# EMMA4Drive: A digital human model for occupant simulation in dynamic driving maneuvers

**Marius Obentheuer[1], Niklas Fahse[2], Monika Harant[1], Michael Kleer[1], Fabian Kempter[2], René Reinhard[1], Michael Roller[1], Staffan Björkenstam[3], Jörg Fehr[2], Joachim Linn[1]**

[1] Mathematics for the Digital Factory
Fraunhofer ITWM
Fraunhofer-Platz 1, 67663 Kaiserslautern, Germany
[marius.obentheuer,monika.harant,michael.kleer,rene.reinhard,michael.roller,joachim.linn]
@itwm.fraunhofer.de

[2] Institute of Engineering and
Computational Mechanics (ITM)
University of Stuttgart,
Pfaffenwaldring 9, 70569 Stuttgart,
Germany
[niklas.fahse,fabian.kempter,joerg.fehr]
@itm.uni-stuttgart.de

[3] Geometry and Motion Planning
Fraunhofer-Chalmers Centre
Chalmers Science Park, 412 88
Gothenburg, Sweden
staffan.bjorkenstam@fcc.chalmers.se

**ABSTRACT**

About two-thirds of all German workers currently commute to their workplace by car without being able to engage in any meaningful activity. In the future, occupants of autonomous driving vehicles will be able to perform new activities, such as regeneration exercises, working, or consuming entertainment media [1]. This leads to many new challenges in assessing the layout of vehicle interiors, both in terms of comfort and vehicle safety. The goal of the EMMA4Drive project is to further develop the muscle-activated multi-body human model EMMA (Ergo-dynamic Moving Manikin) for use in next-generation partially or fully autonomous driving vehicles. The resulting software prototype EMMA4Drive will be able to analyze and evaluate safety and ergonomics equally during driving maneuvers under dynamic loads as a digital image of the occupant. In the automotive industry, digital human models (DHM) are widely used to simulate the human driver in the early stages of product development. Furthermore, detailed finite element (FE) models of the human body are used to simulate the highly dynamic impact and resulting injuries in the human body in crash simulations [2]. Moreover, DHM based on multibody system (MBS) kinematics are widely applied in reachability investigations and (posture-based) ergonomic assessment of the driver [3]. However, to predict active movement in dynamic driving maneuvers such as cornering, sudden braking, or lane change and pre-crash scenarios, neither FE nor simple MBS kinematic models are applicable. For a more detailed overview on DHMs in this application case, we refer to [4]. In this work, we will present an approach for the enhancement of a multibody based DHM to generate human like motions for a highly dynamic driving simulation. For motion prediction, an optimal control problem (OCP) is set up and solved. A model order reduction (MOR) approach is used to transfer driver seat interaction from detailed FE simulations to the Optimal Control (OC) framework. We use our RODOS driving simulator [5] to validate simulation results (e.g., motions, seat pressure distribution) and to identify OC parameter configurations for motion prediction.

**Keywords:** Digital Human Model (DHM), Human Body Model (HBM) Biomechanical Model, Optimal Control (OC), Autonomous Driving

# 1 INTRODUCTION

Over 70% of Germans currently use their cars several times a week or even daily. The number of registered cars has been rising continuously for years, and a trend reversal is not in sight according to current forecasts. At the same time, car sharing concepts combined with autonomous vehicles are making individual mobility attractive and possible for new user groups without driver's licenses, such as young or elderly people and people with disabilities. Autonomous vehicles will establish completely new possibilities for spending time in the vehicle in other ways than before. This will also lead to completely new interior design concepts. From the small single person shuttle to the large-capacity business van with a collaborative workstation, many things are conceivable.

In vehicle development to date, the changes to the predecessor model or a similar series have usually been comparatively minor. As a result, it was possible to draw on expert knowledge and experience, built up over decades, when evaluating occupant ergonomics and vehicle safety. Various types of human models have become established as auxiliary tools in the digital phase of vehicle development. For the "in-crash" phase, highly detailed FE human & vehicle models are used to estimate the damage to occupants in crash situations. In contrast to crash tests with the real vehicle and classical physical dummies, these simulations can be repeated and varied as often as required. The disadvantage, however, is that the simulations are very computationally intensive due to the high number of degrees of freedom. Due to that, they are only applicable for simulating a time range of a few milliseconds and are not suitable for representing active occupant behavior over a broader time frame. Due to the long computation time, only a very small number of representatives (percentiles) of a population is considered in such studies.

Quasi-static kinematic models are used to evaluate occupant ergonomics. They are used to design and evaluate the dimensions of the vehicle. For example, whether the adjustment mechanism of the steering wheel and seat in combination with the height of the headliner and the arrangement of the pedals are suitable for nearly every one of a given population or target group. For this purpose, functionalities are also available in the various tools to generate manikins with different anthropometries in order to account for as much anthropometric variance as possible. Over the years, a functional scope and workflow have been established for both computationally expensive FE models and kinematic models, which are tailored to recurring, very similar application cases. These approaches are often no longer suitable for many questions that arise with completely new interior concepts in autonomous driving since there is no prior knowledge of the new interior concepts from a previous model.

In addition, completely new questions arise with regard to comfort and vehicle safety. This does not only concern fanciful visions of the future: even in current scenarios when the car is controlled by a highway pilot, in case of a "take over request" in dangerous situations or before departures, it must be clarified how long the takeover times are, depending on position and activity, until the driver regains manual control of the vehicle. In autonomous driving, there is also another complex aspect: the design of the controller / ADAS systems. First, in terms of comfort. Which "driving style" is still perceived as pleasant depending on the activity of the occupant(s). On the other hand, in questions of safety. Where humans often could not react at all or only reflexively, ADAS systems with fast calculating processors often still have the option to choose between several possibilities and behaviors. Here, the potential danger of harming the occupants must also be considered.

All these new scenarios and questions have one thing in common: Longer time periods with active occupant behavior must be simulated, and due to the dynamics of the scenarios, inertial effects play a major role. Therefore, both computationally expensive FE models and purely quasi-static kinematic models are unsuitable.

The objective of the EMMA4Drive project is therefore to further develop the dynamic human model EMMA for the investigation of such scenarios. The EMMA model is a highly configurable MBS simulation software, which can be used to build arbitrary models. To generate motions, an optimal control problem is set up and solved, where different behaviors can be generated depending on the supplied objective function. It is sufficient to describe the boundary conditions of a task to be fulfilled in quite general terms. All generated movements as well as joint or muscle actuations, which lead to the fulfillment of the task, are the result of the solved OCP. In contrast to control approaches based on, e.g., motion capture data, EMMA does not require hardware setups, and the behavior changes when physical quantities, such as weight, external forces, or inertial forces resulting from acceleration, change. Thus, EMMA is well suited to make good predictions for human behavior even for unknown scenarios.

In previous investigations with EMMA, such as in assembly planning, good motion predictions could already be achieved compared to laboratory experiments [6]. The challenge in using EMMA in (autonomous) driving is mainly to adequately represent the driver-seat interaction without losing the advantage of fast computation time. For this purpose, a MOR approach [7] is investigated in the EMMA4Drive project: a surrogate model is learned in an offline phase using results from detailed FE simulations. For simulated configurations between driver and seat, the resulting forces and moments are learned and interpolated to states between the simulated configurations using a machine learning approach. The influence of the geometry is included based on simplified collision geometries. In an online phase in the EMMA model, the learned resulting forces between the driver and seat are then output from the surrogate model depending on the configuration and taken into account in the simulation.

Another challenge to prepare EMMA for the "driving test" is to identify suitable parameters for motion prediction using optimal control. To generate different behaviors, different objective functions can be minimized individually or mixed. Even though a lot of experience already exists here for other application fields (e.g., assembly simulation), it is expected that new parameter settings will have to be determined for occupant behavior in dynamic load cases in the vehicle. This should also make it possible to represent different occupant behaviors in the vehicle: occupants aware of the traffic situation and therefore prepared for a lane change or an (emergency) braking situation, will most probably have a different motion profile and sense of comfort than those who are engrossed in another activity in the vehicle and get surprised by the forces occurring.

To evaluate different generated motion profiles of EMMA, driving tests are done using the driving simulator RODOS. Different scenarios (e.g., a lane change or a braking maneuver) are performed with different speeds and accelerations. The test persons either follow the traffic situation attentively, solve tasks on a tablet, or relax with closed eyes in a lying position. During the test, the body (segment) movements are tracked, and the seat pressure distribution is measured. In addition, the perception of comfort is subsequently discussed via a questionnaire. In this way, the correlation between body segment velocities, seat pressure distribution, and comfort can also be derived, which will be used for the evaluation of new scenarios.

In this paper, we give an overview of the perspectives and the actual state of the EMMA4Drive project, which has a duration of 3 years, and we are currently in the middle of the project. In Section 2, we present the MBS software of EMMA and the optimal control framework for motion generation, in Section 3 the implemented MOR approach, and in Section 4 the performed validation experiments. In Section 5, two application examples are shown.

## 2 THE DIGITAL HUMAN MODEL EMMA

The EMMA model is based on a highly configurable MBS simulation software. Limbs are modeled as rigid bodies, connected via joints, that are limited to the range of motion of a human being. The model(s) can be actuated via joint torques, hill muscles, or muscle torque generators (MTG) [8]. The MBS dynamics module is embedded in an OC framework, which handles, among others, the opening and closing of contacts, boundary conditions, and constraints that are to be fulfilled during the entire motion. The desired actuation (torques and muscle or MTG activations) that fulfills the equation of motion of the MBS and the prescribed constraints while minimizing a given cost function, is the output of the solved OCP and results in the motion of the manikin.

A time-continuous OCP is defined abstractly by the following formulas:

$$\min_{q,\dot{q},u} J = \int_I \phi(q,\dot{q},u)dt \tag{1}$$

$$\frac{\partial L}{\partial q}(q,\dot{q}) - \frac{\partial}{\partial t}\frac{\partial L}{\partial \dot{q}}(q,\dot{q}) + F(q,\dot{q},u) + F_{MOR}(q,\dot{q}) + G^T(q)\lambda = 0\,, \tag{2}$$

$$g(q) = 0\,, \tag{3}$$

$$b^- \leq b(q,\dot{q},u,\lambda) \leq b^+. \tag{4}$$

The variable $q$ represents the temporal trajectory of the MBS and the control signals for muscles and joint torques are combined in the variable $u$. In (1), the objective function $J$ is introduced, where $\phi$ is a measure of the state of the system. As a side constraint, the constrained Euler-Lagrange equations (2)-(4) must be fulfilled, where $L$ represents the Lagrangian of the system, $F$ the control forces, and $F_{MOR}$ the force from the reduced interaction model. The function g summarizes the constraints of the dynamical system, $\lambda$ is the corresponding Lagrangian multiplier, and $G \coloneqq \partial g/\partial q$ the constraint Jacobian. Additional equality and inequality constraints can be included in the optimal control problem by the function $b$ with corresponding lower ($b^-$) and upper ($b^+$) bounds. Altogether, the solutions of the OCP are temporal trajectories of the MBS $q$, the control signals $u$, and the Lagrangian multipliers $\lambda$.

In order to solve the optimal control problem, the continuous problem (1)-(4) is discretized into a non-linear problem using the discrete mechanics approach DMOCC (discrete mechanics and optimal control with constraints) [9]. The discrete equations of motion derived in this way have been shown to be superior to standard discretization since they preserve characteristics of the continuous system, such as conservation of momentum and good energy behavior. This results in very stable integrators, which in practice allows for the use of large timesteps when solving the optimization problem (1).

## 2.1 Developments of EMMA for driving

For using EMMA in the application field of occupant ergonomics, some further developments were made. An importer for CAD geometries was developed, which allows to load (relevant parts of) vehicles. Kinematics of e.g., steering wheel, seat kinematics, or gear stick can be modeled as joints and be included in the OCP.

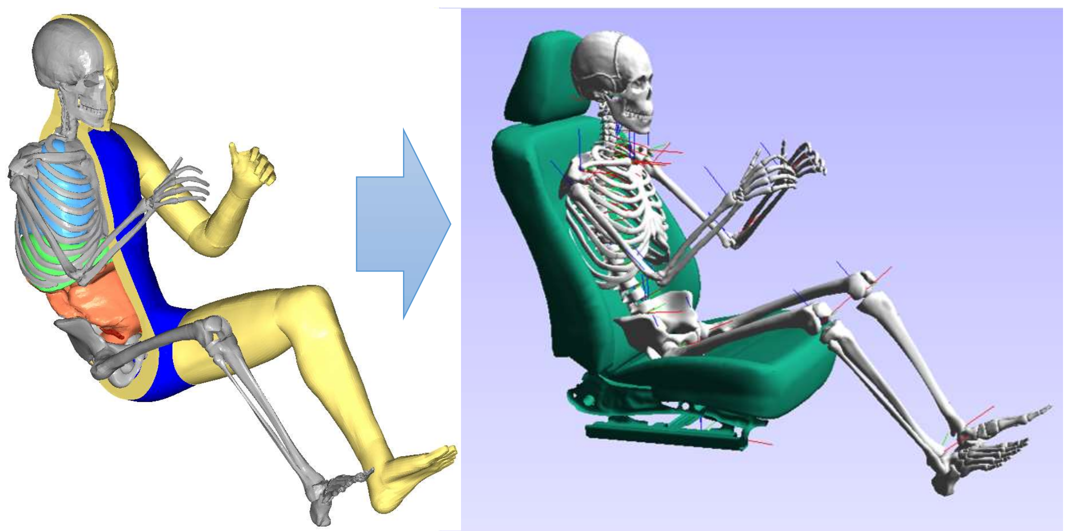

**Figure 1.** *Transfer of the THUMS skeleton (left) as an MBS model for EMMA (right). This allows to transfer position and motions between FE simulations and EMMA, which is also a vital step for the implemented surrogate MOR model. For MBS model control, joint coordinates from the PIPER project were used.*

Further on, it was necessary to be able to import “state of the art” manikins, which was important for two reasons: First, to implement the surrogate model for the MOR approach, it was vital that both sides (on- and offline phase – see Chapter 3) use the same model. Second, it allows to transfer positions and motions between the EMMA4Drive model and well established FE models (both directions). So, EMMA can e.g., be used as a pre-processor tool to position FE Models, which is still not an easy task, especially for new postures. Moreover, the results of EMMA (positions, velocities, accelerations) can be used in post-processing for detailed FE simulations, e.g., when going from *pre crash* to *in crash* phase.

Therefore, the THUMS (**T**otal **HU**man **M**odel for **S**afety) [2] skeleton model was transferred into a rigid MBS in EMMA ($50^{th}$ percentile man). To obtain the properties of the human body parts relevant for dynamics, the properties of the individual FE objects, such as mass, CoM, and inertial components, were also transferred and assigned to specific segments in the MBS model. Joint coordinates definitions to control the model were implemented as described in the PIPER project [10]. The origin-, insertion-, and via points of the 29 Hill muscle, which actuate the 7 DoF arm model in EMMA, were also transferred and assigned to segments of the new skeleton model. All assignments were done via a generic script so that the transfer can be performed automated for further percentile models of THUMS (or a scaling of these) in the future.

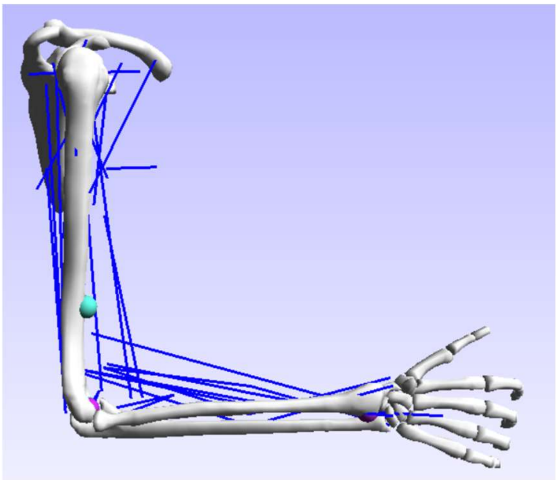

***Figure 2:*** *The 7 DOF arm model of EMMA, with bones as rigid bodies transferred from the THUMBS skeleton model.*

In order to be able to model realistic occupant behavior during (highly) dynamic driving maneuvers, further objective functions were implemented in EMMA and investigated with regard to their effects on the resulting movements. For this purpose, two additional objective functions have been implemented in the OC framework so far: The minimization of the angular momentum at the CoM, a well-known equilibrium criterion, and the minimization of body segment velocities. This can be used, for example, to keep the head still while the rest of the body is shaken or performs compensatory movements to try to maintain equilibrium during a dynamic driving maneuver.

## 3 DRIVER SEAT INTERACTION - MOR APPROACH

The correct mapping of the driver-seat interaction is essential for a realistic occupant simulation. At the same time, nonlinear structural mechanics and viscoelastic structural effects play a major role here, which leads to computationally intensive models. To include realistic behavior while keeping fast calculation times, a MOR approach was chosen for EMMA, which is separated into an online and an offline phase:

In the offline phase, long computing FE simulations are performed, where many possible configurations between driver and seat are considered. The simulations are then evaluated in an automated post-processing. For this purpose, the body was divided into different contact regions. These regions are bound to the bones, which means their (relative) orientation $r$ and velocity $\dot{r}$ is described in the bone coordinate system. This is a crucial step, to define a common language between FE-Simulations and MBS model EMMA. The resulting forces $f^{res}$ and moments $\tau^{res}$ acting between the driver and seat are then evaluated for each contact region and are used as training sets for a machine learning algorithm (including all simulated configurations between driver and seat). That means, for each contact region, a separate surrogate model is trained, which then allows an approximation of the resulting forces $f^{res}$ and moments $\tau^{res}$ between the simulated states.

In the online phase, the surrogate models are then integrated into the OCP: From the EMMA simulations, the orientation $r$ and velocity $\dot{r}$ are passed to the surrogate model, which returns the resulting forces $f^{res}$ and moments $\tau^{res}$. As already mentioned, it is important here as a common basis that the bone models and the defined contact regions are identical. This approach allows the driver-seat interaction to be incorporated into the OCP via a fast-computing model. To achieve good results, of course, a sufficient number of configurations must be simulated in the offline phase in FE, so that a good set of training data is available. In **Figure 3**, the workflow is exemplarily shown at the contact region head-neck support.

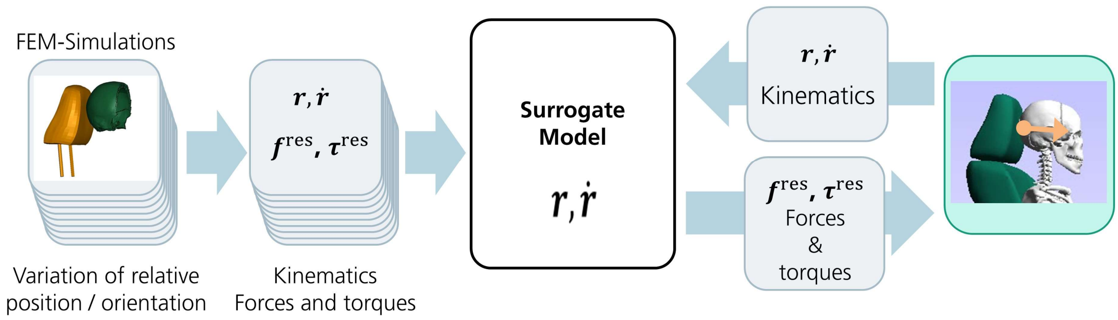


**Figure 3:** *MOR Approach for driver seat interaction at the example of the contact region „head–neck support": In an offline phase (left side), a multitude of different configurations between head and neck support is simulated in detailed FE simulations.*

## 4 EXPERIMENTS AND VALIDATION

Various measurements and hardware experiments are planned within the EMMA4Drive project. These are carried out for several reasons. On the one hand, simulation results are to be validated and substantiated. On the other hand, hardware tests should also help to identify suitable parameter sets for the OCP to be solved, so that the algorithm converges to human-like solutions. Furthermore, they allow, by interviewing test persons, correlations between measurable (or simulatable values) and personal comfort perception.

### 4.1 Pressure distribution seat

With the help of a self-designed seat tilting system, test persons can adjust different sitting postures. An off-the-shelf driving seat is mounted on the tilting system, which can also be tilted far back together with the seat surface. Test persons can thus also adjust postures that are not possible in standard vehicles, but which they find comfortable for relaxing (***Figure 4*** *– left*). This makes it possible to investigate which seat settings people would prefer, for example, for sleeping or reading in an autonomous vehicle. The seat pressure distribution is measured with the aid of a seat pressure measuring pad (***Figure 4*** *– middle & right*). In this way, positions can be identified which may be relevant later in EMMA. To achieve reliable results, for the driver-seat interaction using the MOR approach described above, corresponding training data must be generated for these positions in the offline phase using FE simulations. Furthermore, the FE simulations can be compared with the measured seat pressure distributions to validate the simulation results.

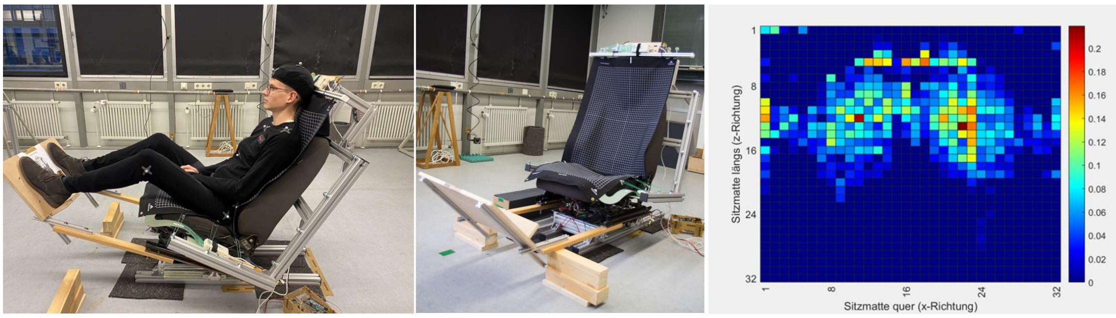


***Figure 4:*** *Experimental setup to measure the seat pressure distribution in different positions. A tilting system allows test persons to adjust the seat so that they find it comfortable for reading or sleeping, for example. With a pressure measurement pad, the pressure distribution is captured.*

By questioning the test subjects, indications can also be obtained whether correlations exist between perceived comfort and seat pressure distribution in static load cases (depending on the activity).

### 4.2 RODOS driving simulator

The RODOS driving simulator is an interactive motion simulator based on an industrial robot at the Fraunhofer ITWM. With 1000 kg payload, RODOS allows the use of series cabs and chassis, so that the feel and haptic impression are close to real vehicles. A seamless projection of an interactive scene is generated within a spherical projection dome of 10 m diameter. Compared to conventional hexapod platforms, the range of motion of the robot system is exceptionally large. It is currently the most powerful driving simulator of the Fraunhofer-Gesellschaft and is used for the simulation and testing of driver-vehicle-environment interaction under excellent reproducible conditions. In the past 10 years, driving simulations have been carried out in both the passenger car and commercial vehicle sectors to support product development from design to evaluation, thus building up expert opinions on the use and assessment of assistance systems.

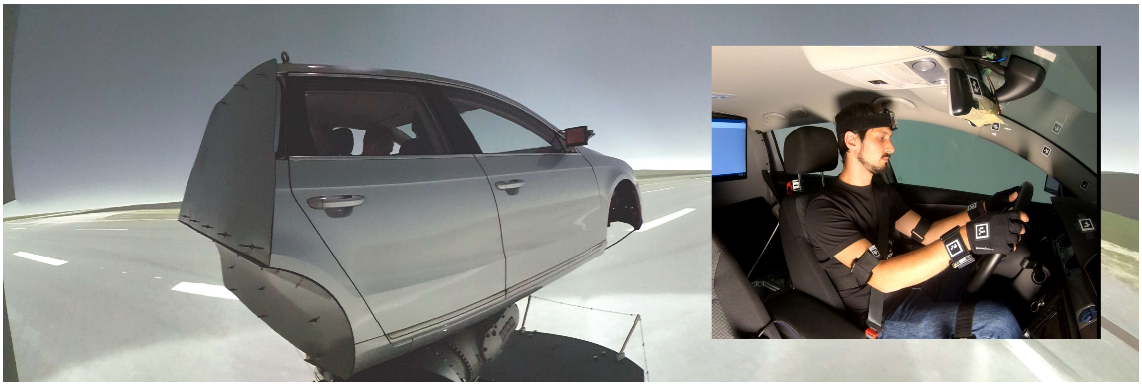

***Figure 5:*** *The driving simulator RODOS enables Occupant Behaviour investigations in different, exactly reproducible scenarios. A series cabin of a passenger car is mounted on an industrial robot, surrounded by a 10m diameter spherical projection dome which generates a seamless projection of an interactive scene.*

For RODOS simulations in the EMMA4Drive project, a modified series cabin of a passenger car is used as depicted in ***Figure 5***. The same vehicle seat is used for static measurements with the tilting system as described above, to allow a comparison of static and dynamic measurements. Occupants' motions are tracked via a camera-based optical tracking system and are additionally filmed with a classical video camera.

A total of 3 scenarios are planned, each with distinctive design variants:

i. Occupant-seat interaction during a lane-change maneuver.
ii. Relaxation in zero-gravity position.
iii. Takeover request of the vehicle in hazardous situations.

For i. a pilot study with 37 subjects has already been conducted [5]. In this study, a swerving maneuver with noticeable lateral accelerations and yaw rotations in three different seating conditions was performed. Condition a) was an “alert” scenario, where participants were sitting upright in a normal driving posture and had to keep their hands on the steering wheel (partially automated driving – level 2), while the ADAS system performed the swerving maneuver. Condition b) was the “hands-free” scenario, where participants were placed in the same upright seating position but were not forced to keep their hands on the steering wheel and were not aware of the traffic situation (focus on a mobile phone). Condition c) was the “reclined” scenario, where test persons were lying back in a fully reclined seat (and did also not monitor the traffic situation).

Subsequent questioning of the subjects evaluated their experience in terms of overall comfort, localization of discomfort, their confidence in the autonomous driving system, and their perception of safety. Significant differences in comfort ratings and confidence were found between the "alert" and "hands-free" conditions, but not between the "upright" and "reclined" seat conditions.

Initial evaluations of the motion data also provide indications of a correlation between attention to the traffic situation and acceleration of body segments, and an associated perception of comfort. In order to better represent these motion behaviors in the EMMA simulation, the objective functions described in Section 2.1 were implemented. In a current evaluation of the data and a planned follow-up study, this relationship will be investigated in more detail (also including measurement of seat pressure distribution, which was not done in the pilot study due to delayed delivery of the measuring pads). An exact replication of the RODOS driving tests in EMMA (with the same vehicle trajectories) is also currently under development.

## 5 APPLICATION EXAMPLES

Two application examples of EMMA simulations are presented below. In 5.1 preliminary investigations can be seen, which were used at the beginning of the project to identify the existing strengths and necessary further developments for an occupant simulation with EMMA. In 5.2, the first results for a driver-seat interaction are presented using the example of head and neck support with the MOR approach described in Chapter 3.

### 5.1 Emergency break with inactive seat belt

In this scenario, an emergency braking maneuver is simulated using an existing MBS EMMA model of the human from previous studies [11]. The arms are controlled by Hill-type Muscles, whereas the rest of the joints are controlled by joint torques. The car is modeled as a simplified platform with pedals, a steering wheel, a backrest, and a seat surface. The feet and buttocks of the Manikin are rigidly connected to the seat surface and pedals, with the constraint forces restricted so that Coulomb’s law of static friction is fulfilled. The position of the feet and buttocks are arbitrary, which means they are a free variable and output of the OCP. The simulation is split into two phases: In the first phase, the platform accelerates to a velocity of 5 $m/s$ from a resting start position (***Figure 6** - left*). During this phase, the manikin is fixed in a position that it can freely choose at the beginning. This is done to prevent the manikin from being able to react in advance to the braking accelerations that will occur in the “future”. At the beginning of the second phase, the platform is immediately stopped (0 $m/s$) by completely absorbing the kinetic energy of the vehicle by a phase-specific constraint force (***Figure 6** – middle*). At the end of the second phase, the manikin is constrained to be in a rest position. As the simulation is performed without an active seat belt, EMMA must absorb all the kinetic energy by muscle forces. As these are limited to human-like force parameters, it cannot counteract the accelerations instantaneously and the upper body of EMMA is accelerated towards the steering wheel (***Figure 6** – right*), to fulfill the task.

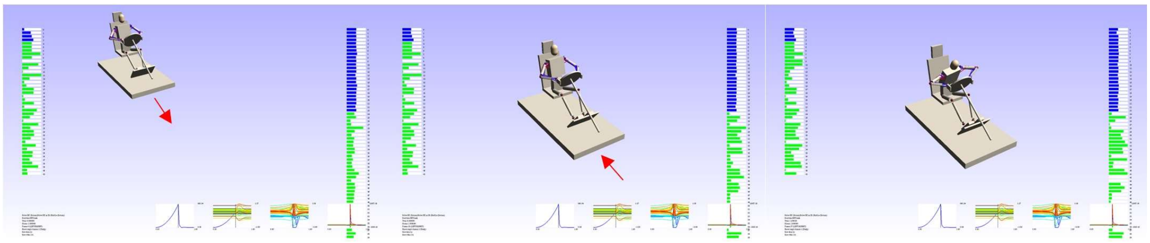

***Figure 6:*** *Simulation of an emergency braking with EMMA*

With this simple preliminary investigation, it could already be shown that the EMMA model is suitable to generate human movements in dynamic driving scenarios. It should be emphasized that all movements and joint and muscle actuation are the pure output of the OCP, and only the few constraints described above had to be defined. This means that no time-consuming forward kinematic positioning of the manikin is necessary, and no motion capture data has to be determined in hardware experiments. The calculation time for the simulation shown is in the range of minutes. This means that different variants (seat positions, acceleration profiles, manikin anthropometries, force parameters of muscles and joints, etc.) can be examined very quickly. This can be used, for example, to identify from a large number of variants those that are critical in terms of occupant safety or comfort. These scenarios can then be further investigated with more detailed and time-consuming FE models.

## 5.2 Head and headrest interaction with the surrogate model

In this use case, initial investigations were conducted to test the surrogate model implemented in EMMA as described in Chapter 3. The EMMA model lies with the upper body fixed in a horizontal rest position and is supposed to move the head from a given start position to a given end position (***Figure 6*** a) & b)). The motion is defined as “rest to rest”, meaning that segment velocities at the start and end configuration are zero. In the case without the surrogate model, the neck support is ignored, which means that the model must hold the given end position by an appropriate joint moment against gravity (see ***Figure 6*** f). In the case of the implemented surrogate model, it can be seen how it outputs a contact force from a certain position, which significantly reduces angular velocity and joint moment in the neck, and influences neck flexion – time curve (***Figure 6*** c) – f)). The corresponding return values of force and moment of the surrogate model are shown in Figure 6 g) & h) in the second row.

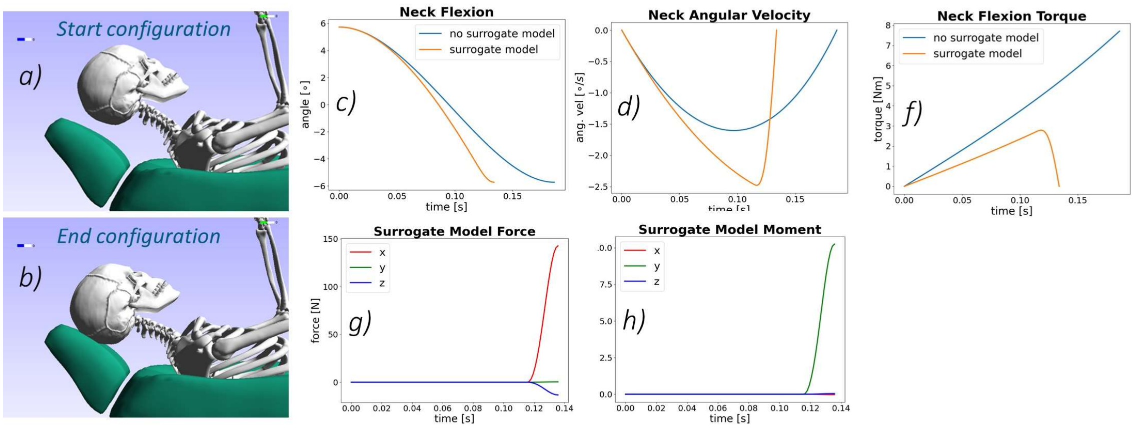


***Figure 7:*** *EMMA Simulation with the Surrogate Model integrated into the OCP*

# 6 CONCLUSIONS

In previous studies, it has already be shown that the MBS model "EMMA" in connection with the optimal control approach is well suited to predict human movements for unknown scenarios, e.g., in the assembly simulation. The used DMOCC approach for discretization allows large time step sizes, which leads to very fast computation times (in the range of minutes). Despite complex biomechanical modeling with, e.g., hill muscles as actuators and resulting redundancy problems, this approach proves to be very robust. In the EMMA4Drive project, initial simulations have already shown that EMMA is in principle also suitable for predicting human behavior over longer time ranges in dynamic load cases in the area of occupant simulation. This fills a gap between the very simple posture-based kinematic models and very complex FE models. The driving tests performed on the driving simulator RODOS allow validation of the simulation results, and the identification of necessary parameters for the OCP. To adequately integrate the driver-seat interaction into EMMA, a promising MOR approach was developed. Using the simple example of head-headrest interaction, the integration into the OCP has already been demonstrated and successfully tested. Whether the approach is also robustly suitable for an entire mapping of driver and seat in different positions has to be investigated in the further course of the project. There are also initial indications for the correlations between (subjective) comfort and safety perception and measurable variables such as body segment velocities and seat pressure distribution. These need to be investigated in more detail in further driving tests and experiments in conjunction with subject surveys. In summary, the EMMA model is a promising tool to support the assessment of new and unknown interior concepts in combination with dynamic load cases, as they will be encountered, e.g., in autonomous vehicle concepts.

## ACKNOWLEDGMENTS

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