A Method for Reproducible Landmark-based Positioning of Multibody and Finite Element Human Models

Christoph Klein, María González-García, Jens Weber, Freerk Bosma, Richard Lancashire, Dominik Breitfuss, Stefan Kirschbichler, Werner Leitgeb

Abstract The basis for comparable occupant simulations with different Human Body Models lies in well-determined initial model positions. Therefore, a repeatable method which positions the Human Models according to a settled target posture is required. Moreover, the existing anthropometric variations between different Human Body Models need to be considered. The available tools are focusing on positioning methods, whereas the required capability to adapt the input target data to a certain Human Body Model's anthropometry was not found in current literature. The presented method covers both steps: 1) the positioning of different Human Body Models to an adapted target position based on their anthropometry and 2) their settling on the seat. For this purpose, a set of consistent landmark coordinates relative to a seat environment is required as target posture for the positioning of different Human Body Models. This procedure is demonstrated for two Finite Element Human Body Models. The trajectories which transfer the models to their target positions, were calculated automatically with an executable script in the software PIPER. Besides, the positioning of the Multi Body Human Body Model was done with the existing Madymo pre-processor. Furthermore, a gravity-based method was applied to reach a realistic contact situation. After the positioning process, it is shown that the three models reach a common posture with the maximum deviation of 10 mm at the knee due to different femur lengths.

Keywords Finite Element Human Body Model, Multibody Human Body Model, Positioning, Anthropometric adaption, PIPER scripting

I. INTRODUCTION

New interior concepts for Highly Automated Vehicles (HAVs) are expected to allow occupants to relax and sit in non-conventional postures. In addition, the introduction of HAVs might lead to new accident scenarios which, together with the new seated postures, will lead to new load cases for the occupants. Currently, homologation and safety rating evaluations are performed using dummies. However, these human surrogates present some limitations to be solved for the safety evaluation of new HAVs. Nowadays, specific dummies are applied to certain load cases. Furthermore, they are designed to fit standard seated positions rather than a relaxed posture in an HAV. In contrast to dummies, virtual Human Body Models (HBMs) allow a more flexible analysis, since they are load case independent and can be placed in relaxed seated postures. Nonetheless, they are usually delivered in only two positions: upright for pedestrian application and seated in a standard driver posture for occupant simulation. The initial positioning phase of an HBM is not only a challenge for its application in HAV environments, but also for their validation and for future virtual testing procedures. Experiments with Post Mortem Human Subjects (PMHS) or volunteers most likely will have a different posture and anthropometry than that of the provided HBMs. To validate those models against the experimental data, they first need to be fitted to the same posture. Furthermore, if different HBMs in different codes are to be compared, a determined and analogous initial position between them is required to achieve comparable and consistent results. This is a needed step for the definition of virtual testing.

One important requirement for a positioning tool to enable the comparison between HBMs in different codes is to be code- and HBM-independent [1] [2].Several methods have been developed for positioning Finite Element (FE) HBMs with the aim of improving the efficiency and accuracy of this process. Mainly, these can be categorised into geometry-based and simulation-based methods [2] [3] [4] [5]. The former method has the advantage of saving computational time. Nevertheless, stresses and strains generated during the positioning are neglected in

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the subsequent simulation steps. Another drawback of the geometry-based positioning is the degradation in the mesh quality of the soft tissues [3] leading to poor numerical initial conditions. Nonetheless, some efforts have been made to enhance the mesh quality after positioning by using smoothening methods [2] [4] [6] [7] .

On the other hand, the simulation-based approaches move the FE HBMs to the desired position by considering physical laws, i.e., material properties or contact forces. One strength of this method is, that the actual deformations are calculated, thus no remeshing should be needed after the positioning process. The most common approach is to set target angles or coordinates to translate the involved body regions of the FE HBMs [2]. By implication, the anthropometry of the test data (PMHS or volunteer) will not coincide with the HBM's anthropometry. Thus, if the exact same coordinates are used the HBM will be morphed rather than merely positioned. Therefore, several researchers [8] [9] [10] [11] [12] [13] have selected the angles as their input data for the positioning. Whereas, the target coordinates were only used when the corresponding HBM was morphed prior to the positioning [14]. Recently, [10] based their target positioning data on a prediction from volunteer testing [15] in which 24 volunteers were seated in three different postures. Additionally, [16] reported a method in which the target data is based on the "Rechnergestütztes Anthropometrisch-Mathematisches System zur Insassen-Simulation" (RAMSIS) ergonomic model, pursuing for a human-like posture, instead of using experimental data. However, this method is mainly addressing a human-like position of HBMs in the vehicle development process.

Besides, reference [17] set the muscle length as the positioning parameter. Following this approach, the model reaches the target position by activating the muscles.

Lately, a reduced order model methodology [18] has been developed for positioning FE HBMs to the desired position based on pre-run simulations. This approach seeks for a simulation-based positioning, while being computationally efficient. Nonetheless, this method is HBM-dependent.

In contrast, the positioning of Multi Body (MB) HBMs is less complicated since they are based on physical joints, hence, contact issues between parts of the body do not play a role. For instance, in case of the Simcenter Madymo HBM the positioning is done using its own dedicated pre-processor [19]

The positioning tools developed to date allow placing an HBM to a certain position. However, none of them enables positioning different models, using different codes and with slightly different anthropometries to the same target position without morphing them. It has been stated that even positioning the same HBM to a certain target using different positioning tools might result in slight differences in the final position leading to up to 30% difference in the rib strains [13] [20]. Therefore, a common, reproducible and HBM-independent tool is desirable to enable comparison between different HBMs.

The aim of this study is to present and demonstrate a simulation-based methodology which enables the positioning of different HBMs to a similar position derived from any input target data. For this purpose, a process is required to scale the input positioning target data to the HBM's anthropometry.

II. METHODS

The HBM anthropometry is unlikely to correlate exactly with another given (human) anthropometry, i.e., from PMHS test or volunteer study. Hence, the coordinates for the landmarks, which characterise the target posture, need to be adapted to the individual HBM. Therefore, in this study the anthropometry is defined by means of a vector-based posture description, which is based on anatomical landmarks on bones. Detailed definitions of the used landmarks can be found in [21] [22] [23]. By implication, the selection of landmarks on the HMBs depends on the available target data.

The aim of the presented method is to position an HBM to the posture of available target data, while maintaining its initial anthropometry. The definition of a posture as shown in Fig 1 can be done in several ways. First, the vectors depicting the HBM are calculated to reach certain angles. Alternatively, as a second possibility, the vectors are calculated to reach certain coordinates. The later method might be required if, the hand should touch the steering wheel, for instance. Depending on the use case and the available target data the posture definition and the required accuracy of the positioning process vary.

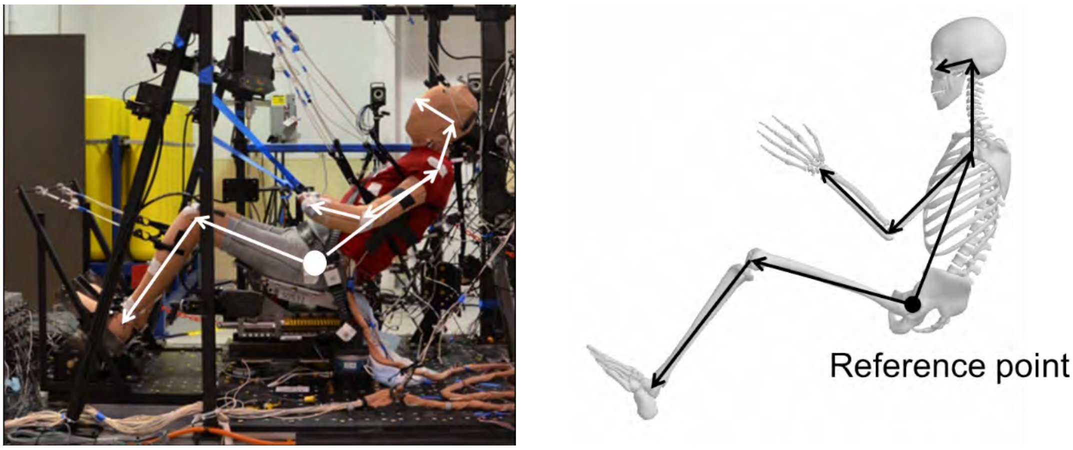

Fig. 1. Vector-based posture description demonstrated on THUMS v3 and on a PMHS **[24]**

The vector-based posture description requires at least one reference point, to which the vectors are related. For this study, the acetabular centre serves as reference point. The reference point for each vector needs to correspond to a known landmark, which also acts as the rotation centre for the depicted body part. This vector-based structure is further defined for the HBM as well as for the test data. Specifically for this publication a PMHS data set is used as test data. The landmarks of the test data are used to define the vector-based posture description in the test data and in the HBM (Fig. 1).
The vector-based posture description is done similarly for FE and MB models, whereas the positioning process differs fundamentally, so different strategies have been pursued. The link between the posture descriptions in both kind of models consists of its corresponding landmarks. Fig. 2 shows the necessary steps in the positioning process.

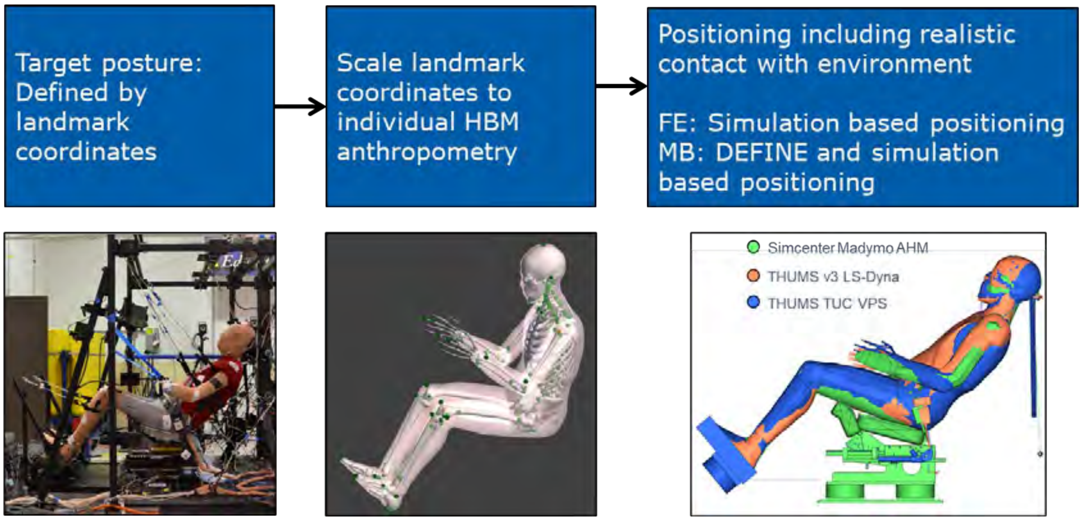

Fig. 2. Positioning process starts with the definition of landmarks from PMHS test **[24]** , followed by the anthropometric adaption of the input data to the HBM anthropometry. Lastly, generation of simulation input files and a gravity-based contact simulation.

Positioning of FE Human Body Models

A tool was developed to position FE HBMs, which is executable in the PIPER software [1] [25]Hence, the tool takes advantage of using the well-defined metadata of PIPER to achieve a HBM-independent positioning process. The developed script entails FE solver input files, which enable occupant positioning simulation. The advantage of an FE solver over a remeshing algorithm is that the FE solver calculation is based on physical laws factoring in, e.g., material properties.

During the positioning simulation, the HBMs are pulled from their delivery posture to the target posture by prescribing kinematic motion. To determine the HBMs target posture, the landmark coordinates of the test data are scaled to the anthropometry of the HBM by using the vector-based posture description. The necessary trajectories to pull the HBM from the delivery posture to the target posture are subsequently calculated. The number of discretization points of the trajectories and the simulation time can be changed by the user via a GUI. For this study a simulation time of 400 ms for the trajectory was chosen, followed by 800ms gravity ramping and resting time to minimize oscillations.

This is done without applying gravity; besides, a geometric offset to the environment is needed to avoid any contact while moving the HBM to the target posture. In order to finalise the positioning procedure and to broach a model with a realistic contact scenario a gravity-based seating method is applied. That method is further explained in this chapter under “Obtaining realistic contact forces”.

Adaption of the target coordinates based on angular position

For the anthropometric adaption of the target coordinates, the aforementioned vector-based description has been used. For each part in that HBM depiction, the number of available target landmark coordinates per body part is decisive for the calculation method.

Rotation centre and one landmark

The vector of the HBM was rotated towards the test data vector. That guarantees target coordinates, which lead to the same angle and maintain the anthropometrical length of the HBM.

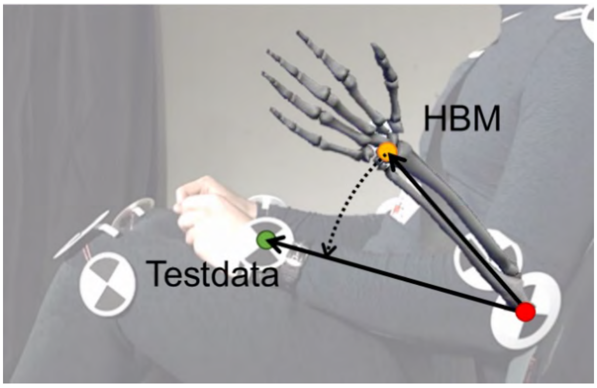

Fig. 3 Computation of HBM target coordinates on basis of a rotation centre and one landmark.

Rotation centre and two landmarks

The rotation centre and two landmarks in the test data define a plane The HBM landmarks are rotated on that plane Since the angle in the HBM (α_{HBM}) and the angle in the target data ($\alpha_{Testdata}$) might not be equal, the coordinates of the HBM landmarks are calculated in order to balance the difference between α_{HBM} and $\alpha_{Testdata}$. Note, that the distances in the HBM between these three points need to stay unchanged.

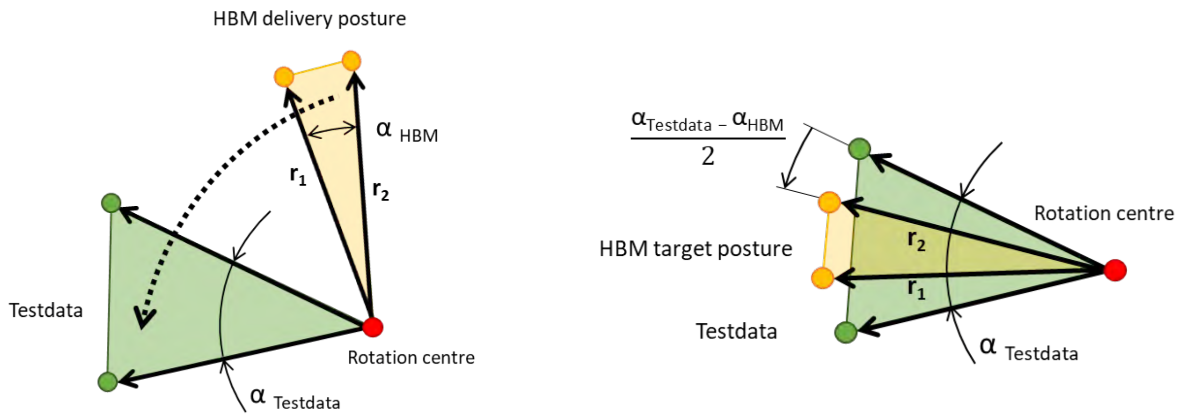

Fig. 4. Computation of HBM target coordinates on basis of a rotation centre and two landmarks.

Adaption of the target coordinates matching exactly the test data coordinates

The method of positioning selected landmarks of the HBM to the same coordinates is shown in Figure 6. In this example the wrist of an HBM has been positioned to target coordinates, defined by the wrist of another HBM with a slightly different anthropometry. Landmark A is rotated to its target position, which prevents the prescription of certain angles for upper and lower arm.

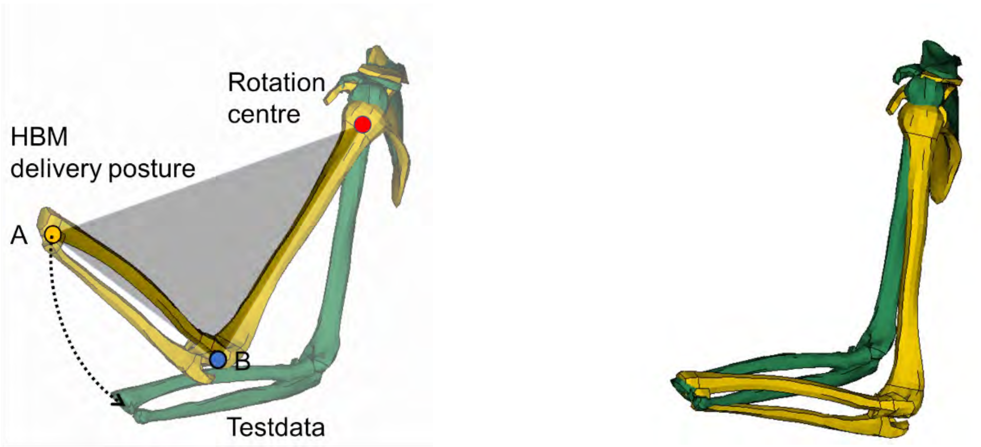

Fig. 5. Positioning the wrist of an HBM to the wrist of another HBM.

That requires degrees of freedom for the landmark B. From a geometrical point of view an infinite number of solutions for the target position of landmark B are possible. To allow a realistic computation of target coordinates for landmark B, a plane is defined by the landmarks A, B and the rotation centre (Figure 6). The computed target coordinates of landmark B need to be part of that plane. That allows the calculation of the trajectories to move the lower arm to the required posture.

Kinematic calculation

The next step is to calculate the trajectories in order to pull the model to its target position. Trajectories are determined for all landmarks with the prior adapted target coordinates. All trajectories are discretised by the same amount of interpolation points (Figure 7). The number of interpolation points can be defined by the user via a GUI. The number of interpolation points divides the trajectory into equidistant sections. Hence it was possible to pull the model along the grid points of the trajectories without breaking the anthropometrical boundaries in each step.

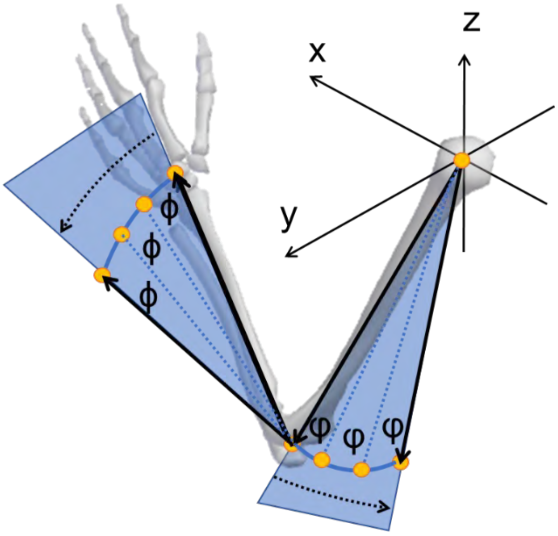

Fig. 6. Discretisation of the trajectories which lead the HBM from its delivery to its target position.

Obtaining realistic contact forces

When the HBM contacts the seat, soft tissue materials and seat materials are deformed. Pushing the model to a certain position in the seat most probably leads to unrealistic contact forces. Therefore, a gravity-based seating method was used.

The positioning of the HBM to the target posture started with an offset to the seat. When the target posture was reached the gravity seating process was launched. The gravity positioning method works in three steps (exemplarily shown for the pelvic bone in Figure 8 to Figure 10).

- To compensate the positioning dynamics in soft tissue parts, the HBM was kept in its position by locking the degrees of freedom of all landmarks, which were used for the positioning. Selected body parts (respectively the skeleton) were switched to rigid body definition. This ensured that the approached landmark position was maintained during the seated process. Note, that the HBM did not have contact with the environment at this step.
- A smooth ramp up from zero to full gravity was applied. At the same time, the displacement of all positioning landmarks of the HM were locked in x and y direction, while the z direction was unlocked.
- The HBM contacted the environment, settled to its final position while its soft tissues were deformed and a steady state was achieved.

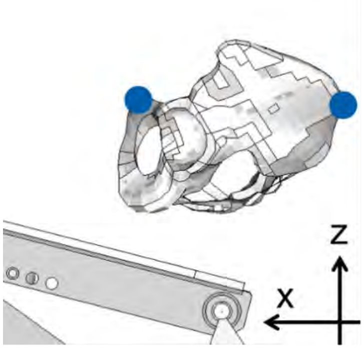

Fig. 7. Initial status: Positioning landmarks are locked

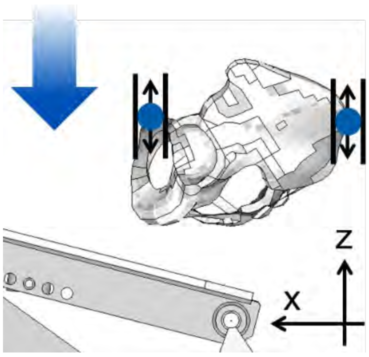

Fig. 8. Positioning landmarks are released in z-direction and gravity is ramped

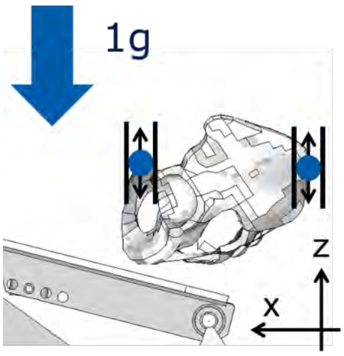

Fig. 9. Steady state is achieved

Positioning of Madymo Active Human Model

The Simcenter Madymo Active Human Model v3.1 is released as a standing and a seated HBM [19]. The default posture of the HBM quite often needs further positioning for use in a seat and environment model. To do that the HBM makes use of a parameter-based positioning method using Madymo's DEFINE functionality. A detailed description of this method can be found in [26] . This method allows users to set parameters that define the initial joint positions of the HBM. Positioning DEFINEs are present for the most relevant joints in the HBM. The DEFINE-based positioning method was developed to enable easy achievement of a certain spine posture. Instead of setting each spine vertebra angle manually, two DEFINEs can be used to set the spine posture: Thorax slouch sets the curvature of the thoracic spine and Lumbar slouch parameter sets the lumbar spine curvature. Slouch values of zero and one respectively represent a default standing and seated spine posture. Visualisation of different spine slouch settings, applied to a seated HBM, can be seen in Figure 12 left.

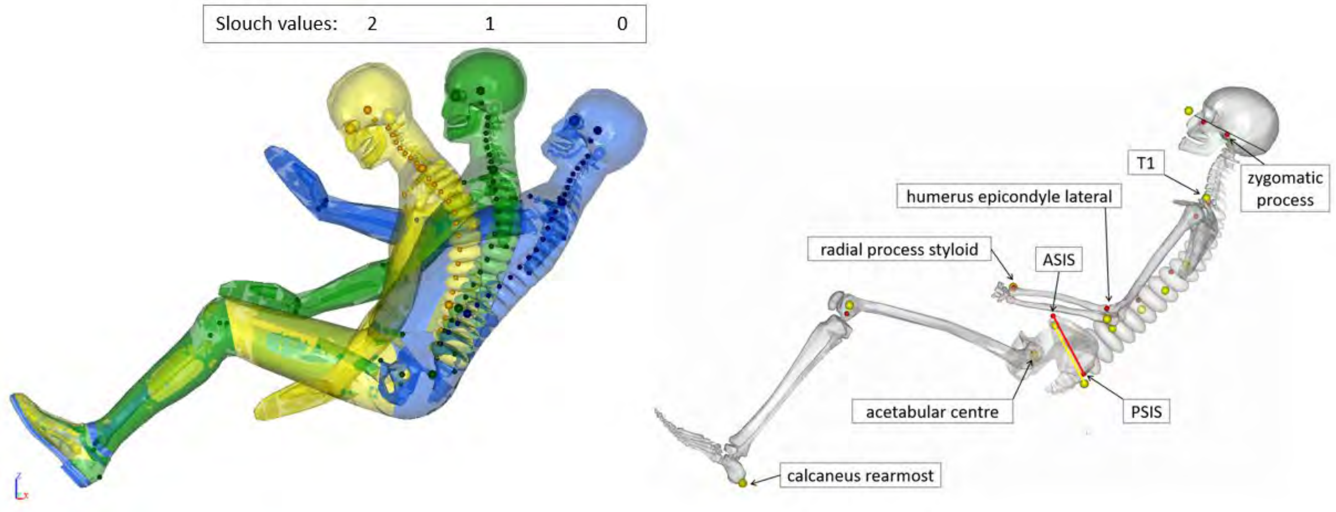

Fig. 10: Example of seated HBM with three different (0, 1 and 2) slouch parameters (left image) and HBM landmarks for positioning (right image).

To be able to position the HBM towards a set of (scaled) target landmarks, equivalent landmarks were identified on the HBM and visualised using 12 mm diameter spherical ellipsoids the centre of each of which defines the location of a landmark. The positioning of the AHM is done in a step by step process using the positioning DEFINEs to map the AHM landmarks on the target UVa landmarks (visualised as 20 mm spheres).
The position of the first joint in the AHM model, which is located between the acetabular centres (Human_jnt), was positioned at the target x-position avoiding seat penetration (a pre simulation was used to calculate the correct amount of penetration for an equilibrium position and determined the final z-position). Then the angle of the pelvis was matched with the target anterior superior iliac spine (ASIS) to posterior superior iliac spine (PSIS) angle(see Fig. 11). In the next step the zygomatic processes (left and right) were targeted to have the same x-location of the left and right porion using the slouch parameters of the spine, keeping the angle of the first thoracic vertebra (T1) to porion aligned. The calcaneus rearmost points (left and right) were then positioned to match the same x-position, while keeping the feet on the footrest. After that the radial styloid process and humerus epicondyle lateral were positioned such that the angles of the upper arm and lower arm matched the target data.

The aforementioned methods and tools were applied to position three different HBMs: The Total Human Model for Safety (THUMS) v3 in the FE code LS-Dyna [27] and THUMS TUC in the FE code VPS [28] and one MB HBM, the Active Human Model in Simcenter Madymo v3.1 (Siemens PLM Software, 2019). The target position was defined according to the posture of PMHS tests [24] in a 48° reclined seated posture.

To consider a headrest and pedals for the feet, which might be a realistic environment, coordinates in x- and z-direction for the heel (centre of medial edge on the posterior calcaneus surface) and in the x-direction for the head (porion) were also defined.

III. RESULTS

Figure 12 shows the three positioned models in a 48° reclined posture in a post processing software.

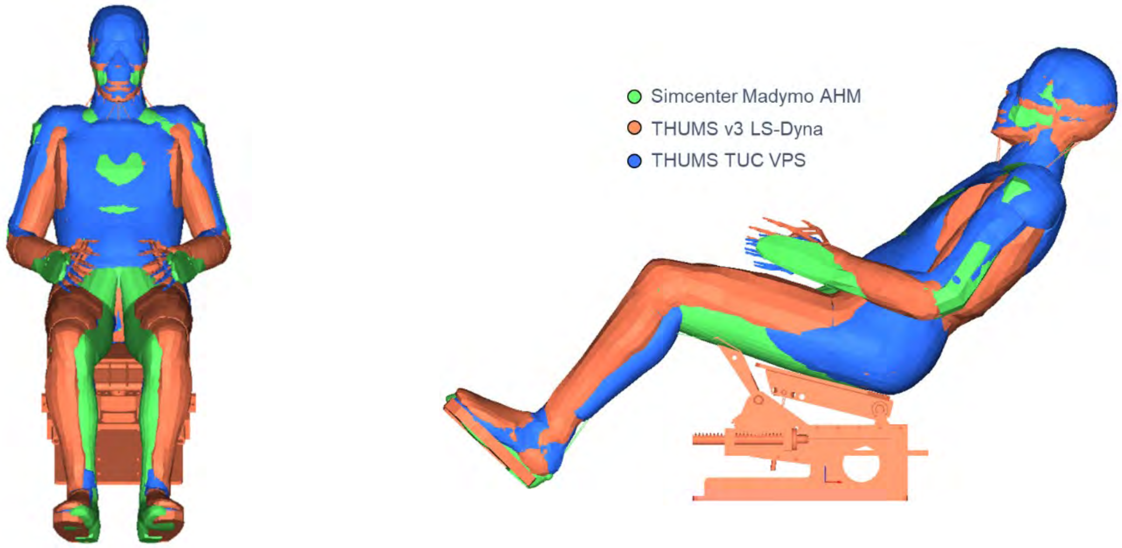

Fig. 11. Positioned HBMs (Simcenter Madymo AHM, THUMS TUC, THUMS v3).

For a better visualisation, the landmarks have been displayed in an x/z diagram in Figure 13. The aims for the positioning of the different body regions are described in more detail below.

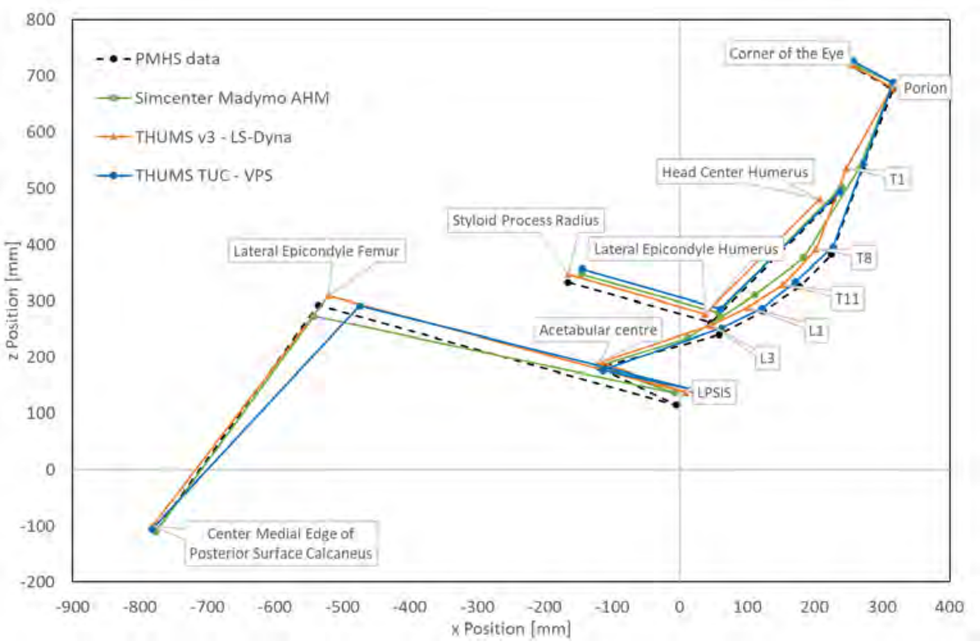

Fig. 12. Positioning of three different HBMs to the target data of PMHS tests.

Pelvis:

A closer look of the pelvis landmarks shows the anthropometric differences between the used models and the PMHS data (Figure 14). For the demonstrated positioning process, the acetabular centre served as the reference point. Hence, all models should have to be positioned exactly to the acetabular centre coordinates of the PMHS data. Figure 14 shows, that this is not the case. This offset is caused by different buttock geometries and soft tissue material properties of the HBMs, which finally led to different positions in the z-direction. Forcing the model to reach equal coordinates for the acetabular centre would cause unrealistic contact forces between the HBM and the seat.

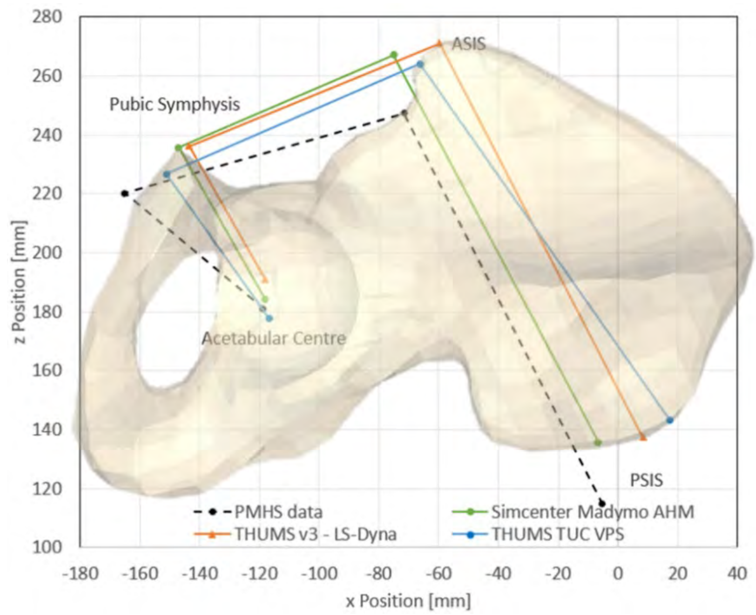

Fig. 13. Pelvis landmarks of the used models and the PMHS data.

Exemplarily, the z-position of the THUMS v3 LS-Dyna for the pelvis (acetabular centre) is shown in Figure 15 to demonstrate the phases of the seatingprocess. After reaching the target posture, the gravity-based seating process was conducted and guarantees realistic contact between the HBM and the seat pan. During the subsequent relaxing phase, the model's position in z-direction, as well as the contact force between the HBM and the seat pan, oscillated until it reached a settled state. The contact force is shown in Figure 16.

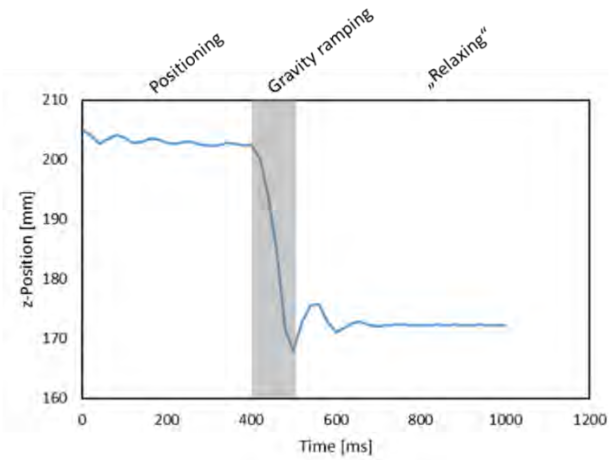

Fig. 14. z-Position of the acetabular - centre during the gravity-based sitting process of a THUMS v3.

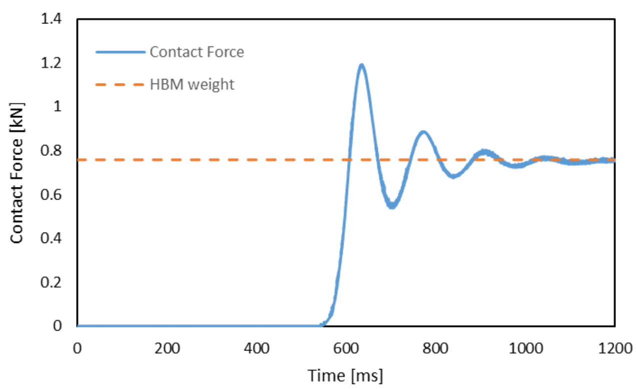

Fig. 15. Contact force between HBM and seat pan of a THUMS v3

Head

Same x-position for the porion and further on a parallel head angle, defined by porion and corner of the eye were achieved. The maximum deviation between the models is 5°.

Upper limbs

Parallel upper arm and forearm positions between the model and the test data were achieved with a deviation of maximum 6°.

Lower limbs

The requested common coordinates for the heels were reached by the models. That causes different angles between the models for the lower leg and the femur. The maximum deviation is 5mm in x-direction and up to 10 mm in z-direction. Different positions in z-direction are caused by the buttock geometry and material properties as already mentioned in the pelvis paragraph.

Spine

The largest differences can be observed in the spine region. The difference between MB and FE models are caused by the different positioning definitions for the spine area, namely the description with the slouch parameters and the vector-based posture description. The deviations between the FE models can be found in different anthropometries in combination with the aim to position the Porion to a certain x-position. That causes different angles for the section T1 to Porion which can be clearly seen in Fig. 13.

IV. DISCUSSION

In the presented research, three 50th percentile male HBMs in three different simulation codes (LS-Dyna, VPS and Simcenter Madymo) were positioned towards input target data obtained from a PMHS test series [24] . The presented method works without any modifications of the model's anthropometry and can be applied to other anthropometries and gender. This approach is chosen to avoid any scaling of the HBMs or morphing of the FE HBMs. An approach which adapts the target position to the anthropometry of the HBM and additionally creates the necessary solver input files to execute the positioning simulation was not found in literature.

As shown e.g. in [29] morphed models can predict the kinematics but need to be enhanced in order to allow injury risk assessment. The main advantage for the FE HBMs in this study is that the positioning is done via simulation, carried out by the FE solver. That means, the deformation of the model is based on physical laws defined by material properties and contact definitions. Positioning the HBMs by geometric transformations would lead to challenges especially in soft tissue covering the joints, in case of large posture changes. As mentioned in [30] these methods neither account for the physics of the model.

Since the three HBMs differ in anthropometry a sub-set of identifiable harmonised anatomical landmarks were defined for each of the HBMs in this study. To which extent the input data can deviate from the HBM's anthropometry has not been investigated thoroughly yet. The method and the tool that were developed in this study used these landmarks to enable comparable and repeatable positioning. Compared to the marionette method as used in [31] the determination of trajectories allows to directly specify the simulation time, whereas for the marionette method the simulation time is defined indirectly by the beam stiffness. [31] demonstrates the ability to position certain skeleton parts to a specified target position, but also reports deviations up to 9 mm for all body segments combined.

In this study, angle deviation between the models and the PMHS data for the pelvis orientation were detected. The presented method aims to position all body segments to their target position and additionally realizing realistic contact forces. Especially for the pelvis, where several boundaries (acetabular centre position, pelvis angle, contact to environment, forces from the lumbar spine and from the femur) influence the degrees of freedom, deviations in the pelvis angle were observed. This was also reported in [12] , where different models were positioned to meet the same pelvic angle (ASIS to PSIS), but then higher deviations were observed for the lumbar spine.

Depending on the focus of the positioning process, certain pre-processing steps are necessary, like an adaption of the vector-based posture description, or a pre-rotation of the model. Moreover, the exact positioning of HBMs to PMHS data or volunteer data is a trade-off between geometric accuracy and stable boundary conditions. Positioning exactly to certain acetabular centre coordinates, for instance, would force the HBM into the seat and lead to unrealistic contact forces – or even positioning the model without any contact with the seat pan. Since the positioning procedure is defined in well described steps, the positioning will result in repeatable HBM end positions.

Due to the different nature of the FE and MB HBM s, the advantages of the presented approach are also clearly different between them. For the MB model used in this study many of the challenges that exist in positioning FE HBMs do not apply, mesh morphing is an example of that. However, creating the mutual comparable positioning landmarks on a rather computationally efficient coarse skeleton helped to achieve a positioning that matches the target data. Although the MB model architecture does not contain all skeletal structures, it is expected that adding more skeleton structures (like for example in the spine and thorax) would further enhance its accuracy.

The application of the presented method is conceivable in following concerns:

- Assessment of new sitting positions and diverse omnidirectional models: Upcoming new sitting positions require methods to position HBMs of different anthropometries to defined sitting positions.
- Validation of active HBMs by means of volunteer tests: The HBMs need to be positioned to the volunteer's position in order to validate the active behaviour of the models
- Virtual testing methods which need to work for models with anthropometric differences, and requiring a reproducible and repeatable seating method

Nevertheless, the presented study has some limitations. It is observed, that current HBMs present limitations in the joint stiffness, which constrains its range of motion and therefore might impede achieving the target position.

The prescribed motion, which was applied on the landmarks (individual selected nodes on the skeleton), may lead to instabilities, such as negative volume or large rotation errors, due to local deformations. In order to avoid these potential instabilities, the bones would need to be rigidised. Prescribing the motion to a set of nodes, rather than to a single node would help to reduce the local deformations, by distributing the load on a larger area. These points remain open and will be subject for future work. In addition, the vector-based posture description uses a simple joint definition, whereas the human joints are more complex in reality. Moreover, the question of model validity after any repositioning simulation was out of the scope of this study, however, research in this area is needed. Finally, the presented method – although simulation-based – does not ensure an acceptable FE model quality, e.g., element quality, penetration, etc., which must be checked and eventually improved by the user after the repositioning of the HBM. The usage of initial stresses within the HBM need to be considered at any restart of the model. Depending on whether the model is positioned for a pre- or incrash simulation internal initial stresses might be considered. An investigation concerning the usage of inertial stress was not done.

V. CONCLUSIONS

This publication presents a simulation-based approach which allows to position different HBMs similarly to a given target position represented by the coordinates of certain landmarks. Since the data source of the target position, e.g., PMHS tests, might have a slightly different anthropometry compared to the HBMs, the target coordinates are adapted to the HBM anthropometry. A tool was developed for FE HBMs which creates the necessary solver input files for a positioning simulation. The approach is demonstrated for two FE Codes (LS-Dyna and VPS) and for a MB code (Madymo).

VI. ACKNOWLEDGEMENT

The work described was carried out within the EU H2020 project "OSCCAR - Future Occupant Safety for Crashes in Cars". OSCCAR has received funding from the European Union's Horizon 2020 Research and Innovation Programme under Grant Agreement No. 768947.
The authors thank Autoliv and the University of Virginia, USA, for providing PMHS data to the OSCCAR project.
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The publication was written at Virtual Vehicle Research GmbH in Graz, Austria, and partially funded within the COMET K2 Competence Centers for Excellent Technologies from the Austrian Federal Ministry for Climate Action (BMK), the Austrian Federal Ministry for Digital and Economic Affairs (BMDW), the Province of Styria (Dept. 12) and the Styrian Business Promotion Agency (SFG). The Austrian Research Promotion Agency (FFG) has been authorised for the programme management.

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