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How to Combine 3D Textile Modeling with Latest FE Human Body Models

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Abstract. Current finite element (FE) approaches to model clothing on the human body in terms of personal protective equipment (PPE) are mainly bound to the discretization of the outer element layer of the human body model (HBM) and the given posture. Costs for PPE prototyping could be lowered drastically if an efficient and posture-independent clothing modeling method would be available, so that the effectiveness of PPE in terms of injury risk mitigation could be assessed in a donned configuration. In the present study, an FE modeling method was developed to map 2D planar clothing structures on arbitrary 3D human body contours. The method was successfully applied to the GHBMC M50-PS with a modular design based ballistic vest including all components, joints and fasteners. The 3D shaped clothing models in combination with arbitrary HBM allow to analyze the structural interaction of protective clothing with the human body in unforeseen dangerous situations. The presented method facilitates the building of full featured FE models of PPE in donned configurations.

Keywords. Clothing modeling, finite element method, human body models, personal protective equipment

1. Introduction

The idea of clothing simulation generally involves two main focuses that are interrelated, i.e. clothing models for engineering applications and clothing models for visualization purposes and computer graphics industry [1]. Since fabric models for engineering applications need to follow physical guidelines, these models are often computationally quite demanding compared to the much simpler, visualization-driven models of animation industry. However, engineering models usually focus on aspects regarding comfort, reliability, performance and ensuring safety for specific operations and because of that, they need to consider the non-trivial fabric characteristics on the material level [2]. Fabrics specially designed for personal protection in automotive, civil and military applications are outstanding materials often combining low weight and high flexibility at high tensile stiffness and tenacity [3]. The benefit of these materials comes with the burden to handle the constitutive non-linearities with regard to finite deformations, anisotropy, hysteretic properties, and failure mechanisms at comparatively affordable computational costs. While there are continuum and non-continuum based constitutive models, only

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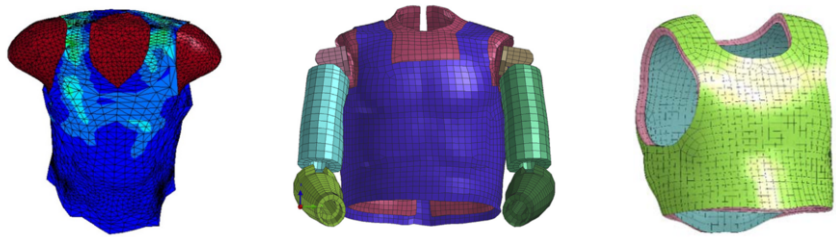
the continuum models seem to be able to accurately handle all possible modes of deformation, including buckling and wrinkling, and are therefore preferable towards non-continuum models [4].

With FE models of anthropomorphic test devices (dummies) and virtual HBM coming into play, the interest in donning clothes to the body contours of these models has increased. If product designers and textile manufactures could assess the effectiveness of their products directly on the human body by virtual simulation, financial and temporal costs for prototyping could be drastically decreased [1]. Nevertheless, a universal modeling technique capable of fitting a particular piece of clothes to a given body shape and posture is – to the knowledge of the authors – currently not available.

Therefore, the aim of the present study is to propose a universal method for donning 2D representations of clothes to complex and arbitrary 3D body shapes as a pre-staged modeling step for FE simulations. FE models of clothes in 2D shape are considered to require much less modeling effort than for 3D models, while an arbritary element mesh size can be defined. The method shall be able to consider arbitrary HBM types with respect to body size, stature, gender and arbitrary postures to enable its use in applications other than the automotive domain, e.g. body armor, work safety, sports and healthcare applications. This study also presents a reasonable alternative to the current commonly used methodology of skin mesh based extrapolation of body contours for 3D textile modeling [5,6,7], which is not able to capture more complex textile setups on the level of individual layers and is restricted to the mesh discretization of the body skin. The modeling workflow and the implementation of the developed algorithm will be demonstrated for a complex ballistic vest consisting of soft and hard ballistic components and several joints and fasteners. The present study is limited to the modeling method and the creation of the FE input deck. Simulation and post-processing of results are subject of future work.

Literature Review

Though there is an endless list of constitutive models for describing the structural behavior of fabric materials [8,9,10], there are only a few studies dealing with FE clothing models in a donned shape directly on a dummy model or HBM (Figure 1). Ishimaru et al. developed an FE model to dress knitted fabrics to an HBM, sew the pieces together, and calculate the resulting clothing pressure and therefore introducing a method to design virtually tight-fitting clothing [11]. Long et al. analyzed draping effects of single layer clothes on the human body due to gravity [12]. Aggromito et al. investigated how distributing equipment on the body of military helicopter pilots affects the injury potential during a crash [5]. For this study the primary survival gear carrier sitting on top of the flight suit and the body armor of the upper torso had to be modeled. The discretization of the carrier was based on the given mesh of the torso. Brolin and Wass used a virtual HBM to investigate dangerous accidents in equestrian sports [6]. The protective capacity of a safety vest with respect to falls, kicks and horse trample had been assessed. Again, the mesh of the vest model had been based on the external torso geometry. Li et al. applied the modeling approach of Brolin and Wass to a study where protective vests shall reduce the injury risk of aged people when falling down accidentally [7]. The model was based on CT scanning data of a 65-year-old female. Again the bulk mesh had been constructed by offsetting the nodes of the skin. Grassi et al. introduced the concept of a belted safety jacket for powered-two wheelers, and by design of experiment, they verified the effec-



(a) Single layer shirt [12] **(b)** Survival gear carrier [5] **(c)** Equestrian vest [6]

Figure 1. Examples on textile simulation with HBM and dummy models from literature: (a) Shirt draping study; (b) primary survival gear carrier; (c) equestrian protective vest.

tiveness of such a jacket in collisions with other vehicles and the potential to reduce the injury risk of the rider [13].

2. Methods

Preparing an HBM simulation for an injury risk analysis usually requires to include the HBM from-the-shelf into the main input deck, add a proper position and orientation and include all mandatory constraints, e.g. contact definitions. For occupant scenarios, a pre-loading phase will allow the occupant model to settle into the seat under gravity, and seat belts to tighten [5,14]. When it comes to other domains of application and arbitrary body postures, the user relies on the pre-processor's capability of altering the position of upper and lower extremities of the HBM. Considering the influence of PPE, one needs to include additional modeling steps to the conventional workflow.

Basic principle. The authors assume that it is feasible to build an FE model of the protective equipment in its 2D tailored or undonned shape and propose the workflow illustrated in Figure 2. The body hull of the HBM in the posture of interest has to be extracted from the FE model and a simplified target geometry has to be defined. The latter shall be so small in scale that it fits into the interior space of the modeled protective equipment. No information about the FE nodes and the element connectivity of the original HBM mesh shall be lost during this transformation. If successful, contact definitions can be installed between the miniaturized HBM skin and the interior surface of the protective equipment. A kinematic boundary constraint shall shift back each node to its original position on the body hull. Hence, the protective equipment will be transformed to the individual body contour of the HBM of which the skin has been extracted from. This method has the benefit that the clothes will be perfectly shaped according to the contour of the applied HBM. A drawback is that compression effects that might be exerted by tight clothes on the human body currently cannot be taken into account.

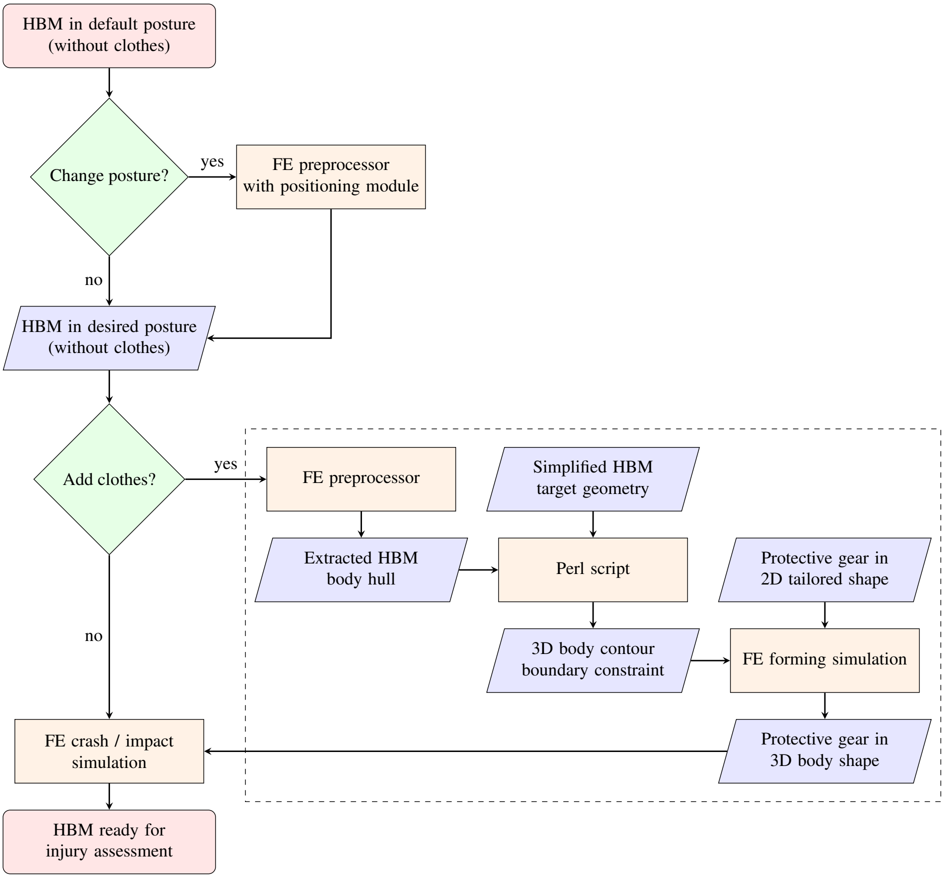


Figure 2. Workflows for preparing human body models for FE simulation and injury risk assessment with and without clothes. The integration of clothes in a donned shape with regard to HBM requires additional modeling steps (denoted by the dashed box).

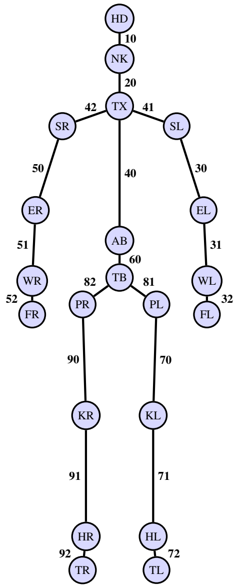
2.1. Algorithm

For the scope of this work, the authors implemented a Perl script[2]. to automatically map the FE mesh of a body hull geometry on a simplified target geometry. The script has been designed for input decks of the FE code LS-DYNA and makes use of the specific command `*BOUNDARY_PRESCRIBED_FINAL_GEOMETRY` [15] that implements a linear transformation of nodes from one configuration to another.

Phase 1 – Connectivity

When the surface mesh of the body hull is extracted, it has to be associated to a simplified and scalable target geometry that is defined by the user. The authors used a linearized mesh of 21 target nodes and 20 target elements for the current study. The connectivity of these elements is shown in Figure 3a. The coordinates of the nodes (Figure 3b) have

[2] `https://gitlab.cc-asp.fraunhofer.de/human-body-dynamics/perl-dynaskin`



(a) Target mesh geometry.

Node	Joint / End
HD	Head
NK	Neck
TX	Thorax
SL	Shoulder (L)
SR	Shoulder (R)
EL	Elbow (L)
ER	Elbow (R)
WL	Wrist (L)
WR	Wrist (R)
FL	Fingers (L)
FR	Fingers (R)
AB	Abdomen
TB	Tailbone
PL	Pelvis (L)
PR	Pelvis (R)
KL	Knee (L)
KR	Knee (R)
HL	Heel (L)
HR	Heel (R)
TL	Toes (L)
TR	Toes (R)

(b) Target nodes.

Elm	Body part
10	Head
20	Neck
30	Arm (L)
31	Lower Arm (L)
32	Hand (L)
40	Thorax
41	Shoulder (L)
42	Shoulder (R)
50	Arm (R)
51	Lower Arm (R)
52	Hand (R)
60	Abdomen
70	Leg (L)
71	Lower Leg (L)
72	Foot (L)
81	Pelvis (L)
82	Pelvis (R)
90	Leg (R)
91	Lower Leg (R)
92	Foot (R)

(c) Target elements.

Figure 3. Discretization serving as simplified HBM target geometry. The chosen level of the discretization is arbitrary, i.e. a finer level of discretization could have been used if needed as long as the target geometry is placed in the interior of the HBM body hull.

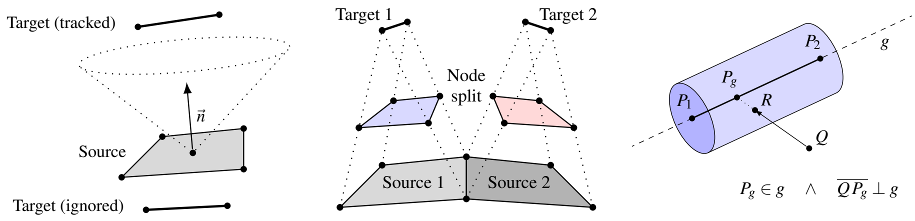
to be aligned with the centers of the corresponding body parts in the posture of interest. The script will then loop over each element of the source mesh and look for the closest element of the target mesh (Figure 3c). This search is implemented by a linear nearest neighbor search [16] based on the closest distance between both elements. The algorithm is extended by a conical search domain aligned in the direction of the element normal. This constraint will filter out target elements which otherwise would have been wrongly associated as shown in Figure 4a. Body regions that require this constraint have been identified near the fingers and toes and along the whole upper extremities if positioned very close or in contact to the torso.

Phase 2 – Fragmentation

The nearest neighbor search will yield results where adjacent elements of the source mesh are connected to different target elements. The nodes connecting those source elements will be projected to either the one or the other target element, which in return will produce highly distorted elements unsuitable for FE simulation. In order to avoid such distortions, the algorithm applies a nodal splitting technique that obviously results in a fragmentation of the source mesh.

Phase 3 – Morphing

The final step is to shift the nodes of the source elements to the projected locations on the target elements. The target elements are assumed to be of cylindrical shape with a non-



(a) Connectivity **(b)** Fragmentation **(c)** Nodal projection

Figure 4. Algorithm to implement the 3D body contour boundary constraint: (a) Nearest neighbor search to find element connectivity; (b) source mesh fragmentation where required; (c) nodal projection on target element surface.

zero radius and hemispherical ends (Figure 4b). Nodes can either be projected directly on the element's surface or scaled by a constant ratio with respect to the original distance between source and target node. Each source node will be mapped via an orthogonal projection on the closest point on the center line of the target element (Figure 4c). In order to disable the evaluation of constitutive equations, all source elements are associated with material card `*MAT_NULL`.

2.2. Examples

The algorithm has been tested successfully for five different human body models of three different HBM suppliers, i.e. the GHBMC pedestrian models for adult 5th percentile females and adult 50th and 95th percentile males [17], the THUMS occupant model for adult 50th percentile males [18], and the ViVA OpenHBM for adult 50th percentile females [19].

In Figure 5 and Figure 6, the results of the mapping algorithm have been illustrated for the body contours of the GHBMC model variants F05-PS and M50-PS. The latter (1.75 m height, 77 m weight, 593 components, 840,000 elements) has been used for the final part of this study, i.e. the donning of a ballistic vest to an arbitrary body posture.

Figure 7 and Figure 8 illustrate the extrusions of the body contours of the occupant model of the THUMS M50 and the ViVA OpenHBM model. The implemented method thus works successfully independently of the model type and the body posture.

3. Results

3.1. Model Setup

A body armor protective vest manufactured by MVS (Figure 9a) was used as reference for the model development [20]. The vest consists of a modular structure with long range rifle protection in the front, back and abdominal area and all-round protection in the flank area. The main two components of the protective vest are the front and the back structures which are connected with Velcro fasteners on the shoulders and in addition, on the sides of the torso to adapt the vest to the body. The protective vest is supplemented by a removable collar and groin protection. These parts are not considered in the model. The

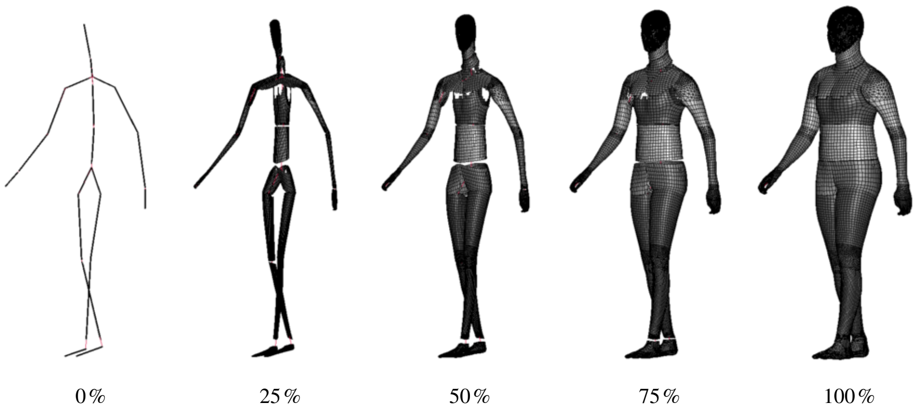


Figure 5. GHBMC adult female 5th percentile as pedestrian in walking posture (F05-PS).

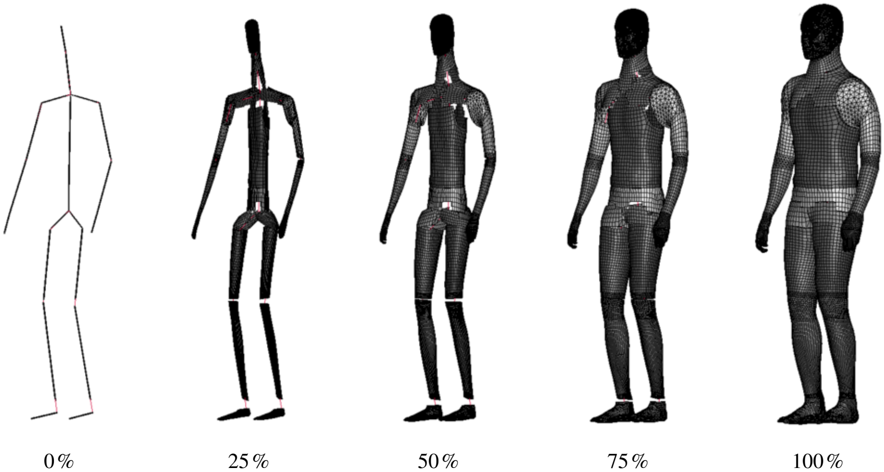


Figure 6. GHBMC adult male 50th percentile as pedestrian in standing posture (M50-PS).

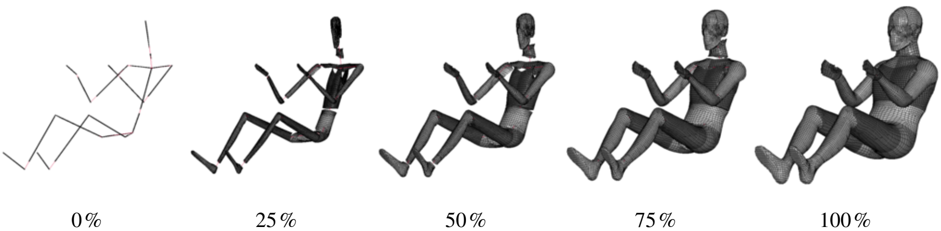


Figure 7. THUMS adult male 50th percentile as occupant (AM50-Occ).

0 % 25 % 50 % 75 % 100 %

Figure 8. ViVA OpenHBM for adult female 50th percentile as occupant.

(a) Vest used as reference

(b) Developed vest model

Figure 9. Front view of the body armor protective vest. Hard armor plate removed and placed on the carrier component. (a) Reference vest; (b) FE model.

front and back components have the same structure and differ only in their dimensions. They consist of an outer shell (the carrier), the trauma reduction layer (foam shock absorbent), the soft ballistic armor (three aramid fiber packages, total 40 layers), and a hard armor (boron carbide or silicon carbide with an additional ultra-high molecular weight polyethylene composite plate).

All components of the vest were modeled and meshed using the pre-processor Femap [21]. The textile components were created as planar 2D surfaces with a defined thickness. The front and rear carrier contain a soft ballistic component and a shock absorber component and an additional pocket for the placement of the hard armor. This modular structure allows the exchange of the individual components in order to carry out parameter variation studies of the materials and geometry. The implemented material models for the expansion process are simplified and after the expansion subsequently adapted. The material stiffness and contact definitions were iteratively adjusted to avoid fabric folds and strong element distortions.

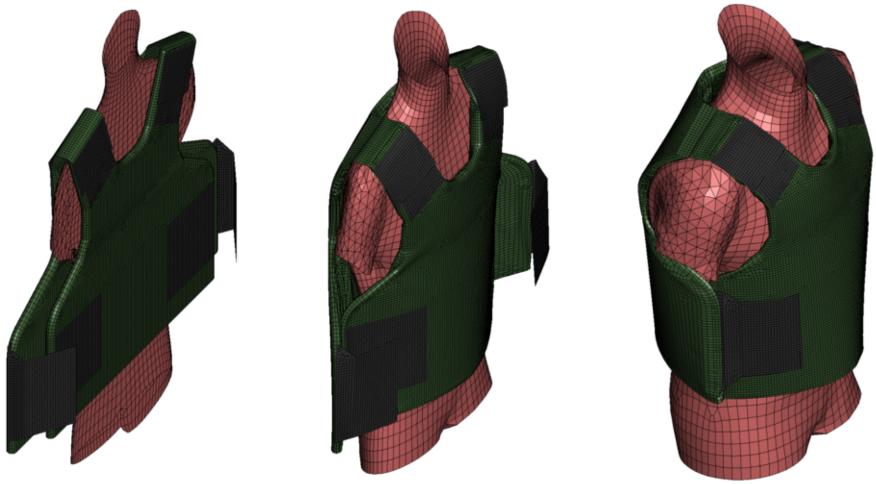


Figure 10. Expansion of the FE vest model from 2D planar to 3D state with the body contour of the GHBMC M50-PS.

3.2. *Model Expansion*

In the initial state of the FE forming simulation (Figure 9b), the main components are placed over each other with a small gap in between. The flattened skin shell of the GHBMC M50-PS is positioned in the gap (Figure 10). The hard armor plates are placed over the location of the designated pockets in the carrier components. As these are made of high-strength material and are not being bent during the simulation, the plates diffuse into the pockets during the expansion. The Velcro fasteners in the shoulder area lie on top of each other and are closed up via contact conditions. The Velcro fasteners in the flank area are half-open and progressively fastened during the FE forming simulation via load curves and contact conditions. Predefined load vectors ensure that the lateral Velcro fasteners close during the fitting simulation. All formable structures are aligned to the body surface (Figure 11a). Subsequently, a new initial state is defined in LS-DYNA, which is free of initial stresses, since the material models are adjusted. The full GHBMC M50-PS model is placed in the expanded protective vest (Figure 11b) and is ready for further analysis.

4. Discussion

In this study, a nodal mapping method has been applied to the body contour of a full HBM in order to transform the FE clothing model of a ballistic vest from a 2D planar shape to a 3D donned configuration. The process is implemented using a forming simulation to determine the final nodal positions of the PPE model. The stamping tool, which is usually rigid in forming simulations is replaced by a dynamic geometric boundary constraint that forces the flexible textile from the inside to the final 3D body shape.

(a) Expanded vest including inner structure

(b) GHBMC M50-PS in expanded vest

Figure 11. FE protective vest model in donned configuration: (a) Detailed view of the expanded ballistic vest including inner structure; (b) full body HBM combined with protective vest.

Using the proposed method, the authors showed that complex FE models of 3D body shaped clothes based on the much simpler 2D representation can be obtained in an efficient way (Figure 9 and Figure 10). Textile models in 2D shape are considered to require much less modeling effort than 3D models while an arbitrary element mesh size can be defined. Further, it could be shown that the method can be applied to any HBM type and many body postures (Figure 5, Figure 6 Figure 7). This allows not only to apply this method to any other protective clothing besides ballistic vests, such as PPE for motorcyclists, vulnerable road users on micromobility-vehicles, American football players or alpine skiers, it also presents a reasonable alternative to the current commonly used methodology of skin mesh based extrapolation of body contours for 3D textile modeling [5,6,7].

4.1. Limitations

While the method has been tested successfully for HBM of several distributors and various body postures, the method is still limited to postures that are close to a neutral position with adjacent upper and lower extremities. This restriction still poses difficulties to the modeling of textile preforms. In future studies, the method shall be improved in such a way that textile preforms can be modeled in perfectly flat 2D shape, allowing a miniaturized HBM contour in a neutral posture being inserted and expanded to an arbitrary body posture that is required for the load case simulation of interest. The validation of the implemented FE models and their usability will be realised in future works.

4.2. Outlook

In forthcoming studies, the ballistic vest FE model will be adapted to the GHMBC variants F05-PS and M95-PS to provide comparability analysis. Furthermore, the imple-

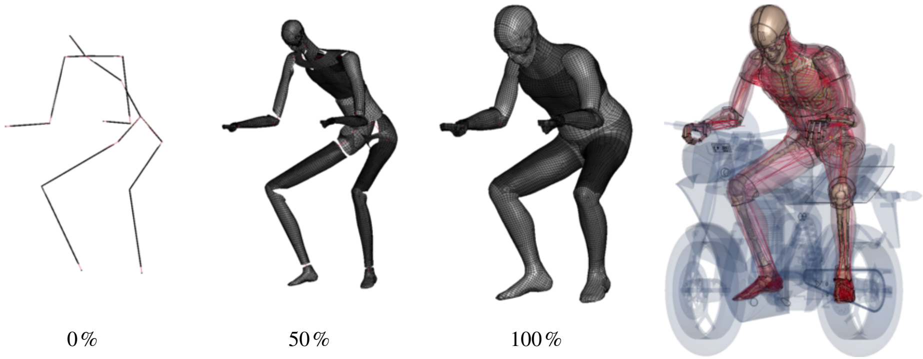


Figure 12. THUMS AM50 as a motorcycle rider to assess the efficiency of PPE (under development).

mentation of advanced material models and an investigation of various armor piercing projectiles will be carried out.

A positioning and forming simulation of a THUMS AM50 to a motorcyclist model is currently under investigation (Figure 12). In addition, a motorcycle jacket FE model is under development that will demonstrate the effectiveness and the protective capabilities of PPE in traffic accident scenarios.

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