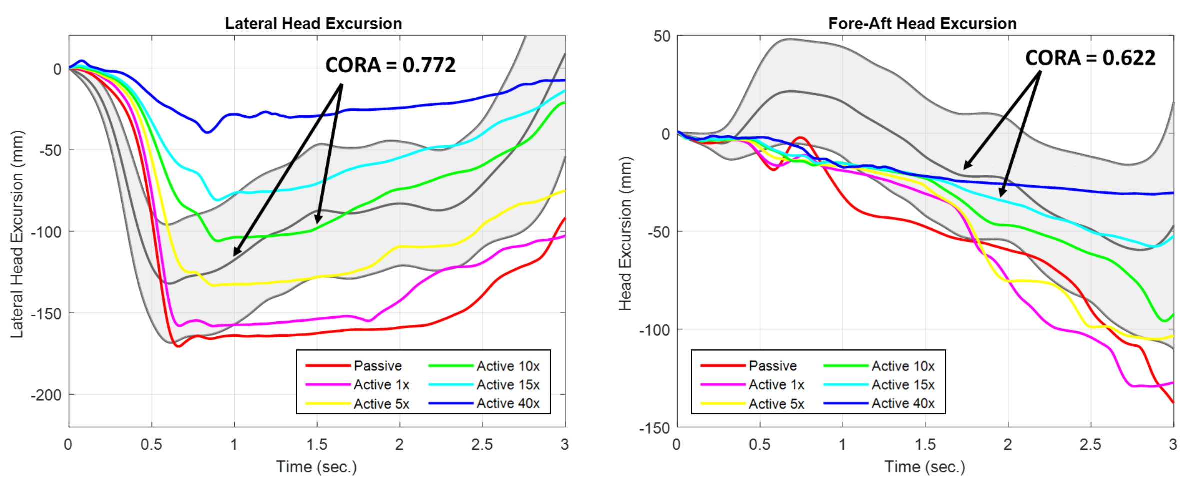


Figure 16. Head forward and lateral excursion time histories from active GHBMCsi-pre under different levels of PID controls in turn-and-brake condition

Table 3. PID coefficients for simulating different levels of active muscle forces

PID Coefficients			Passive	Active					
				1x	5x	10x	20x	30x	40x
Fore-Aft	Lumbar	*Kp*	0	10	50	100	200	300	400
		Ki	0	1	5	10	20	30	40
		Kd	0	0	0	0	0	0	0
	Cervical	*Kp*	0	50	50	50	50	50	50
		Ki	0	0.0375	0.1875	0.375	0.75	1.125	1.5
		*Kd***	0	1500	1500	1500	1500	1500	1500
Lateral	Lumbar	*Kp*	0	20	100	200	400	600	800
		Ki	0	1	5	10	20	30	40
		Kd	0	0	0	0	0	0	0
	Cervical	*Kp*	0	-100	-100	-100	-100	-100	-100
		*Ki**	0	-0.0625	-0.3125	-0.625	-1.25	-1.875	-2.5
		*Kd***	0	-1200	-1200	-1200	-1200	-1200	-1200

* Negative coefficients are due to the negative rotation direction relative to the reference coordinates.
** *Kd* was kept constant in all simulations.

Parametric GHBMCsi-Pre Model

Model Development Through Mesh Morphing

For the past few years, UMTRI has gathered data and developed robust methods to enable rapid creation of parametric human models that can account for the wide range of occupant size, shape, and age for both males and females. Figure 17 illustrates the basic steps of developing parametric human FE models representing occupants with a wide range of human attributes. The process begins with statistical models of human geometry (skeleton and external body surface) that describe morphological variations within the population as functions of human parameters (age, sex, stature, and/or BMI). Mesh morphing methods are then used to rapidly morph a baseline FE human model into other geometries while maintaining high geometric accuracy and good mesh quality.

Given a target age, sex, stature, and BMI, the statistical human geometry models (Klein, 2015; Klein et al., 2015; Reed and Ebert, 2013; Shi et al., 2014; Wang et al., 2016) predict thousands of points that define the body posture, the size and shape of the external body surface, ribcage, pelvis, femur, and tibia geometries. These models were developed previously based on 3D body scan and CT data from a total of more than 500 subjects. The skeleton and external body shape geometries are integrated together based on body landmark and joint locations shared in both models. Once the target geometries are developed, the baseline model is morphed to match the target geometries using a landmark-based mesh morphing technique based on radial basis functions (RBF). This parametric FE modeling concept has been applied in several studies at UMTRI (Hwang et al., 2016a, b;; Zhang et al., 2017a, b). Because UMTRI used the GHBMCsi model as one of the baseline models in a previous study (Zhang et al., 2017a), in this study we used a similar process to parameterize the GHBMCsi-pre model.

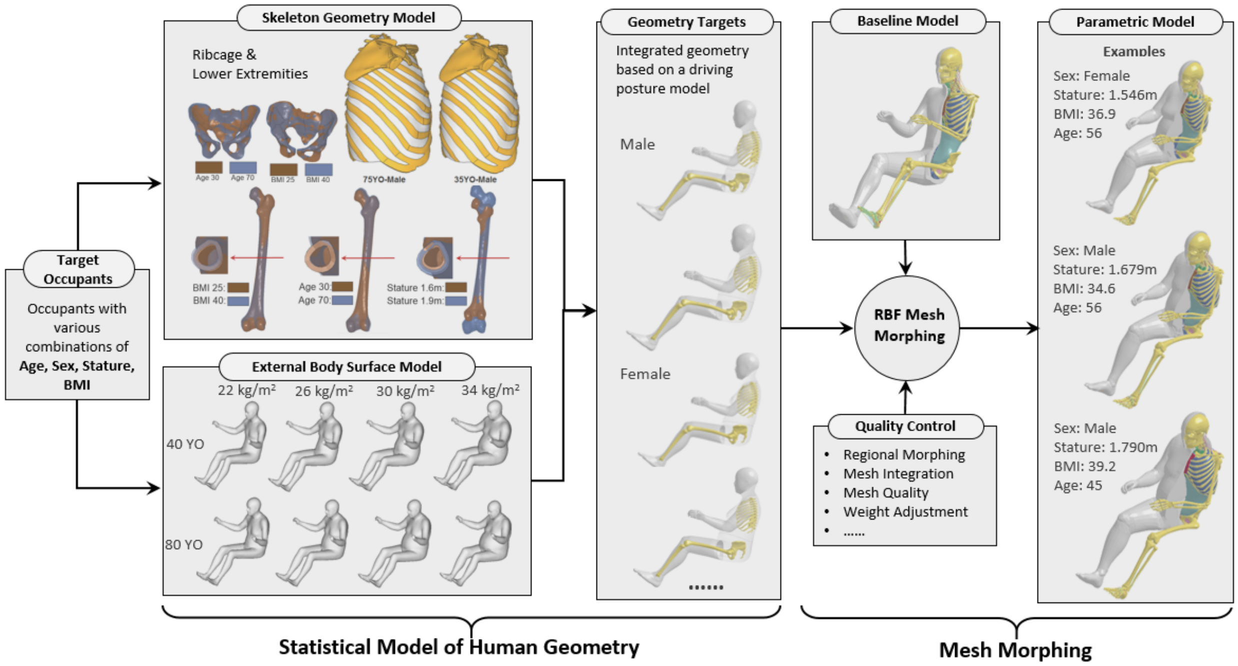


Figure 17. Method for developing parametric human FE models

In this study, we generated 12 human models representing 3 statures (5th percentile female, 50th percentile male, and 95th percentile male), two levels of BMI (25 kg/m^2 for non-obese and 40 kg/m^2 for obese), and two ages (20 and 70 years old). Figure 18 shows the 12 morphed GHBMCsi-pre models. The mesh qualities of the morphed models are comparable to the GHBMCsi-pre model. Specifically, in average, each model only has seven elements (0.002%) with Jacobian value less than 0.3, and 99.9 percent of the elements are with Jacobian value between 0.5 and 1.0.

Because a majority of the body parts in the GHBMCsi-pre model are rigid bodies, once the FE mesh of the GHBMCsi-pre is parameterized, mass scaling for each rigid body is necessary. The weights and volumes of 12 major body regions (each body region contains multiple parts of the GHBMCsi-pre) were first measured for the 12 morphed GHBMCsi-pre models. Body region target weights for each morphed model were then approximated using Equation 3. Each body region's mass differences from its target were then calculated and a scaling factor (Eq. 4) was assigned to each body region. All parts within the same body region in turn have their material density scaled by the scaling factor to adjust their weight distribution (Eq. 5).

$$Body\ Region\ Target\ Mass = Subject\ Weight \times \frac{Body\ Region\ Volume}{Subject\ Total\ Volume} \quad (3)$$

$$Body\ Region\ Mass\ Scaling\ Factor = \frac{Body\ Region\ Target\ Mass}{Body\ Region\ Current\ Mass} \quad (4)$$

$$Part\ New\ Density = Part\ Current\ Density \times Body\ Region\ Mass\ Scaling\ Factor \quad (5)$$

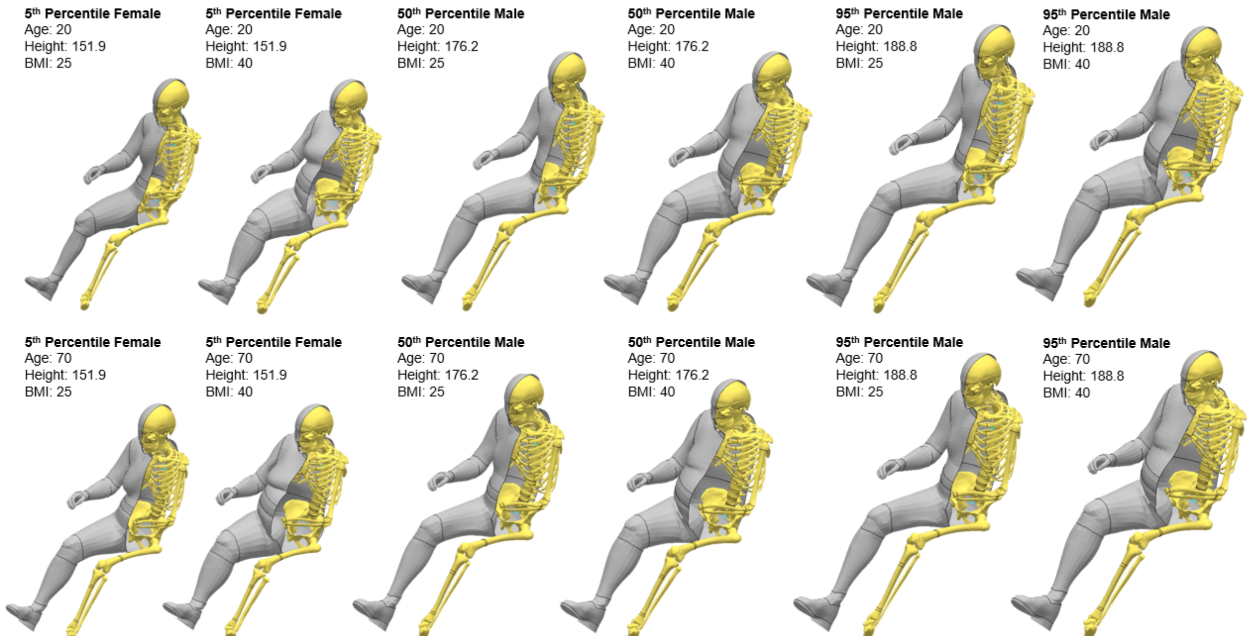


Figure 18. A total of 12 morphed GHBMCsi-pre models

Validation Targets for Parametric GHBMCsi-Pre Models

One of the greatest challenges of this study is to consider the effects of occupant size, age, and sex in occupant pre-crash kinematics prediction. Although the geometric variations can be considered by morphing the baseline midsize male model into occupants with a wide range of human attributes, the understanding of occupant characteristics on pre-crash motions is also critical. Figure 19 shows age, BMI, and stature effects on the maximal head forward excursion in the abrupt braking condition in UMTRI's subject testing. It is interesting to notice that older occupants tend to produce smaller head excursions than the younger occupants, and higher BMI occupants tended to produce smaller head excursions than the leaner occupants. Stature effects were not statistically significant, and excursions were not different for males and females.

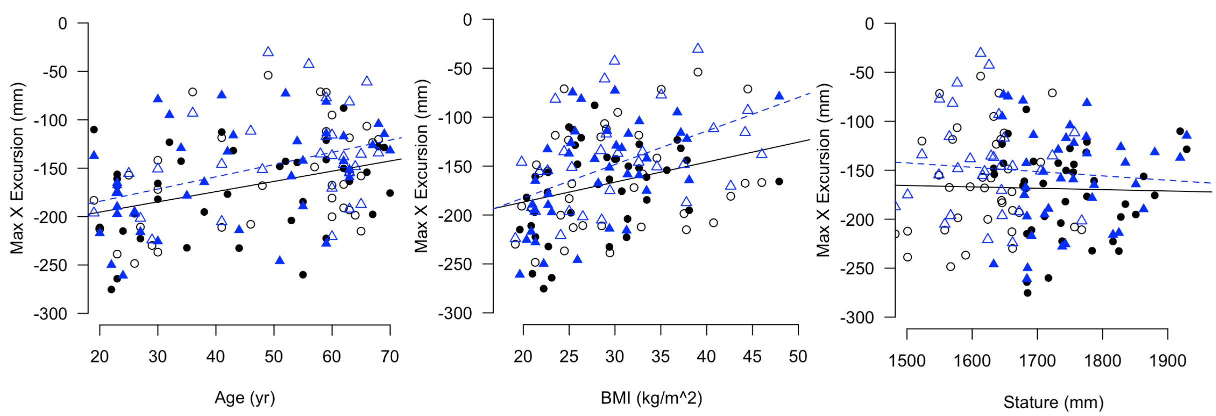


Figure 19. Effects of age and BMI on the maximum forward excursion in braking trials. The first braking event is shown as circles and a solid regression line; the second event is triangles and a dashed line. Note: Data from male and female participants are shown as filled and open symbols, respectively.

In this study, we conducted functional analyses using the excursion data from the UMTRI subject testing to estimate excursion histories for a given set of age and BMI. Only age and BMI were used, because sex and stature are not statistically significant predictors for head excursions. The functional analysis methods developed at UMTRI include principal component analysis to reorganize the data points in an orthogonal manner and regression analysis to predict excursion histories from occupant characteristics. With the functional analysis, time-varying excursion targets for different ages and BMI levels were generated.

Figure 20 shows examples of head CG excursion corridors for braking using this functional analysis approach. As noted above, forward head excursion in braking is only significantly related to age and BMI. The functional analysis demonstrated these effects by exercising the model with extreme values of these two variables. Corridors were generated by simulating 1000 trajectories for each passenger category based on the residual variance from the functional regression and computing the standard deviation at each time point from these simulated trajectories.

For turn-and-brake events, the subject testing did not show significant effects from stature, age, or BMI. Therefore, in this study we only used a single set of testing corridors to represent the whole population.

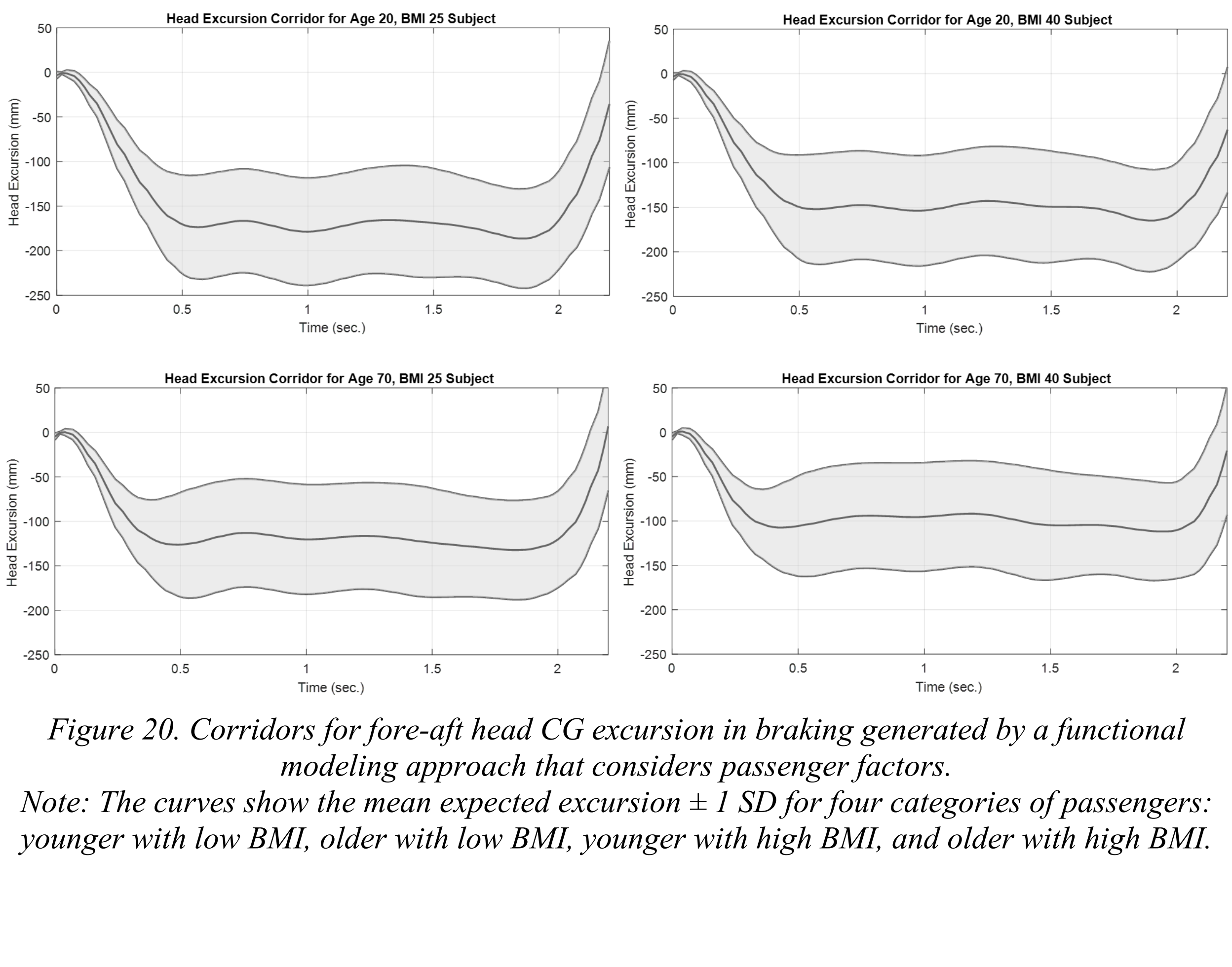


Figure 20. Corridors for fore-aft head CG excursion in braking generated by a functional modeling approach that considers passenger factors.

Note: The curves show the mean expected excursion ± 1 SD for four categories of passengers: younger with low BMI, older with low BMI, younger with high BMI, and older with high BMI.

Parametric GHBMCsi-Pre Responses Without Muscle Activations

After the 12 models were morphed (Figure 18), they were first used in the abrupt braking simulations without adjusting any joint stiffness and without PID controls. We found that all BMI 25 models produced reasonable kinematics, while all BMI 40 models significantly over-estimated the head excursions. Therefore, we started increasing joint stiffness in the same scale for all BMI 40 models. Figure 21 and Figure 22 show, after the joint stiffness adjustment for the high BMI models, head forward excursions from all morphed GHBMCsi-pre models in the abrupt braking condition without any muscle activation. Overall, the head excursions of all morphed models are all within a reasonable range compared to the corresponding test corridors. There are stature effects on the head excursion, in which small female had lower head excursions than those from midsize male and large male, except for the older, low BMI, female model. However, all model responses are either slightly over the upper bound of the testing corridor or within the corridor. Note that all the low BMI models share the same set of joint stiffness values, and all the high BMI models share another set of joint stiffness values in the current study. We assumed age and stature do not affect the joint stiffness without any muscle activations.

Figure 23 and Figure 24 show the head lateral and forward excursions of all morphed GHBMCsi-pre models in the turn-and-brake condition without any muscle activation. The joint lateral stiffness values were kept the same for all morphed models. Simulation results in the turn-and-brake condition showed that low BMI models sustained higher excursions than those from high BMI models without any muscle activations. The stature effect is not clear.

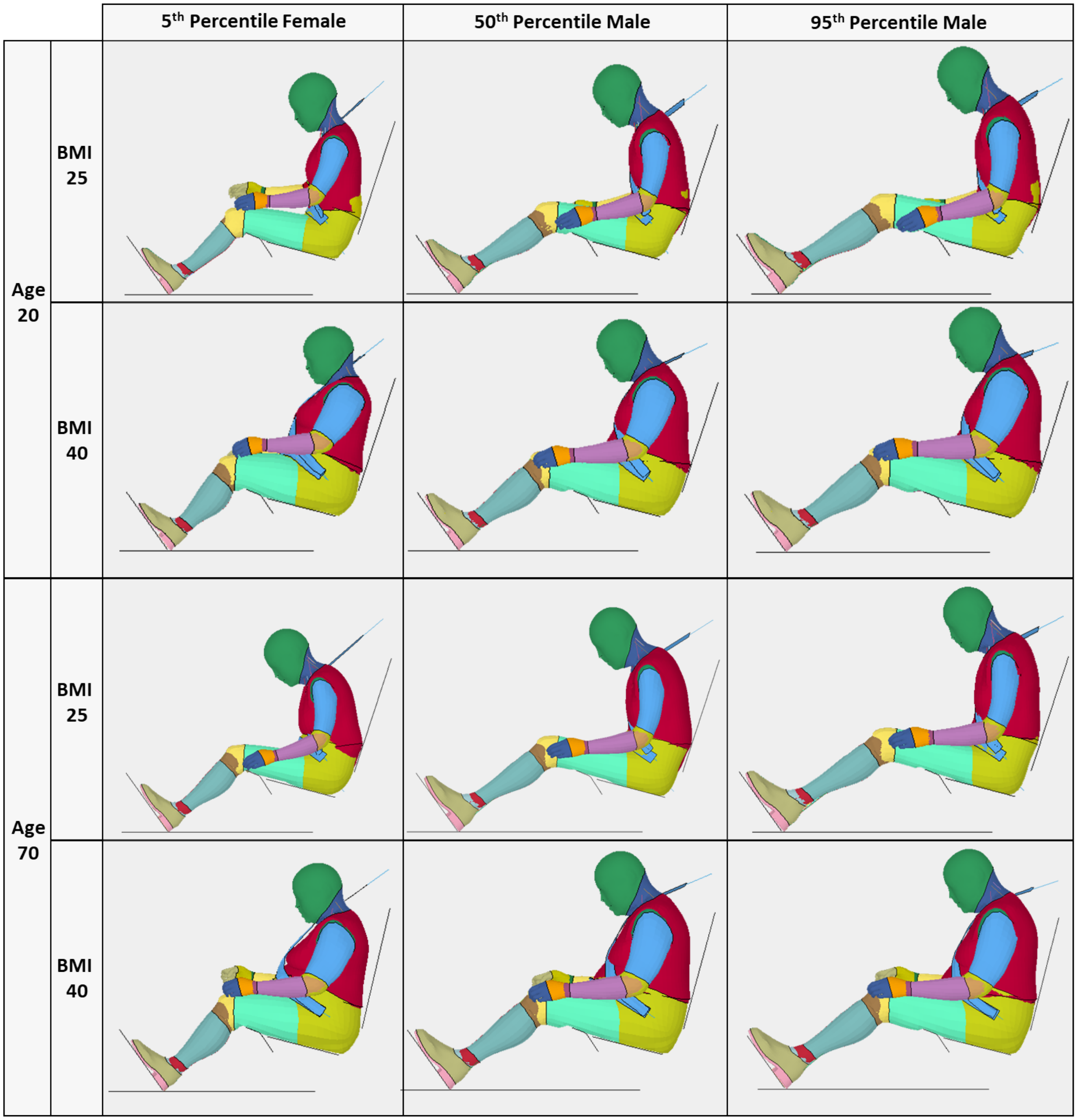


Figure 21. Maximal head forward excursions for 12 morphed GHBMCsi-pre models in abrupt braking condition without muscle activation

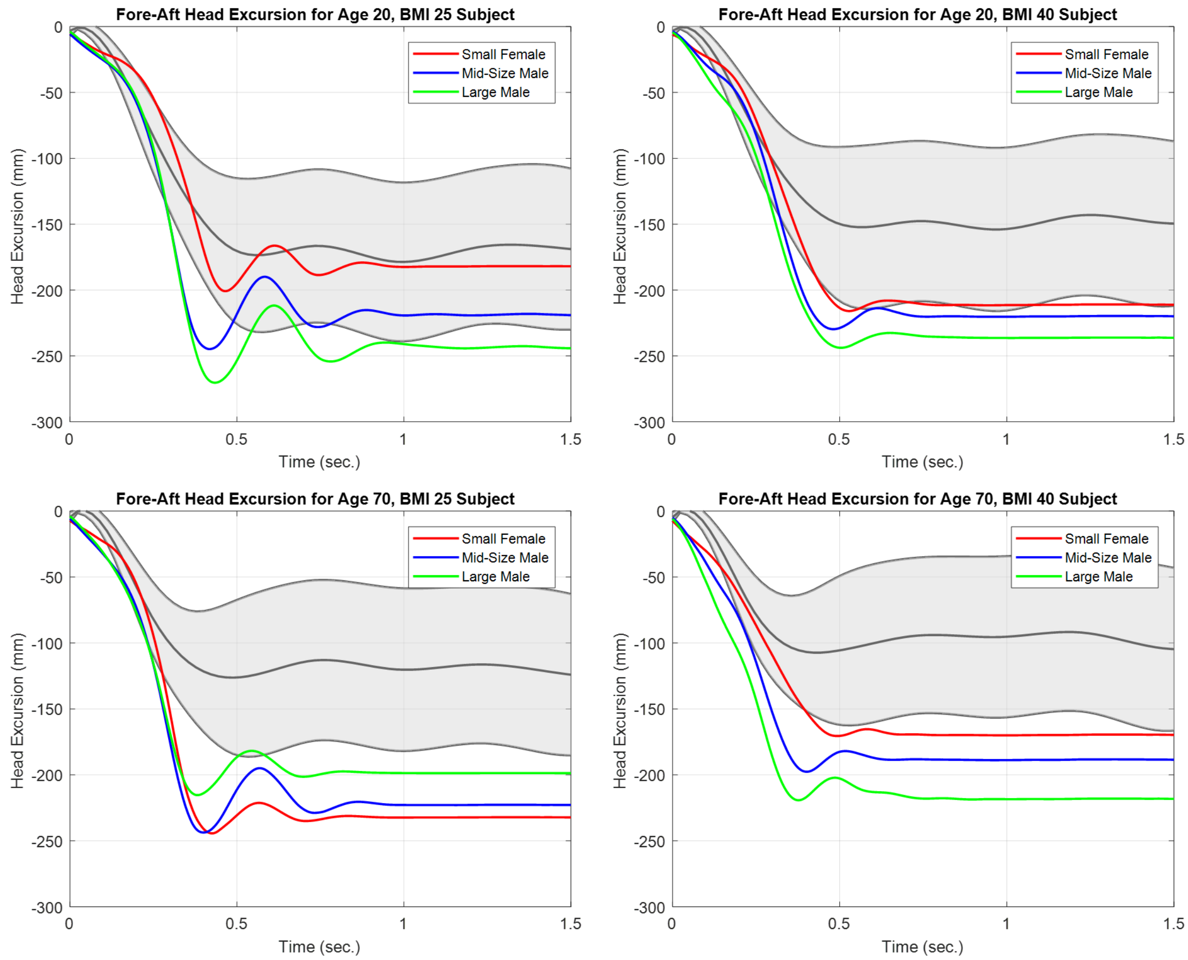


Figure 22. Head forward excursion time histories from all 12 morphed GHBMCsi-pre models with varied stature and BMI in abrupt braking condition without muscle activation. Note: Black curves and grey area represent subject testing corridor corresponding to the specific age and BMI.

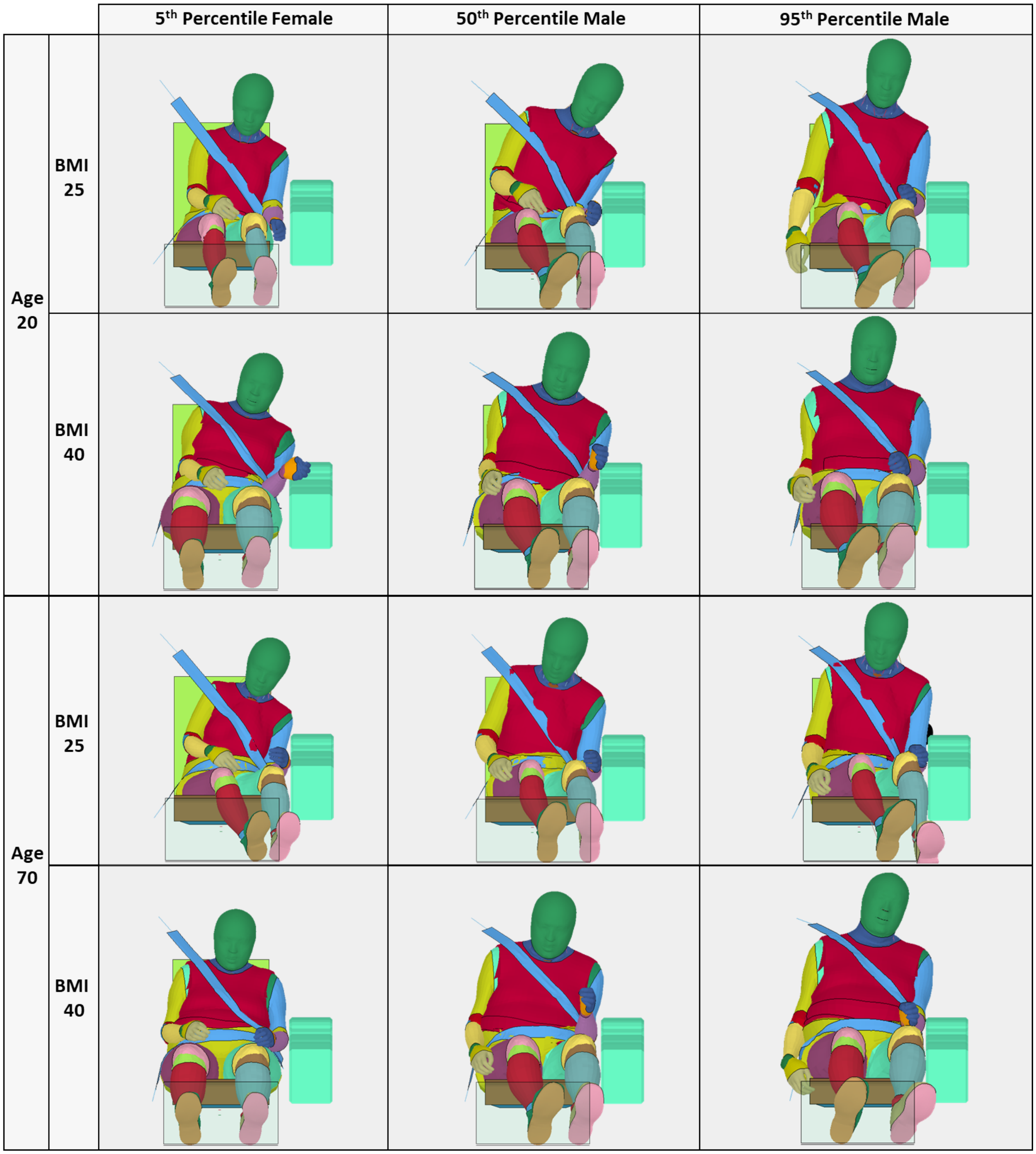


Figure 23. Maximal head lateral excursions for 12 morphed GHBMCsi-pre models in turn-and-brake condition without muscle activation

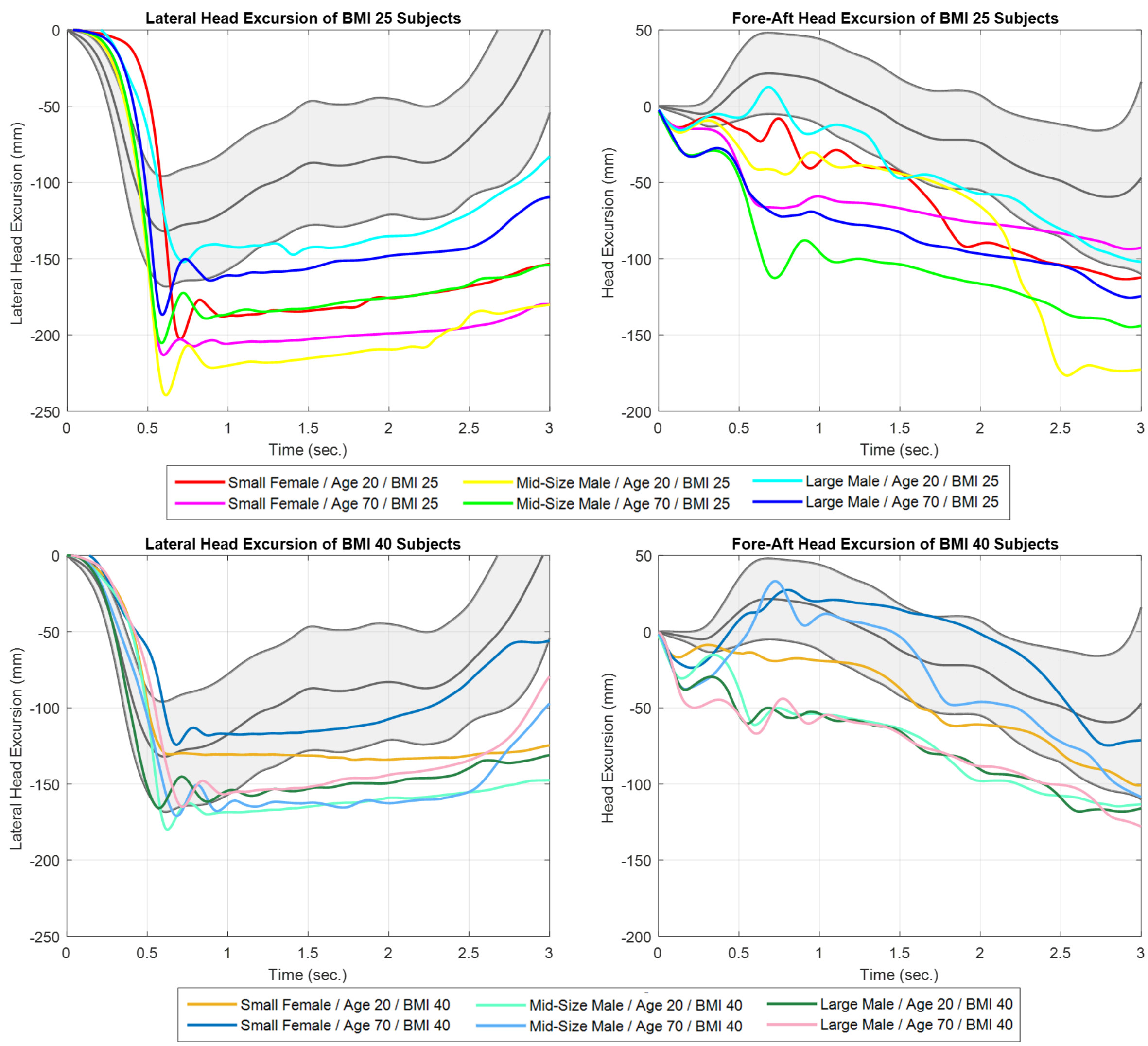


Figure 24. Head forward and lateral excursion time histories from all 12 morphed GHBMCsi-pre models with varied stature and BMI in turn-and-brake condition without muscle activation. Note: Black curves and grey area represent subject testing corridor for the whole population.

Examples of Parametric GHBMCsi-Pre Responses With Muscle Activations

Figure 25 and Figure 26 show head forward excursions of two morphed GHBMCsi-pre models (first: midsize male stature, age 20, and BMI 40, second: small female stature, age 20, and BMI 25) with different levels of PID controls in the abrupt braking condition. The PID coefficients were set the same as those reported in Table 3. By controlling the PID coefficients, the forward head excursions of both morphed GHBMCsi-pre models covered the full range of the corresponding subject testing corridor. These results demonstrated that the same PID coefficients can effectively control the occupant kinematics in a similar way among the occupants with a wide range of size and shapes.

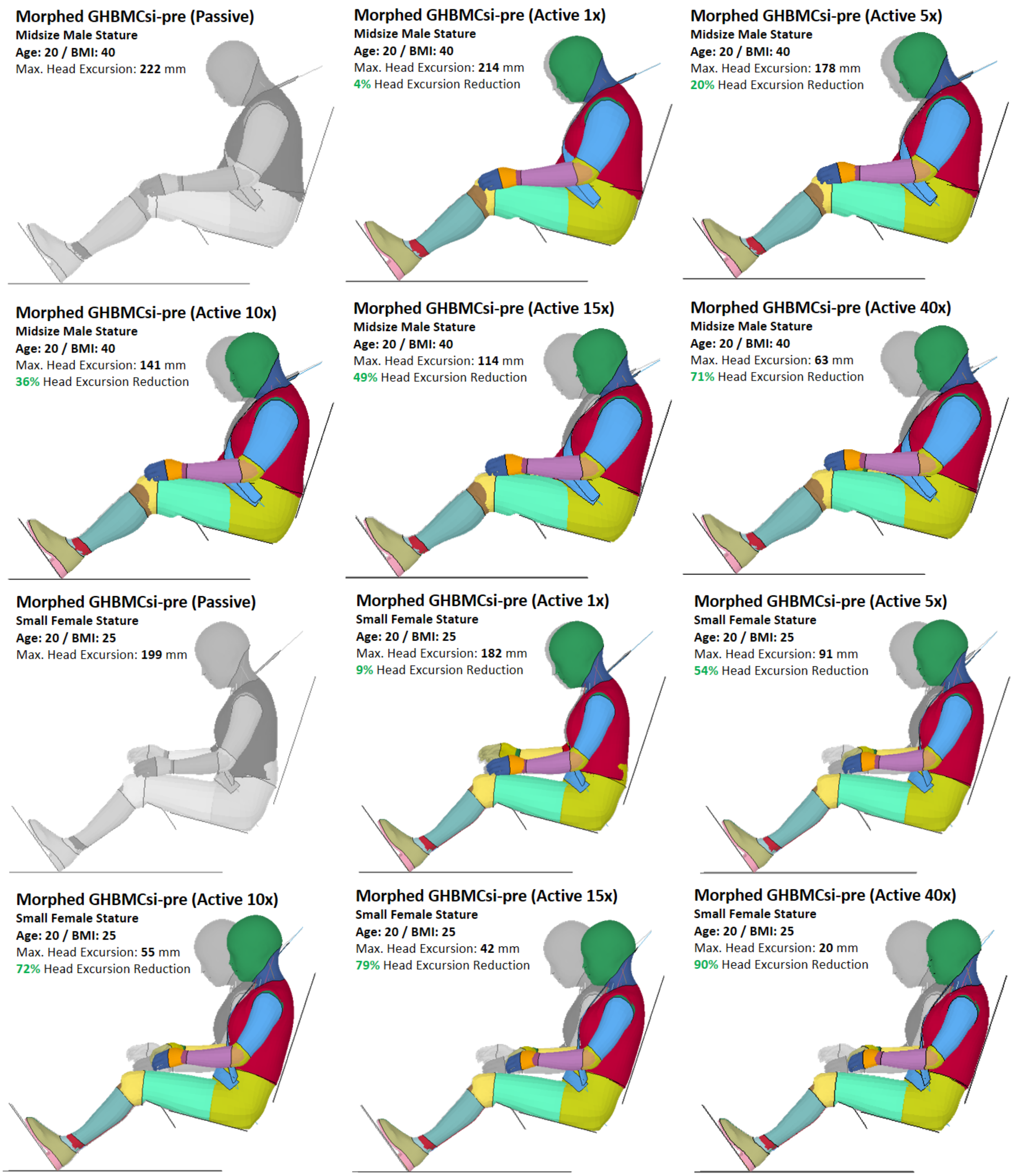


Figure 25. Maximal head forward excursions from two morphed GHBMCsi-pre models (first: midsize male stature, age 20, and BMI 40, second: small female stature, age 20, and BMI 25) without (grey) and with various levels of PID controls (color) in abrupt braking condition

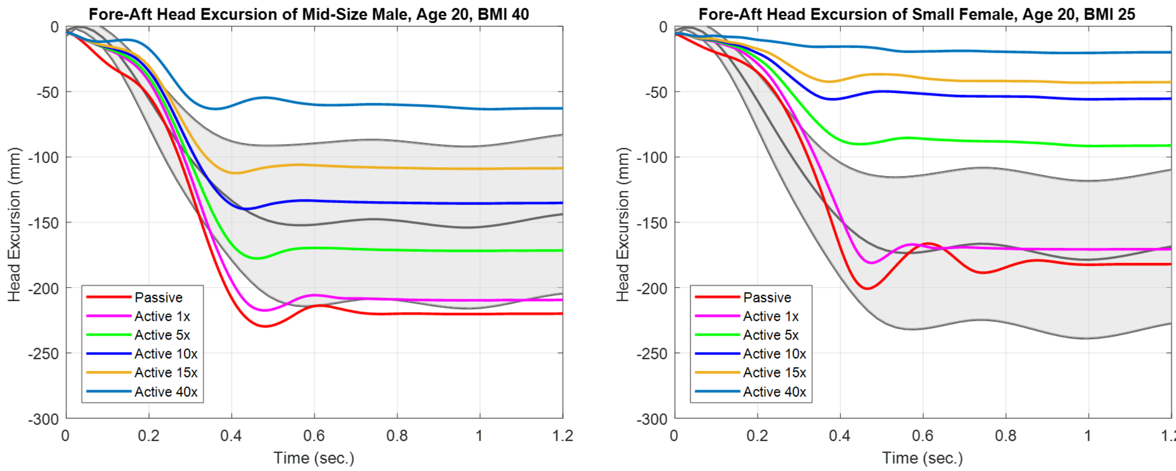


Figure 26. Head forward excursion time histories from two of the active GHBMCsi-pre models (first: midsize male stature, age 20, and BMI 40, second: small female stature, age 20, and BMI 25) with different levels of PID controls in abrupt braking condition

Similar to the abrupt braking simulations, and show head lateral and forward excursions of two morphed GHBMCsi-pre models (first: midsize male stature, age 70, and BMI 20, second: small female stature, age 20, and BMI 40) with different levels of PID controls in the turn-and-brake condition. The PID coefficients were set the same as those reported in Table 3. By controlling the PID coefficients, the lateral and forward head excursions of both morphed GHBMCsi-pre models covered the full range of the subject testing corridors. These results demonstrated that the same PID coefficients can effectively control the occupant kinematics in a similar way among occupants with a wide range of size and shape.

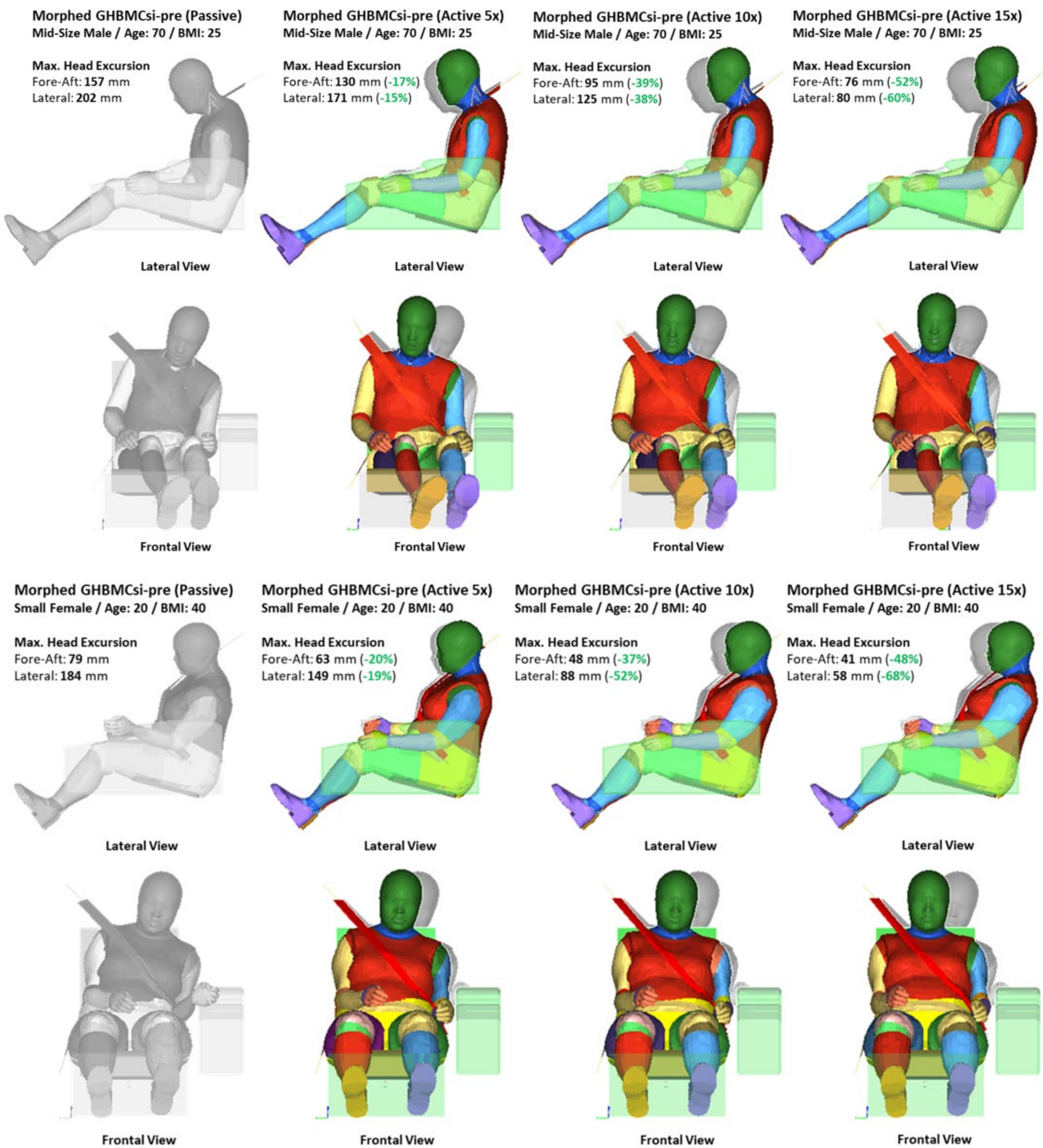


Figure 27. Maximal head forward and lateral excursions from two morphed GHBMCsi-pre models (first: midsize male stature, age 70, and BMI 25, second: small female stature, age 20, and BMI 40) without (grey) and with various levels of PID controls (color) in turn-and-brake condition

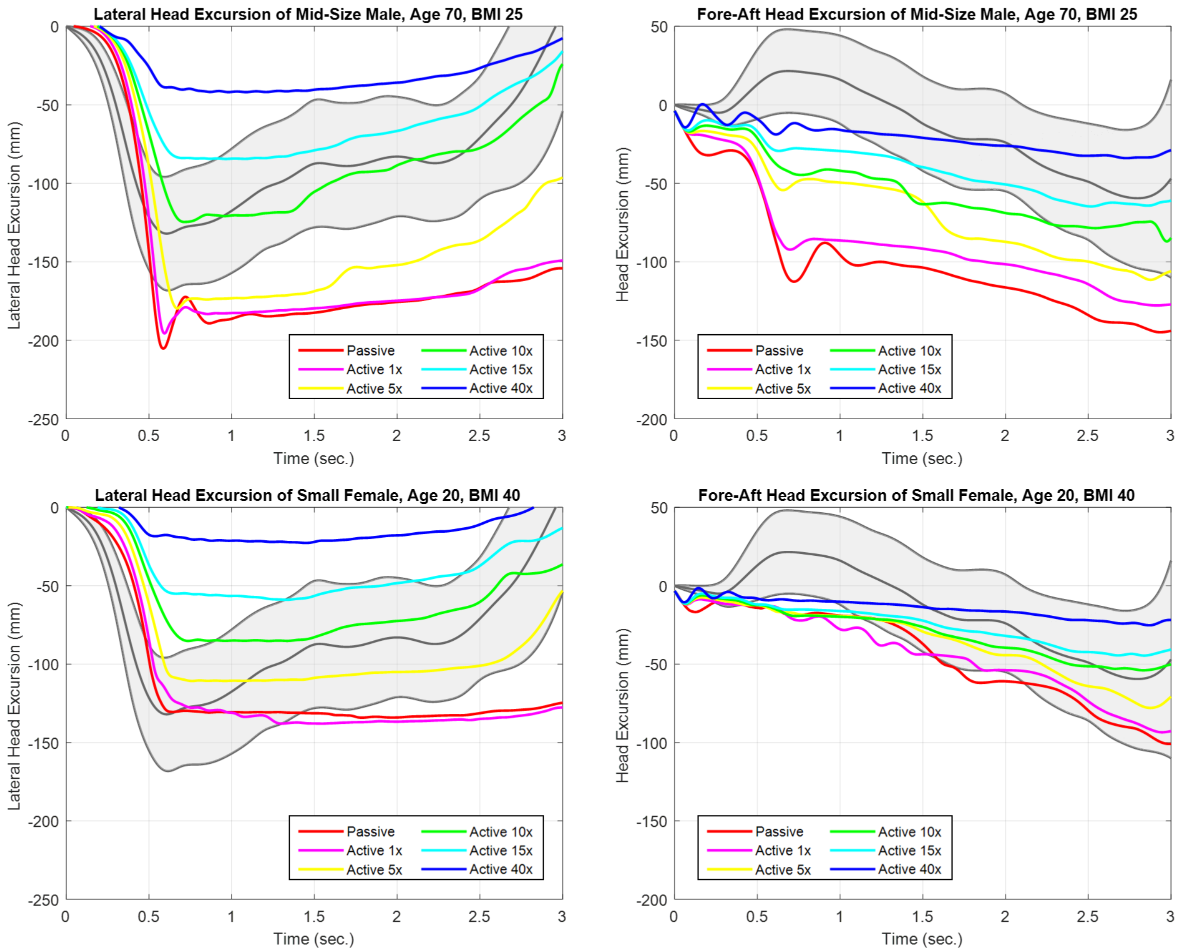


Figure 28. Head forward and lateral excursion time histories from two of the active GHBMCsi-pre models (first: midsize male stature, age 70, and BMI 25, second: small female stature, age 20, and BMI 40) with different levels of PID controls in abrupt braking condition

Task 3: GHBMCsi Positioning Tool

Because the active GHBMCsi-pre model is developed based on the GHBMCsi, the posture and position predicted by the GHBMCsi-pre can be used to position the GHBMCsi. The two models share the same bone and external body surface geometry and the same joint locations. Therefore, the bone locations, joint angles, and body surface geometry associated with the GHBMCsi-pre model can be directly applied to the GHBMCsi. For the limbs, the joint angle changes can be done by Ls-PrePost with the existing tree structures defined in the GHBMCsi. For joints in the torso and spine, any joint angle change may be associated with body surface and internal organ shape changes. In this study, we used a mesh morphing tool developed previously to morph the soft tissues that are affected by the torso and spine joints. Examples of using mesh morphing to reposition a GHBMCsi model into GHBMCsi-pre-predicted postures in abrupt braking and turn-and-brake conditions are shown in Figure 29 and Figure 30. We have generated a set of Matlab functions to perform the repositioning of the GHBMCsi model through mesh morphing. Those functions allow users to read the nodal coordinates from the results of the active GHBMCsi-pre and morph the GHBMCsi into the posture defined by the nodal coordinates.

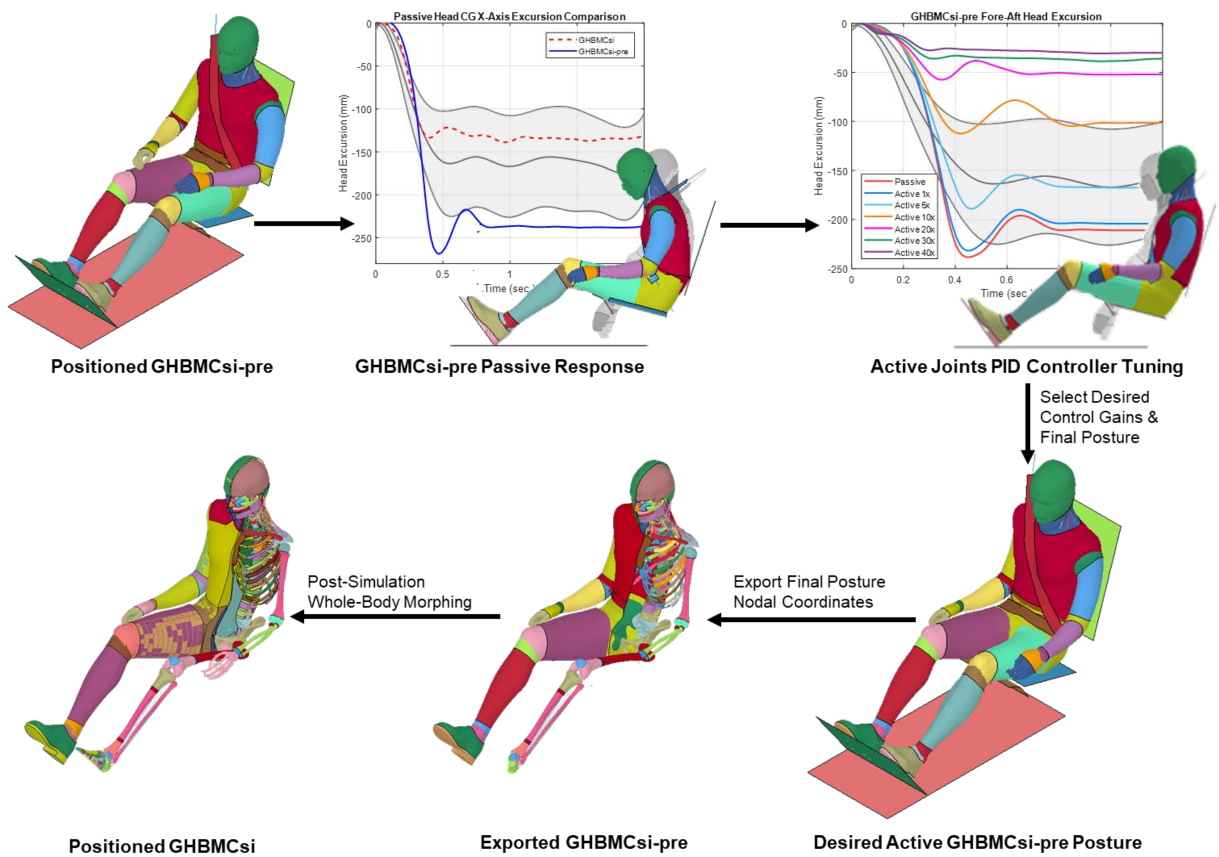


Figure 29. Demonstration of the process for using active GHBMCsi-pre responses in a braking event to position the GHBMCsi for crash simulations

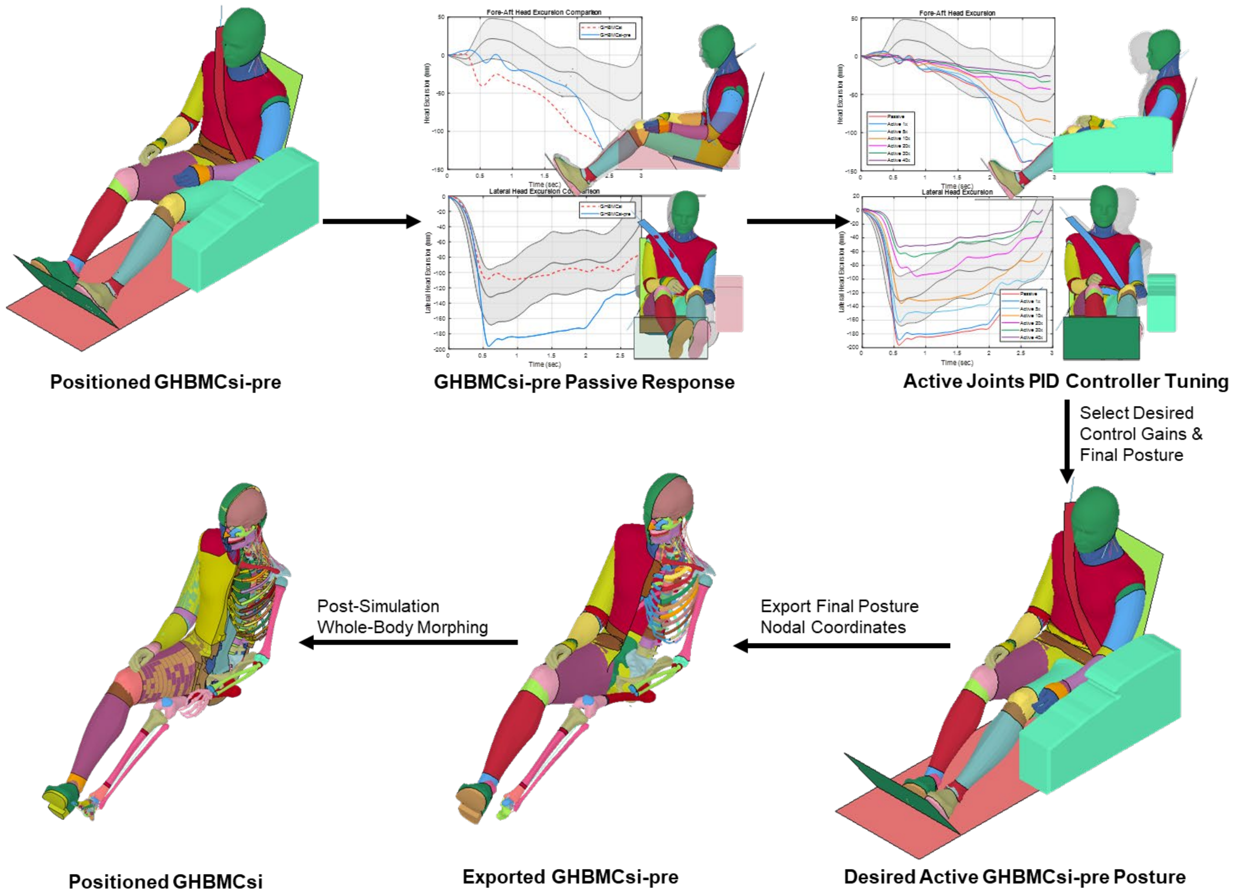


Figure 30. Demonstration of the process for using active GHBMCsi-pre responses in a turn-and-brake event to position the GHBMCsi for crash simulations

Discussion

Model Efficiency

Although active FE human models (e.g., SAFER model and THUMS v5/v6 model) have advanced significantly in the past few years, they are typically computational expensive. Given the fact that the period of pre-crash vehicle maneuvers can be 15 to 30 times longer than a crash event, a much more efficient active FE human model is needed. In this study we developed an extremely efficient FE human body model by simplifying and rigidizing the midsize male GHBMCsi model. The resulting model, GHBMCsi-pre, is essentially a rigid-body-based model with PID controllers that maintains the same skeleton and body shape geometry as the GHBMCsi model. These modifications significantly reduced the time needed to conduct a simulation under pre-crash maneuver condition. A one- to three-second braking or turn-and-brake event requires less than 4 hours to run using 16 cores on the cluster system at the University of Michigan, which is quite manageable for most research labs.

Joint Angle Versus Joint Angular Velocity for PID Control

In this study we used angular velocity as the PID control target. This is different from many previous studies, which typically use joint angle as the PID control target. Using joint angle or angular velocity as the PID control target will have profound impact on how each PID coefficient (k_i, k_p, and k_d) affects the results. For example, if joint angle is used as the target, k_i, k_p, and k_d are corresponding to the accumulated angle, instant angle, and angular velocity, respectively. If joint angular velocity is used as the target, k_i, k_p, and k_d correspond to the instant angle, angular velocity, and angular acceleration, respectively. Moreover, if joint angle is used as the target, the intent of the PID control is to keep the joint angle as zero, which means that the occupant tries to maintain the original posture. If joint angular velocity is used as the target, the intent of the PID control is to keep the joint angular velocity as zero, which means that the occupant tries to stop his/her motion.

In this study, we tested the PID controllers for both angle and angular velocity controls, and we found that both approaches can control the occupant kinematics with different levels of PID coefficients. However, because the goal of the active muscle control is to cover the variation of occupant behaviors in pre-crash maneuvers, using angular velocity as the control target allows easy control of head excursions by controlling the k_i (coefficient corresponding to the joint angle). Moreover, subject testing data showed that occupants are not necessarily trying to maintain their original posture in pre-crash maneuvers, instead they may ride on the belt and allow certain body motion. Therefore, we believe that using joint angular velocity as the PID control target is more consistent with the behavior of occupants in pre-crash maneuvers.

Age, Stature, and BMI Effects

The UMTRI subject testing revealed that age and BMI were significantly related to occupant head excursions in pre-crash maneuvers, while sex and stature were not significant. In an abrupt braking event, older occupants tend to have smaller head excursions than younger occupants, and higher BMI occupants tend to have smaller head excursions than lower BMI occupants. However, there is no evidence to show that age will significantly change the occupant biomechanical passive responses in pre-crash maneuvers. Therefore, we anticipated that the lower head excursions associated with older occupants are mainly due to behavior. Older occupants tend to be more cautious and use muscles more to control their head movement in a braking event than younger occupants. Because we have demonstrated that we can use different sets of PID coefficients to control occupant head excursions in the full range of testing data, the active GHBMCsi-pre models are able to account for the age effects through PID controls.

On the other hand, when we morphed the midsize male GHBMCsi-pre model into high BMI occupants, we had to increase the joint stiffness to match the test corridor. It is not clear whether increasing the joint stiffness is the best way to simulate high BMI occupants. We have conducted simulations under pre-crash braking conditions with the original midsize male GHBMCsi and a morphed GHBMCsi with the same height but BMI of 40. These two models share the same material properties. The results show almost identical head excursion time histories in these two models. This result, to some extent, indicated that the lower head excursions associated with higher BMI occupants may not be due to the increased weight or changed weight distribution. Nevertheless, by increasing the joint stiffness, the high BMI models can match the testing results well.

Although stature was found to be not significant in the subject testing, in the simulations we did find that in abrupt braking condition, smaller females tend to have smaller head excursions than taller male occupants, except for the older lean female model, while midsize male and large male models with the same BMI typically have similar head excursions. All the excursions are within the range of subject testing results, so we did not further change the joint stiffness values for models with different statures.

Limitations

This study has several limitations. First, all simulations were conducted with a single set of occupant restraint and passenger compartment models, and the seat model is semi-rigid. Although we think that this active human body model should be able to work in other pre-crash environments, further evaluations are needed.

Second, the GHBMCsi-pre model is intended to simulate occupant passive motion without muscle activations. However, pure passive responses are not possible to achieve with volunteer testing, and such responses may not be even useful for predicting occupant postures in pre-crash maneuvers. Therefore, we used the GHBMCsi-pre model to match or be slightly over the upper bounds of the testing corridors. We believe that this strategy is reasonable for the purpose of the current study, but it is also a compromise between testing data and modeling reality.

Lastly, causal explanations for the smaller head excursions observed with older and higher BMI occupants have not yet been identified. Intuitively, people may think the opposite, that is, older occupants may have higher excursions due to slower reaction or weaker muscles, and higher BMI occupants may have higher excursions due to higher weight and kinetic energy. In this study, we used different PID controls to account for the age effects, and we used different joint stiffness values to account for the BMI effects. Although the simulation results covered the full ranges of all testing corridors, further investigations are needed to find the root of age and BMI effects on occupant pre-crash kinematics.

Summary

In this study we developed and demonstrated an efficient tool to accurately predict occupant pre-crash kinematics in response to different types of vehicle pre-crash maneuvers.

We first conducted a literature review and found that crash avoidance maneuvers can be divided into three categories: braking, steering, and a combination of braking and steering, with braking being the most common maneuver in the field. We also found that an efficient and parametric active FE human model for pre-crash maneuvers is not currently available. Previous subject testing showed consistently high variability of occupant movement in evasive maneuver events, which may be due to the large variations in posture-maintenance tactics adopted by the individual.

We then developed an efficient active FE human body model by simplifying the midsize male GHBMCsi and adding PID controllers in the joints to simulate active muscle effects. The results showed that the newly-developed active human body model can effectively account for different levels of muscle activations and match the large range of occupant kinematics in braking and turn-and-brake maneuvers by controlling the PID coefficients. Twelve models were also generated by morphing the midsize male model into occupants with a range of age, stature, and body shape. The morphed models have also shown the capability to cover the range of kinematics in pre-crash maneuver events based on subject testing results with given sets of occupant characteristics (i.e., age and BMI).

Finally, we developed a morphing tool that can use the result of a pre-crash occupant kinematics simulation to position the GHBMCsi for crash simulations.

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