# Realistic articulation, positioning and simulation of Human Body Models using Oasys LS-DYNA tools

Manu Agarwal, Galal Mohamed

Arup

## 1 Introduction

The application of human body models (HBMs) in numerical simulation offers exciting opportunities in automotive development in areas such as comfort, ergonomics, and safety. These models are used to simulate human body kinematics and injury responses and risks in a variety of simulated impact scenarios. The industry leading THUMS and GHBMC family of models are usually provided in two standard postures – occupant and pedestrian. The occupant posture is typically a driving posture in an up-right position, whereas the pedestrian is a walking posture with fixed arm and leg angles. These standard postures are limiting and do not reflect the diversity of postures which an occupant or pedestrian can assume at the point of a collision. Furthermore, current trends in vehicle automation are also expected to give rise to new seating postures such as forward or backward facing reclined seats. A major challenge for users, however, is that these models are not provided with pre-configured information to aid positioning making it a very difficult and time-consuming effort.

This paper describes efforts to support quick and easy positioning of HBMs using the Oasys LS-DYNA Environment with the aid of pre-configured positioning tree files. These tree files allow users to achieve realistic articulation and positioning of complex HBMs using Oasys PRIMER, a world-leading LS-DYNA pre-processor, to prepare them for simulation-based positioning using the power of LS-DYNA. A case study of positioning an average male occupant THUMS Version 7 model [1] on a mountain bike is presented to illustrate the modelling workflow in the Oasys LS-DYNA Environment [2].

## 2 Simulation-based positioning

Simulation-based positioning is one popular method of positioning HBMs. In Oasys PRIMER, the 'marionette' method is adopted whereby the user defines a target position by interactively moving specific body regions. Once a desired target position is achieved, PRIMER automatically creates cables to "pull" the HBM into position during an LS-DYNA analysis. After the analysis has completed, the deformed nodal coordinates from the final state of the analysis are imported back into the original HBM model as input for other subsequent analyses. This workflow is summarised in Figure 1.

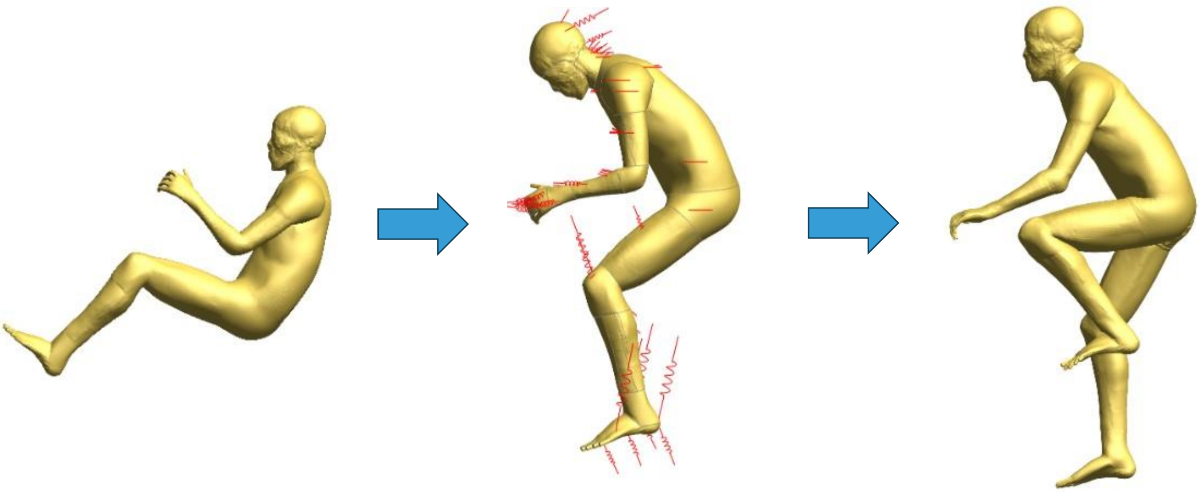


*Fig.1: Simulation-based positioning workflow in Oasys PRIMER (THUMS Version 7 AM50-O model)*

One advantage of simulation-based positioning is that initial penetrations that can occur during traditional ‘rigid body’ pre-processor positioning are avoided. Also, during the positioning analysis, the simulation considers all the complex internal material properties and contacts that are defined in the occupant and seat model. This makes simulation-based positioning more realistic.

Body positioning of HBMs is made possible with the aid of an include tree file, which is simply a collection of ordinary LS-DYNA entities such as nodes, rigid beam elements, coordinate systems, constrained joint definitions etc. but with extra PRIMER-specific data to describe how groups of body parts, called assemblies, are related and in what order. These PRIMER assemblies are connected in a hierarchy in which ‘parent’ and ‘child’ relationships are strictly defined. For example, the pelvis is a parent to the ‘upper leg, which in turn is ‘parent’ to the lower leg, which is ‘parent’ to the foot. Thus, the foot is a ‘child’ of the lower-leg, and grandchild of the upper leg and so forth. This relationship is illustrated in Figure 2. The tree file also contains generalised joint stiffness definitions between assemblies, which define the (local) axes a child may rotate about with respect to its parent. These joint definitions include stop angles of rotations, determined by anatomical research, to ensure that joints are articulated realistically.

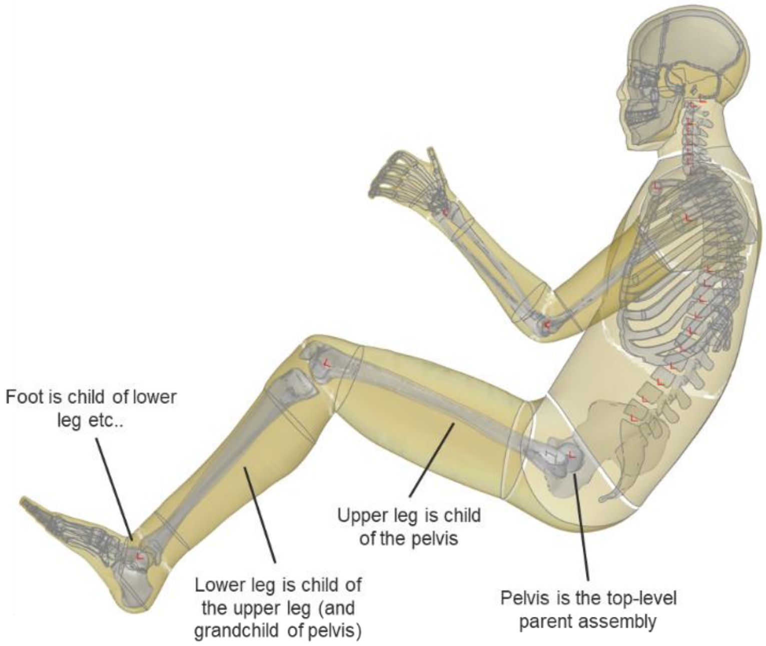



*Fig.2: Parent-child hierarchical relationship of pelvis assembly defined in PRIMER positioning tree file (THUMS Version 7 AM50-O model)*

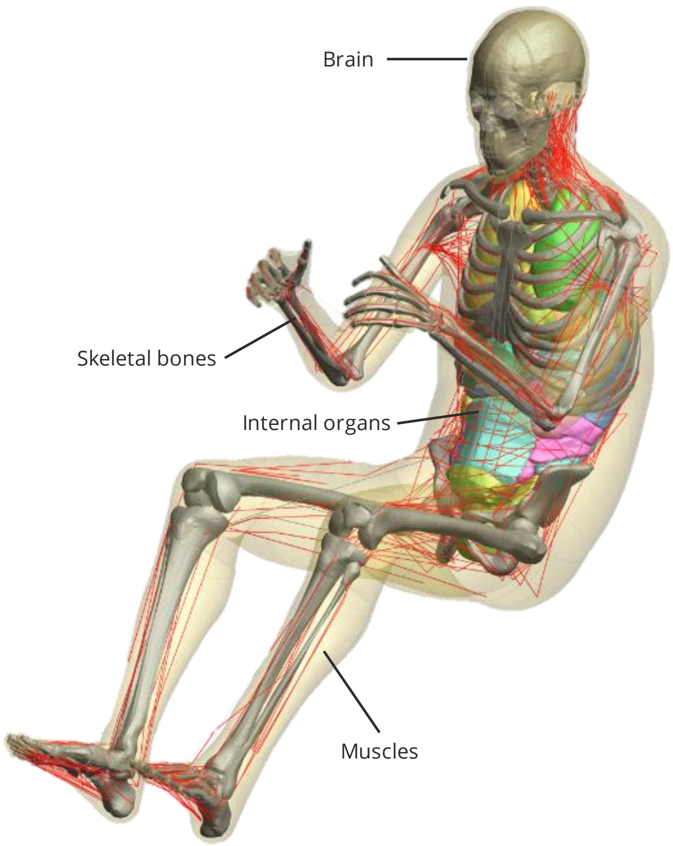
PRIMER positioning tree files have been developed for the most popular THUMS [1] and GHBMC [3] family of models.

## 3 Case study: THUMS on a Bike

A practical example of positioning an average male occupant THUMS Version 7 model [1] on a generic mountain bike is demonstrated using the Oasys LS-DYNA Environment v20.0 [2].

### 3.1 Introduction to THUMS Version 7 model

THUMS Version 7 was developed based on Version 6 with significant improvements for simulating impact kinematics and injuries of occupants seated in a reclined seating posture, as well as in an upright seating posture, in vehicle frontal collisions [1]. The current THUMS Version 7 family include: the average size male model (AM50), the small size female model (AF05) and the large size male model (AM95) in an occupant posture, respectively. The AM50 occupant model, as illustrated in Figure 3, is used for the purpose of this study, and contains approximately 840,000 nodes and 2.1 million elements. The height is 179 cm, and the weight is 78 kg, which is close to the AM50% size. The occupant model also




contains muscle activation features to simulate changes in occupant posture, considering changes in musculature activity prior to a vehicle collision. Thus, combined emergency manoeuvres and crash events, or other long duration crash events, can be simulated. There are three types of muscle activation conditions: sleeping, relaxed, and braced conditions. The sleeping condition is assumed as a driver's condition without muscle activation. The relaxed condition is regarded as the inattentive condition, where the muscle activations are obtained from the muscle controller using the PID control for posture control. The braced condition is assumed to be one of the driver's attentive conditions, where the muscle activations are obtained from the muscle controller using the PID control for both posture and force control. Furthermore, the model can be used with and without skeletal bone fracture and erosion. More detailed information is available in the THUMS Version 7 Manual [1].

*Fig.3: Anatomical view of THUMS Version 7 AM50 Occupant model*

### 3.2 Positioning workflow using the Oasys LS-DYNA Environment

#### *3.2.1 Pre-analysis steps*

The first step of the positioning workflow is to read the unmodified THUMS Version 7 AM50 occupant model into Oasys PRIMER v20.0 and add the corresponding PRIMER tree file to the main keyword input deck to enable positioning. It is important to note that the contents of any PRIMER tree file, such as the joint definitions, are configured based on the posture and label numbering of the original HBM model. The tree file sits on top of the original HBM model and is only used for positioning – it is not modifying the original HBM model in any way.

An optional step is to turn off the muscle activation and bone fracture features by invoking the respective '…no_activation' and '…no_fracture' include files. The include file structure is shown in Figure 4.

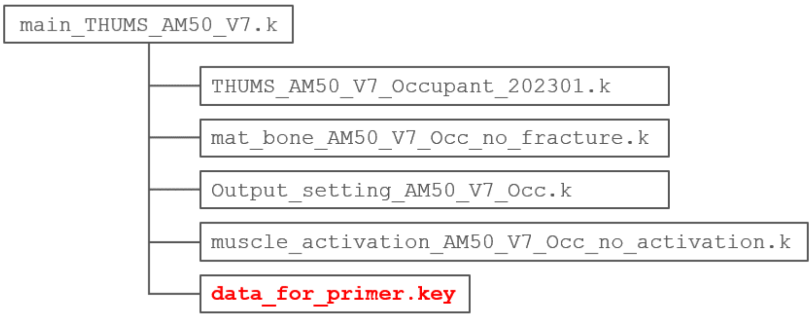



*Fig.4: Include file structure of THUMS Version 7 AM50 Occupant model and corresponding PRIMER positioning tree file (data_for_primer.key)*

The next step is to open the HBM positioning tool in Oasys PRIMER via the 'Safety → HBM & Seatqsquash' button. PRIMER can create models to position a HBM and/or squash the seat foam in a single or multiple stage analysis. It does this by creating cables to pull the HBM into position, meaning that the deformations and interactions between the various internal parts that can occur during positioning are considered.

The tool works through a series of steps to create the LS-DYNA analysis. The first step is to move the HBM to the starting position, which is the position where the analysis starts at time = 0. The next step in the workflow is to specify the target positions with the aid of a preconfigured positioning tree file. As previously discussed, the position tree file is a special case of general PRIMER mechanisms with the difference that they are made of a hierarchy of assemblies (group of parts that are treated as a rigid body) linked together at joints. The joints have joint stiffnesses that both define the local axis system for each of the connected assembly and define angles of rotation between the axes to limit the assembly articulation. These local axes of each assembly pair are coincident in the original orientation of the HBM model and when the assemblies are pulled away from or towards each other, these assemblies must always remain connected at joint nodes. Positioning can take place by any combination of three methods:

1. **Rotate angles:** assemblies are rotated about their parent joints, one degree of freedom at a time. Assemblies below the current one is moved as a rigid unit. This method uses explicit coordinate geometry to update positions and is precise.
2. **Drag assembly:** Assemblies are treated as a general mechanism and can be dragged to any achievable position subject to the physics of the structure and any stop angles defined in joint stiffness. This method is approximate since it is iterative, and small geometric errors may be introduced that can require a final correction step to make sure that joint nodes are coincident.
3. **Move points:** like 'drag assembly' with the difference that movements are defined as explicit dragging of specified points on assemblies rather than free dragging of assemblies. These points are defined with coordinate positions or node labels. The solution method is iterative, giving the same minor errors in geometry.

In this example, the THUMS AM50 occupant model is positioned on the mountain bike using a combination of all three methods by moving the feet onto the pedals, and the hands onto the handlebar. The head and spine are also adjusted to achieve a representative cycling posture. It's worth noting that only the arm and hand assemblies on the left side of the HBM were adjusted; the opposing right side assemblies (or siblings) were simply reflected using the new '**Mirror'** option in PRIMER v20.0. This works by mirroring the position of assemblies which have an opposite matching 'sibling' assembly by copying the angles from one side of the HBM to the other. Finally, to make it easier to visualise the parts when positioning, the **HBM Visualisation panel** was used to visualise and customise the visual properties of the different portions of the HBM. The visualisation table creates visualisation entities automatically to break the HBM entities into categories based on assemblies and anatomy (i.e., skin, skeleton, flesh, organs etc).

It is good practice to save the current rotations of each joint to a dummy angles file (.daf file), to ensure that progress is not lost. The .daf file can be read back in at any time during the positioning workflow or in a new PRIMER session. When read back in, the angles are applied to each assembly in turn, working down the HBM tree from the root, repositioning the HBM to the previously saved configuration.

Once the target position is defined and accepted by the user, PRIMER automatically attaches up to three cables to stiff parts of each assembly and creates a new model. Cable properties are automatically calculated based on their length, to ensure that the model is pulled into position in the specified time. As shown in Figure 5, the cables shrink to zero length using the ***DEFINE_CURVE_SMOOTH** keyword. The cable properties include a shrink and settling time, which are set by the user, to determine the termination time for the analysis. These timings are also used in the definition of the ***DEFINE_CONSTRUCTION_STAGE** card, which outputs a dynain file at the end of each positioning stage.

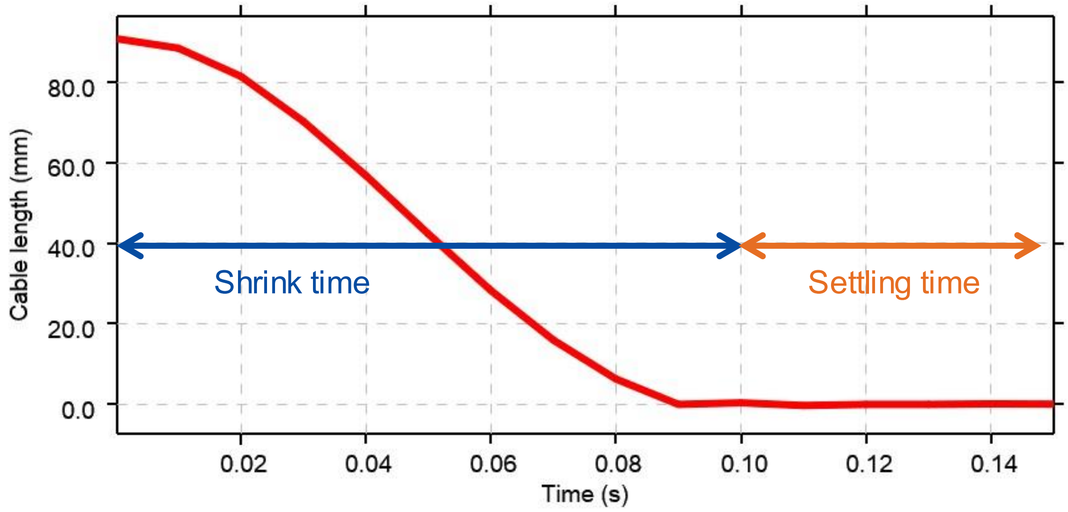



*Fig.5: Shrink and settling time of positioning cables attached to stiff parts of each HBM assembly.*

*3.2.2 Run in LS-DYNA*

The final model is submitted for analysis using LS-DYNA MPP SP R12.2-86-g831c51f1f6 Intel-MPI on 16 cores. Although the smallest time step of the original THUMS Version 7 AM50 occupant model is 1.5e-07 sec, mass scaling is added by default via ‘DT2MS = -2.56E-7 sec’, which took approximately 16.5 hrs to run. Further investigations were made to optimise run times by adding mass scaling via the DT2MS parameter and exploring other ***CONTROL_MPP** decomposition options to improve the overall load balance. A summary of timings is given in Figure 6. Figure 7 shows the scalability of the best run time analysis for 16, 32 and 64 processors. Further details on the background of the DECOMP_TIMINGS options can be found in Ref. [4].

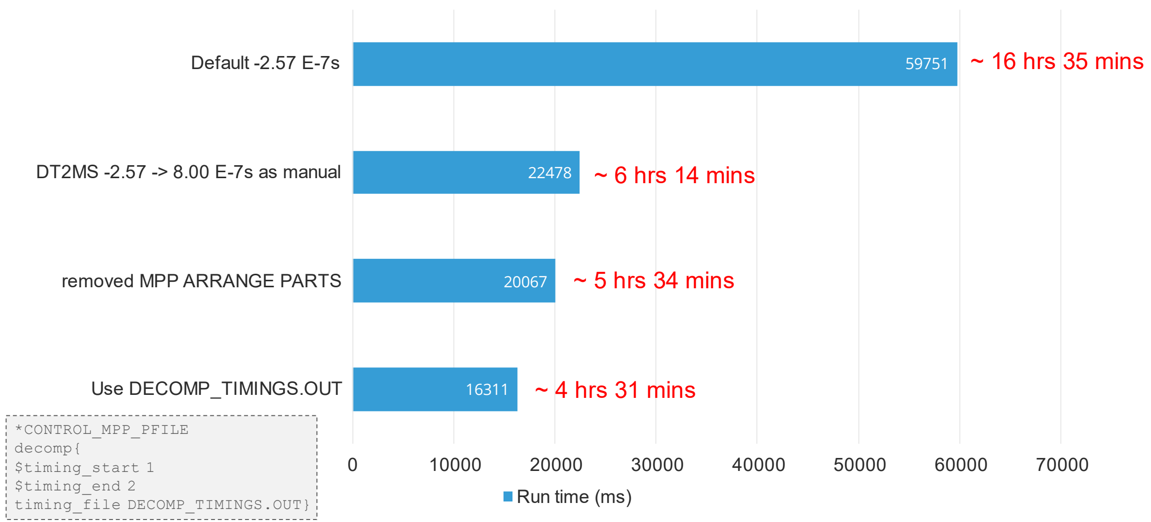



*Fig.6: Sensitivity study of run times for THUMS Version 7 AM50 Occupant positioning analysis*

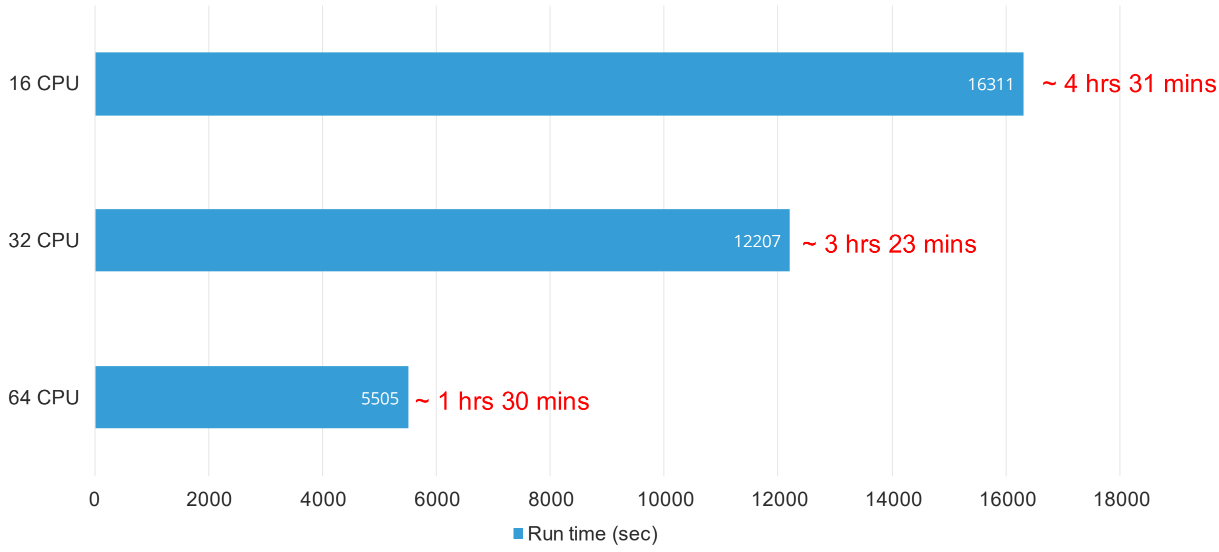



*Fig.7: MPP LS-DYNA processor scalability of THUMS Version 7 AM50 positioning analysis*

### *3.2.3 Post-analysis steps*

Once complete, the analysis produces a dynain file for each positioning analysis, which will have a name like "end_stage001_dynain". This contains nodal coordinates and initial stress information from the analysis which can be imported back into the original model using PRIMER's 'Node Import' tool, as shown in Figure 8, to achieve a positioned, penetration free model. Changing the default posture, however, of the THUMS Version 7 to a different posture can introduce two commonly found issues, as reported in the THUMS manual [1], relating to 1D sliprings and joint angle parameters (**`*PARAMETER`**). 1D sliprings are used to model muscle-tendon parts and require the definition of the seatbelt elements IDs on either side of the slipring. During positioning, the IDs of the seatbelt elements change as the elements pass through the slipring nodes, meaning that the slipring definition now refer to the wrong seatbelt element IDs. Error messages, for example, "`*** Error 30229 (INI+229), belt node (node ID) not coincident with slipring node (node ID)`", are commonly reported. Thus, the slipring definition must be updated to account for the new seatbelt elements on either side. From v20, Oasys PRIMER now has the option via the 'Node Import' function/button to automatically update the seatbelt element IDs on either side of the slipring.

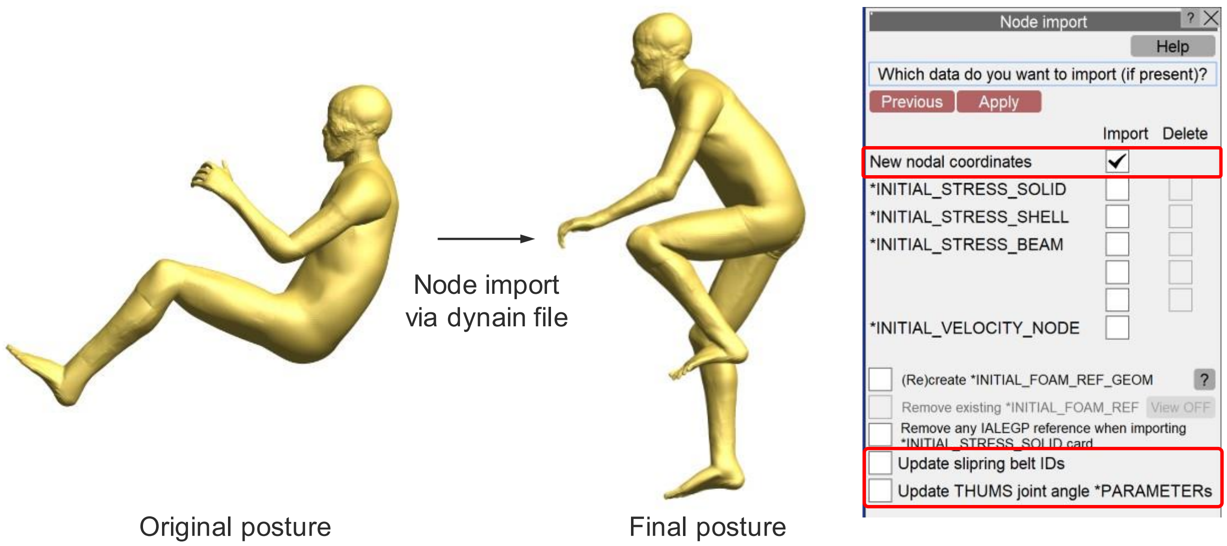



*Fig.8: PRIMER node import tool to update the nodal coordinates via the dynain file, update slipring belt IDs and THUMS joint angle parameters (muscle-active models)*

An additional enhancement to the node import tool in PRIMER is the automatic update of the initial joint angle parameters. In both relaxed and braced muscle conditions, the target angles used for the PID muscle activation controller must be updated from the initial joint angles defined in the original posture of the THUMS Version 7 model, with those obtained from the results of the pre-simulation.

Once the node import step is complete, the final posture from the pre-simulation analysis, shown in Figure 9, is ready for the main crash analysis.

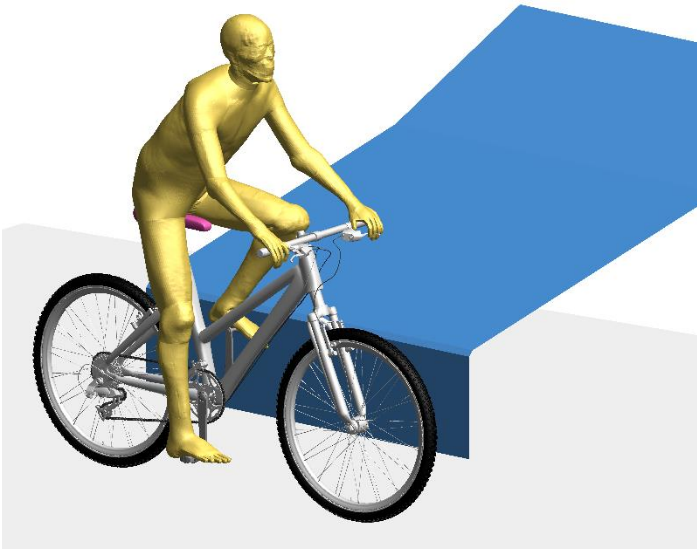


*Fig.9: Final posture of THUMS Version 7 AM50 model, ready for the main crash analysis*

## 4 Linked mechanisms

In PRIMER, a mechanism is a collection of two or more rigid bodies or "assemblies" joined together by "connections" or joints, which are written out as a post *END keyword. Mechanisms have no concept of hierarchy and the connectivity between assemblies can be arbitrary. The HBM position tree file, however, is a special case of general PRIMER mechanisms with the difference that they are made of a hierarchy of assemblies (group of parts that are treated as a rigid body) linked together at joints.

Prior to Oasys PRIMER v20.0, the link between a HBM definition and a mechanism could only be organised in a hierarchy where a "parent" mechanism drives the motion of a "child" dummy/HBM definition via connected degrees of freedom, permitting the HBM's position to be driven by the motion of its parent mechanism. This is a one-way treatment in which motion of the mechanism "drives" articulation of the HBM, but not the other way round. In addition, only one connection between parent mechanism and child HBM is permitted which is not adequate when the HBM needs to interact more generally during positioning. From v20.0 onwards, a new feature is introduced to convert a dummy or HBM definition into a mechanism, which has useful applications for pedestrian protection and vulnerable road users.

For example, as shown in Figure 10, the following five connections are likely to be considered when positioning a HBM on a bicycle:

- 2x hands on handlebars
- 2x feet on pedals
- 1x buttocks on seat

If the motion of the legs is to drive the pedals around and the hands are to turn the handlebar the "HBM is a child of the mechanism" approach will simply not work. Rather the HBM and bicycle assemblies need to be siblings, equal in priority, and able to connect with one another in an arbitrary fashion. The process works as follows:

- Assemblies are added verbatim but have their "child" assembly information removed.

- Mechanism connections are added between assemblies to reproduce the tree connectivity of the HBM.
- Connections permitted to move in more than one degree of freedom are modelled as mechanism PIN joints. If a **`*CONSTRAINED_JOINT_STIFFNESS`** definition is used to limit movement in some local coordinate system ("stop angles") this is copied over and will limit rotation about the pin in the mechanism in the same way.
- Connections limited to rotation about a single degree of freedom are modelled as mechanism HINGE joint. If joint stiffness definition is used to define stop angles these will use the existing angular limits in the mechanism to limit rotation.

A new mechanism is then created using the next free label for mechanisms in a model. The mechanism will be entirely free-standing and independent of the HBM, and the existing HBM definition will be unchanged. Since both HBM and mechanism refer to the same underlying elements and nodes either can be used to articulate the model. Alternatively, HBM trees may also be imported directly into mechanisms, see PRIMER v20.0 manual for further details [2].

Continuing with the THUMS on a bike example, a bike mechanism is first created in PRIMER by grouping different parts of the bike model into assemblies and creating various connections between these assemblies (e.g., a LINE connection between the bike frame assembly and the seat assembly, a HINGE connection between the handlebars and the bike frame assemblies, and PIN connections between the pedals and the crank). Using the new linked mechanisms features in PRIMER v20.0, the existing HBM definition is then converted into a mechanism by importing the HBM assemblies and connections between those HBM assemblies into the previously created bike mechanism. Additional connections are then created between the bike and HBM assemblies (i.e., pedal and feet, hands and handlebars, buttock and seat). This 'linked mechanism' can now be used to setup multiple angles of pedal rotations to drive the motion of the legs. This in turn can drive a multi-stage positioning analysis where a sequence of different feet/leg positions can be achieved in a single LS-DYNA analysis. In this scenario, PRIMER creates multiple sets of cables in series and (optionally) writes out the dynain files at the end of each intermediate stage using the **`*CONTROL_STAGED_CONSTRUCTION`** keyword. This approach allows the user to specify several different end positions in one analysis – so slightly different positions can be achieved without having to go back and redo much of the initial part of the analysis. The sequence of leg postures obtained from a multi-stage positioning analysis is shown in Figure 11.

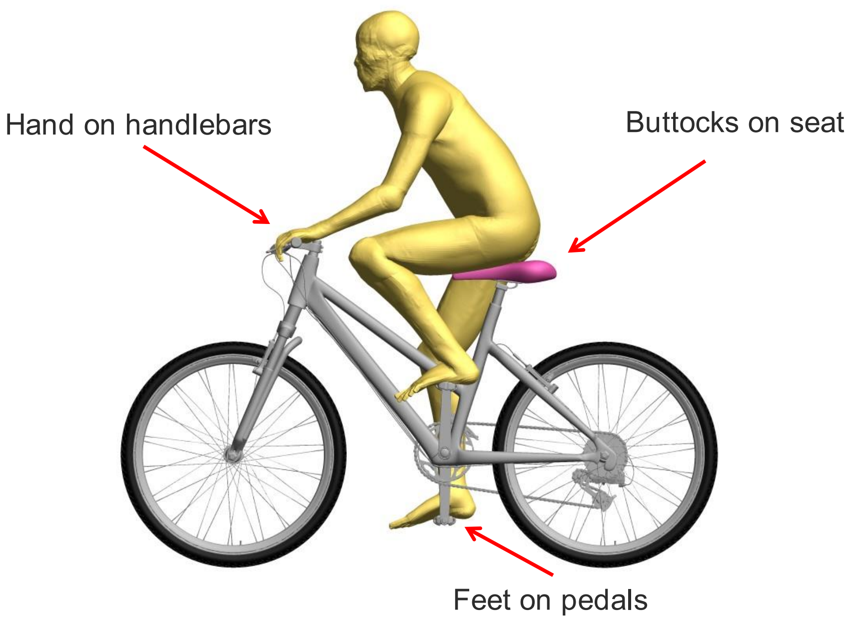



*Fig.10: Possible linked connections between a HBM and bike model*

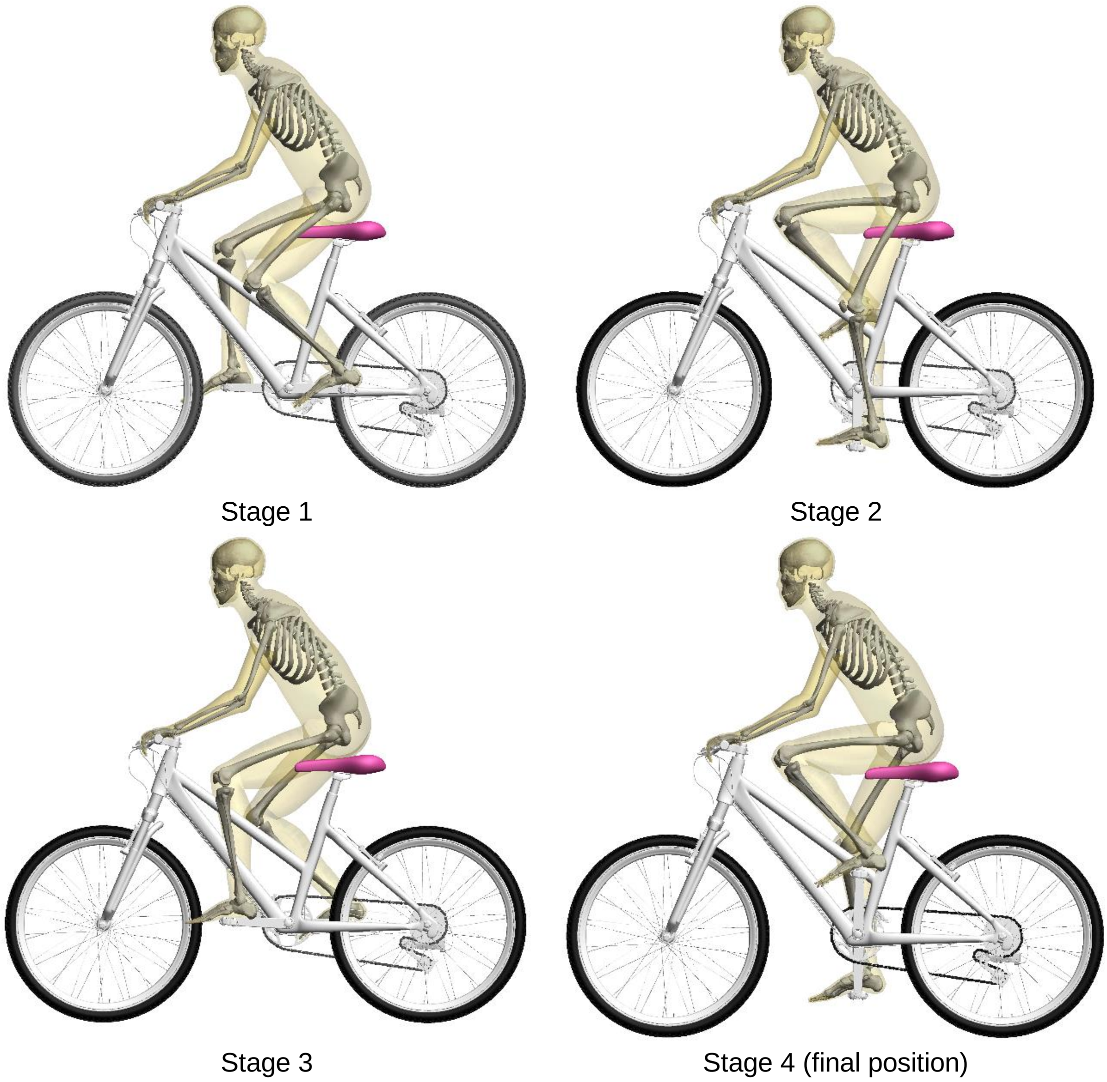



*Fig.11: Sequence of postures obtained from a multi-stage positioning analysis.*

## 5 Conclusion

This paper describes efforts to support simulation-based positioning using the power of LS-DYNA and the Oasys LS-DYNA Environment. An example of positioning a THUMS Version 7 average male occupant model on a bike is presented using the latest positioning capabilities and tools in Oasys PRIMER v20.0. This work was extended further by allowing the THUMS model to interact more generally with the bike by creating 'linked mechanisms' between the two assemblies.

In summary, PRIMER positioning tree files:

- enable easy, interactive positioning of highly complex HBMs
- include realistic biofidelic joint detailing for example, bending and straightening of the spine, and realistic shoulder/clavicle movement
- include realistic stop angles to ensure appropriate relative movement between the various parts of the model
- support linked mechanisms

HBM positioning trees are available to all Oasys LS-DYNA customers for the most-popular industry leading GHBMC and royalty-free THUMS models.

## 6 Literature

[1] Documentation of Total Human for Safety (THUMS) AM50 Occupant Version 7. Toyota Motor Corporation, Toyota Central R&D Labs., Inc. January 2023.

[2] Oasys® PRIMER 20.0 User Manual. Ove Arup & Partners Ltd: Solihull, UK, 2023
[3] Global Human Body Models Consortium, Elemance, LLC, North Carolina. https://www.elemance.com
[4] Improvement of domain decomposition of LS-DYNA MPP R7 and R8, Mitsuhiro Makino. Dynapower corp. 10th European LS-DYNA Conference 2015, Würzburg, Germany.