Evaluation of a dummy design by using a human body model

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1 Abstract

Human body models for occupant protection became popular in the last years. They started to turn from high sophisticated research tools to reasonably applicable tools to support some specific areas of occupant safety.
This study is focused on the evaluation of the BioRID-II shoulder design by using the THUMS human body model.
After the introduction of the BioRID-II into several test protocols to assess whiplash associated disorder, some serious concerns about the dummy's performance emerged. Various simulations and tests indicated that the dummy's shoulder design may cause unrealistic loads. Simulation runs with the THUMS in the same test environment were used to verify this assumption. The overall kinematics and therefore the accelerations of human body model and dummy model correlate well. A comparison of forces and moments between both is difficult because of the completely different internal structure of human and dummy. However, in-depth analyses showed that the simple dummy shoulder causes direct neck loads, while a human shoulder distributes the load through clavicles and scapulas to the whole rib cage.
The same artefact was observed at the recently developed model of a female rear impact dummy (EvaRID) that is based on the BioRID-II design. The THUMS was scaled down to the size of the EvaRID by keeping almost same relative differences in size as observed between BioRID-II and THUMS. The dummy artefact could be verified with the downscaled THUMS, too.
In summary, a human body model is a complex, not easy to handle but helpful tool to evaluate the performance of crash test dummies and to identify dummy related artefacts. While the overall kinematics between dummy and human model are somehow comparable, forces and moments may differ because of the different internal designs of dummy and human body model.

2 Introduction

The passive safety of vehicles has been improved in the last decades significantly. This progress is enabled by newly developed and optimised technologies as well as by tighten requirements of legislative bodies and consumer organisations. In the early stage of passive safety the avoidance of fatalities and severe injuries was in first priority. It could be achieved with more simple dummy designs and less accurate measurements. Meanwhile the prevention of any kind of disorder is requested by some organisations. It requires more biofidelic dummies and it mostly results in high sophisticated dummy designs. These new designs and low thresholds of the performance criteria can result in serious problems regarding repeatability and reproducibility (R&R) of the dummy responses. Furthermore, unintended load paths which are probably not relevant when testing at high crash severities may influence the dummy's measurements, too.
A dummy is always a more or less simple model of a human body and in most of the cases the differentiation between right or wrong dummy design is difficult. Human models could help to analyse the kinematics and load distribution in detail and to compare it with a dummy.

This study is focused on the BioRID-II dummy which is used to analyse and access the loads obtained in rear-end crashes at low crash severity. Studies of PDB showed the poor reproducibility of some BioRID-II responses [1], [2]. A highly repeatable and reproducible test set-up was developed to minimise all variances caused by the test environment. The most essential part is the re-usable carbon fibre seat shown in Fig. 1. It eliminated all variances caused by repair or replacement of a seat after each test.

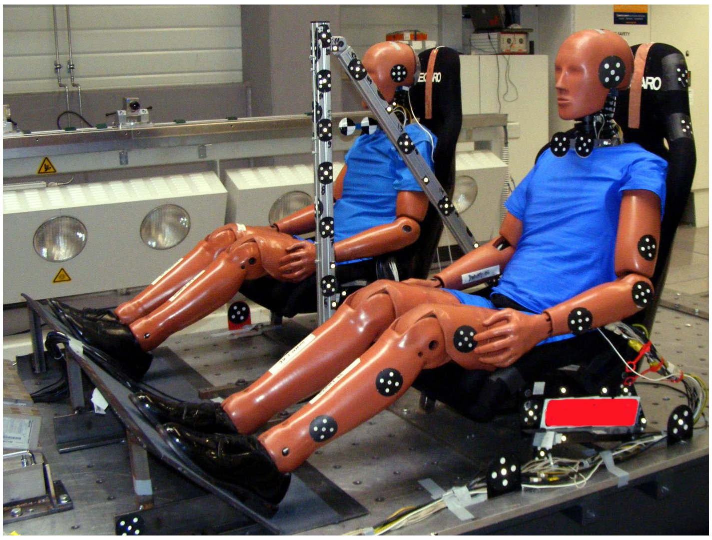

Fig. 1 Set-up of the BioRID-II evaluation tests

The stiff design of this seat is causing a side effect. It amplifies artefacts of the dummy that are probably less obvious when using a soft standard seat [2]. However, the carbon fibre seat indicated that there is an unintended load path through the shoulder of the BioRID-II to the upper neck. Fig. 2 depicts the upper neck shear force with and without the shoulder load path. The load path was disabled or minimised by removing two bolts at the T2 level. This effect was verified with four BioRID-II specimen. The vertical lines in Fig. 2 visualise the starting and ending time of the contact between head and headrest.

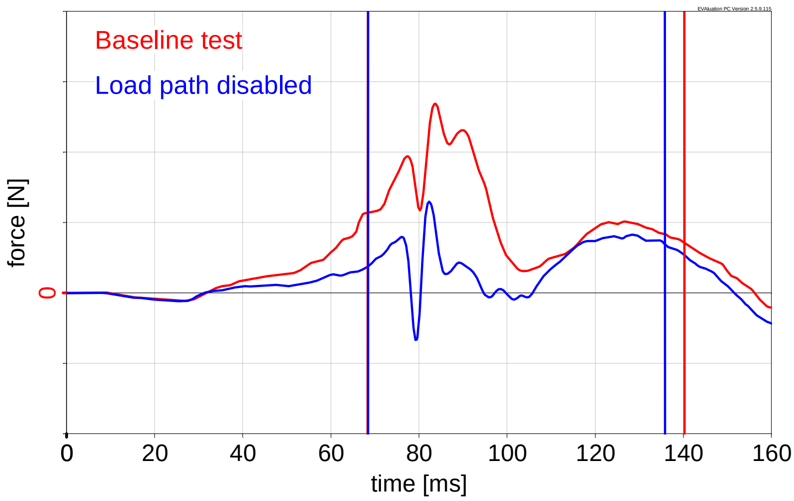

Fig. 2 Upper neck shear forces – baseline test and test with disabled load path

3 Method

The artefact of the unintended shoulder load path was accidently found in a study to identify the causes of the poor reproduciblity of some BioRID-II responses. It is difficult to get the final evidence that this load path is a pure dummy artefact. Therefore, it was decided to run simulations with the BioRID-II model and the THUMS in the same test configuration and in a configuration with a standard vehicle seat.

The general procedure to verify the findings is to compare the overall kinematics, the distribution of the loads, and the recorded responses between dummy and human model. However, as the internal

structure of dummy and human differ significantly, the direct comparison of some local motions and responses might be difficult.
At first, the focus is on the good correlation of the overall kinematics between dummy model and human body model. It requires similar mass distribution and inertia. Secondly, if it is comparable, then the accelerations of the significant body parts should correlate as well. In the next step the transfer of the loads from seat to dummy/human is compared. Finally, the internal load paths in the shoulder area are analysed.
The result of this analysis may not give a clear answer but it may show artefacts caused by the different designs of dummy and human.

The method was applied to the BioRID-II and the THUMS, and the findings were verified with the EvaRID and a downscaled THUMS.

4 Set-up and preparation of the simulation runs

4.1 Occupant models

4.1.1 Dummy models

The FAT BioRID-II model release 3.0 was used in this study. The shoulder area of this latest model is much more detailed modelled than that of its previous releases.

This study was completed with simulation runs using the female rear impact dummy model EvaRID release 1.1.1. The EvaRID model was developed within the European research project “ADSEAT” [3]. This dummy model is a downscaled BioRID-II with some local modifications of the geometry and tuned material properties. As it is derived from the FAT BioRID-II model release 2, the level of detail of the shoulder area is rather small (Fig. 8).

4.1.2 Human models

Two human body models were used in this study. Both are based on the THUMS model developed by Toyota Motor Corporation and Toyota Central R&D Labs. The baseline 50th percentile male model has been modified and re-validated by DAIMLER AG to meet some additional requirements.
This baseline model was used as counterpart of the BioRID-II and a downscaled THUMS completed the studies with the EvaRID.

4.1.3 Positioning

The two dummy models as well as both human models were placed into the seats by using pre-simulations. The posture of the BioRID-II was taken from the test series. It was also used as reference for EvaRID and both human models. Attention was paid to the backset, the distance between back of the head and the headrest of the seat. It is identical for both groups of occupants, BioRID-II and THUMS, and EvaRID and downscaled THUMS. The postures of the four models in the carbon fibre seat are shown in Fig. 3.

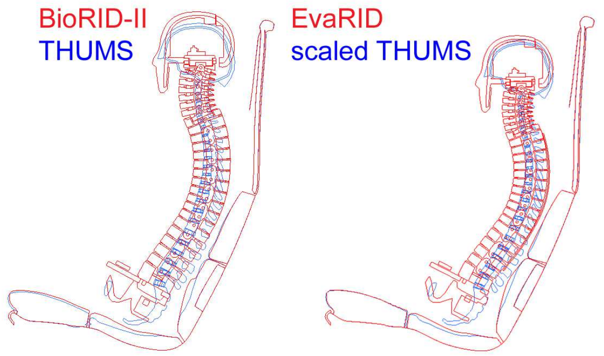

Fig. 3 Posture of BioRID-II, THUMS, EvaRID, and downscaled THUMS (carbon fibre seat)

The curvatures of the spine of dummy and human model are slightly different. It is the natural position after the positioning under gravity for each model. Additional constraints to get exactly the same curvature are not used because the resulting pre-stresses would probably distort the simulation results. The achieved postures are absolutely sufficient for the objectives of this study.

4.1.4 Anthropometry and scaling of the human model

The 50th percentile male (AM50) THUMS was scaled down to the size of the EvaRID by keeping the relevant differences between THUMS and BioRID-II. In a first step the THUMS AM50 was globally downscaled. Afterwards the size of head, torso, and pelvis was locally downscaled to the sizes of the EvaRID.

As shown in Fig. 3, the size of dummy and the corresponding human model in the carbon fibre seat is not exactly the same. The shoulder height of BioRID-II and THUMS is almost the same but the BioRID's T1 vertebra is at the C6/C7 level of the THUMS. So the sitting height of the BioRID-II is approximately 30 mm higher.
The situation is similar for EvaRID and downscaled THUMS. While the shoulder height is identical, the 1st vertebra T1 of the dummy is at the C6/C7 level of the human. The sitting height of the EvaRID in the carbon fibre seat is approximately 12 mm higher than that of the downscaled THUMS.
All described geometrical differences, especially the different levels of T1, are probably caused by the different anthropometrical data that was used to design THUMS and BioRID-II. The spine's curvature is also controlled by shape and stiffness of the seat. So the observed differences in sitting height are shorter in the softer standard vehicle seat.
As the focus of this study is on the shoulder load path, it is essential that the important contact areas like back and shoulder are almost identical for dummy and human model. It is achieved for both groups of occupants.

Beside the geometrical modifications, the masses of the body segments had to be adjusted, too. It was done by reducing the density of some materials such as the flesh of the arms. Tab. 1 shows the differences of the masses of the four occupant models.

	BioRID-II and THUMS AM50	EvaRID and downscaled THUMS
Head and neck	+36%	+33%
Torso	-5%	-10%
Upper extremities	-27%	-13%
Lower extremities	+12%	+14%
Total	+1%	+1%

Tab. 1 Relative differences in mass between dummy and human model

4.2 Seats

The carbon fibre seat was used as the reference seat in this study. The model was developed and validated to support the development of the BioRID-II dummy model.

A model of a standard vehicle seat was used to check whether the findings in the carbon fibre seat are transferable to other seat designs. The seat model was provided by the DAIMLER AG and it is fully validated for rear impact tests.

4.3 Crash pulse

All test and simulation runs used the trapezoid crash pulse SRA16 (Δv=16 km/h), shown in Fig. 4. It is a low severity pulse that was used in most of PDB's test series to evaluate the BioRID-II [2].

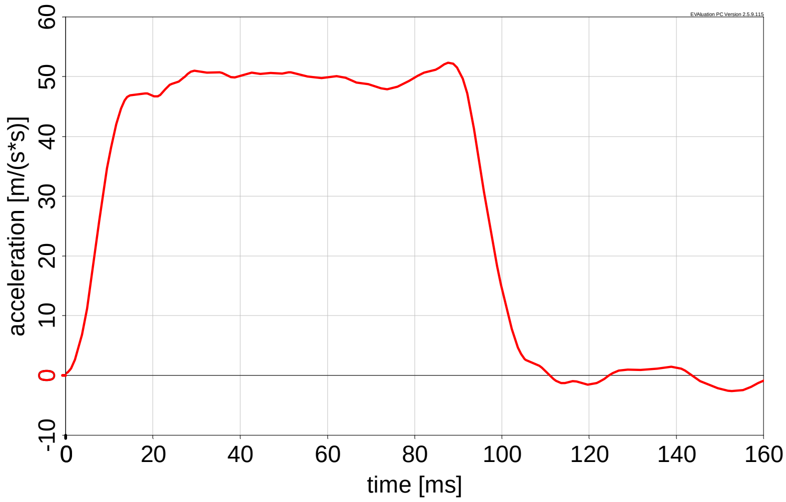

Fig. 4 Crash pulse

5 Shoulder design of human, BioRID-II, and EvaRID

The shoulder of a human is shown in Fig. 5. If a load is applied from the back to the shoulder area, it is distributed by the shoulder blades to the back of the rib cage and by the clavicles to the sternum. There is no direct load path to the first thoracic vertebra (T1) or any other vertebrae of the upper torso. T1 is loaded over clavicles and sternum indirectly. The connection between these bones is elastic and not rigid. Therefore, load are always damped. A certain load is also absorbed and distributed by the soft tissue which is not shown in this figure.

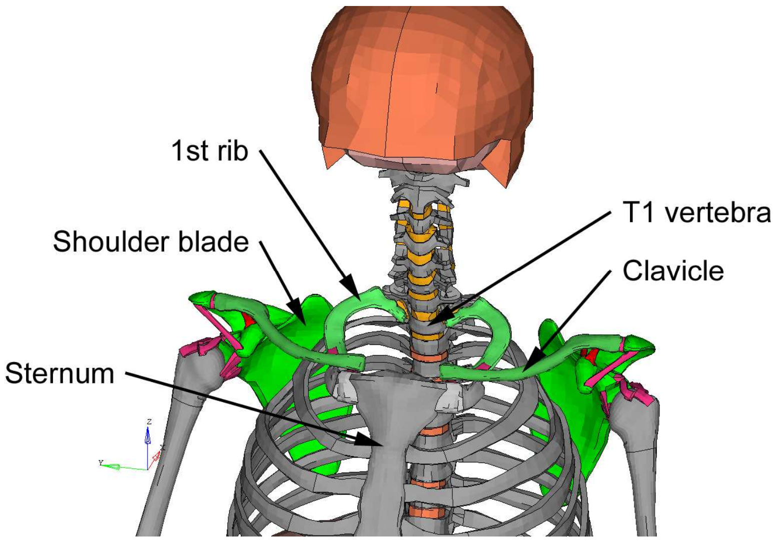

Fig. 5 Human shoulder design (THUMS AM50)

The probably most important part of the BioRID-II is the spine. Every vertebra of the human spine is represented by a dummy vertebra. These dummy vertebrae are connected by torsion springs. The designed range of motion of the dummy's spine is limited to the sagittal plane (xz plane). As shown in Fig. 6, the dummy has no rib cage. The torso is made of silicone. Various rigid bolts connects the torso with the vertebrae. Two inner and two outer metal plates are moulded into the shoulder area of the silicone torso. The upper arms are fixed to the outer plates and there is no other connection of these plates to the dummy's skeleton. Bolts at T2 and T4 level on the left and at T2 and T5 level on the right hold the inner plates. These bolts are rigidly fixed to the spine. The inner plates can slide and rotate along the bolts' longitudinal axis.

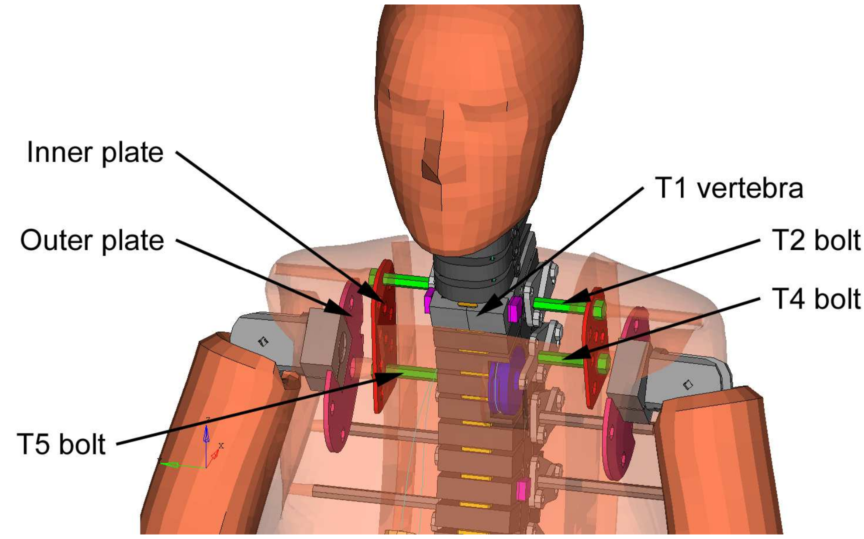

Fig. 6 Shoulder design of the BioRID-II (model release 3.0)

The distribution of shoulder loads applied from behind differs to that of a human. Firstly, the silicone torso and the outer plates are bend towards spine and chest. At a certain level of compression of the inner plates slide along the bolts towards the spine (Fig. 7). The inner plates may also limit or lock the spine's rotation between 2nd and 5th vertebra but this was not analysed in this study. The loads are transferred directly by the compressed silicone and the bolts at T2 and T4/5 to the spine.
The design of the BioRID-II does not offer the opportunity of a human-like distribution of those shoulder loads.

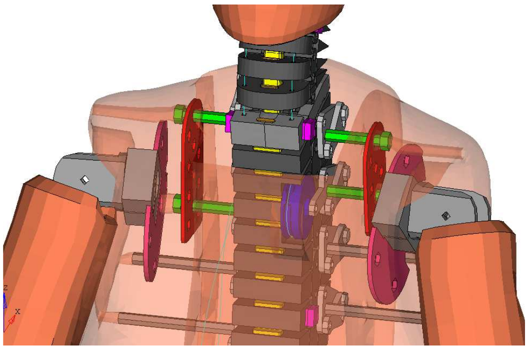

Fig. 7 Compressed shoulders of the BioRID-II (carbon fibre seat)

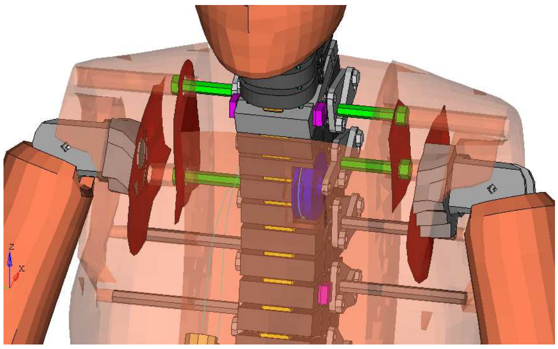

Fig. 8 Shoulder design of the EvaRID

The EvaRID model is based on release 2 of the BioRID-II model. So inner and outer shoulder plates are made of shell elements instead of solids (Fig. 8). The sliding of the inner plates along the bolts is probably less exact.

5.1 Dummy modifications

All bolts that connect the silicone torso to the spine are equipped with 5-axis loadcells to measure forces (x, y, z) as well as torques (x, z) between bolt and vertebra.

In some simulation runs both T2 bolts were removed to disable or minimise the shoulder load path. The removal allows more rotation of the spine above the T2 level but the overall kinematics of the dummy remains almost the same.

6 Results

6.1 Carbon fibre seat

6.1.1 Overall kinematics

The basic requirement to compare the shoulder loads of BioRID-II and THUMS is the good correlation of the kinematics represented by the accelerations of the most important body regions. The general shape of the acceleration signals and the gradients of loading and unloading are of major interest. The signal's peak can be influenced by the modelling that have only a little effect on the kinematics (e.g. bottoming out of tissue material). Therefore, the correlation of the peaks' magnitudes was not in priority.
Fig. 9 to Fig. 12 show the longitudinal accelerations of head, the vertebrae T1 and T8, and the pelvis. Generally, the correlation between both occupants is good but pelvis acceleration of the human raises earlier and with a higher gradient. This is caused by the posture of the THUMS. Compared to the dummy, the human model's back of the pelvis has no clearance to the lower backrest of the seat (early rise of the signal). Furthermore, the cushion is bottomed out at approximately 60 ms (change of the acceleration's gradient).
The drop of the BioRID-II's T1 acceleration at approximately 80 ms is probably caused by the chosen test set-up. At the same time other signals show peaks or valleys as well (e.g. upper neck shear force).

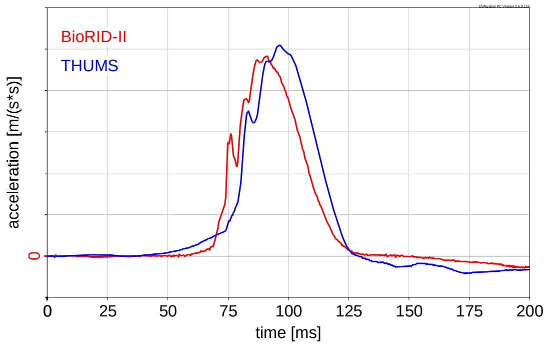

Fig. 9 Head acceleration (x)

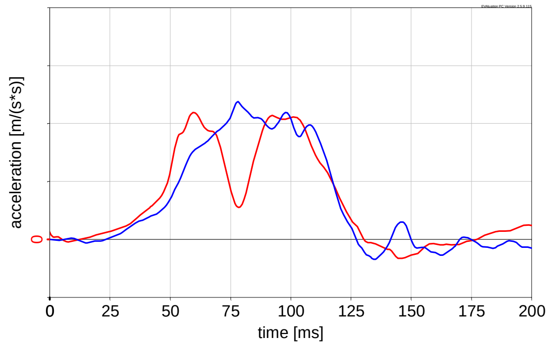

Fig. 10 T1 acceleration (x)

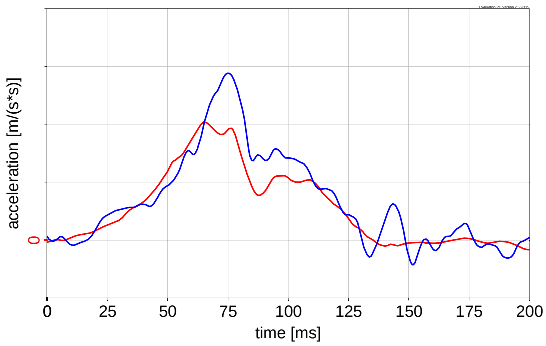

Fig. 11 T8 acceleration (x)

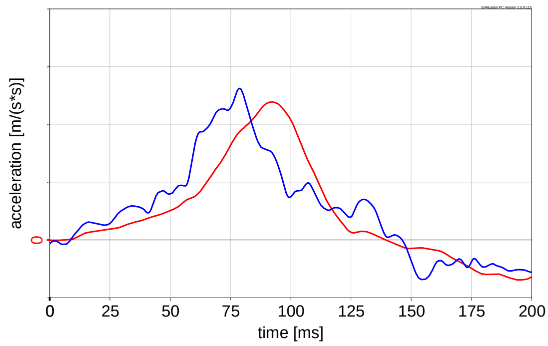

Fig. 12 Pelvis acceleration (x)

The vertical accelerations of dummy and human models differ significantly but their magnitudes are generally lower than those of the longitudinal accelerations. The BioRID-II shows significant vertical accelerations and the THUMS not. The human model is pushed into the backrest of the seat with almost no vertical motion. The pelvis of the dummy rotates backwards, lifts the upper body and the curved spine straightens.

In summary, the correlation of the overall kinematics of dummy and human model, especially in the main loading direction x, is sufficient to start investigations on the shoulder load path. The shoulder load path is not affected by the minor vertical loads.

6.1.2 Distribution of the shoulder loads

In a first step the load transfer from the seat to the back of the occupant was analysed. Fig. 13 depicts the back of BioRID-II and THUMS at the time of the maximum compression of the shoulders at approximately 100 ms. The transferred forces ranges from blue (low contact forces), green (medium) to red (high). Most of the load is applied to the pelvis. The shoulder area is mainly loaded through the upper arms.

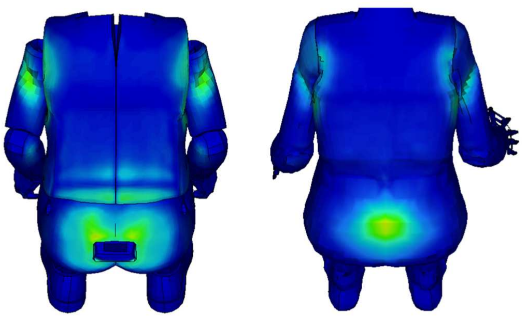

Fig. 13 Contact pressure between occupant and carbon fibre seat

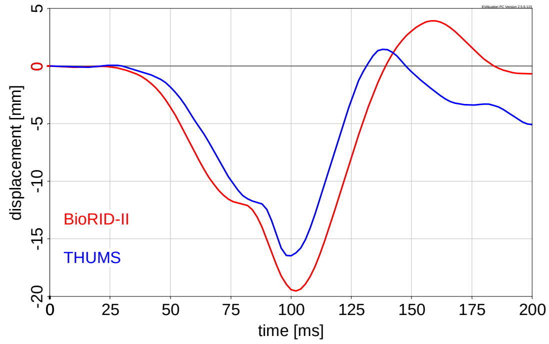

Fig. 14 Lateral compression of the shoulders

The lateral compression of the shoulders, measured between left and right articulatio humeri, is shown in Fig. 14. The difference between dummy and human model is low (less than 5 mm). The compression starts earlier in the BioRID-II because of the upper arm foam which is stiffer than the arm flesh of the human model. The different unloading characteristics beyond 130 ms are not of interest.

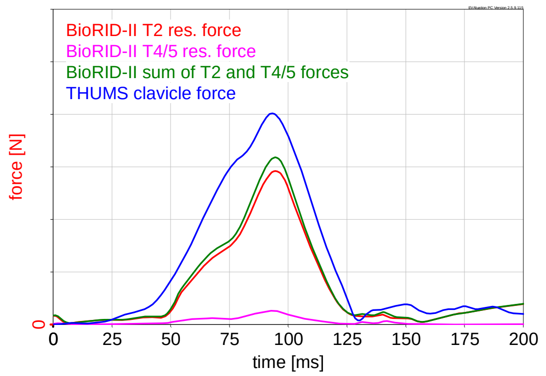

Fig. 15 Left shoulder forces

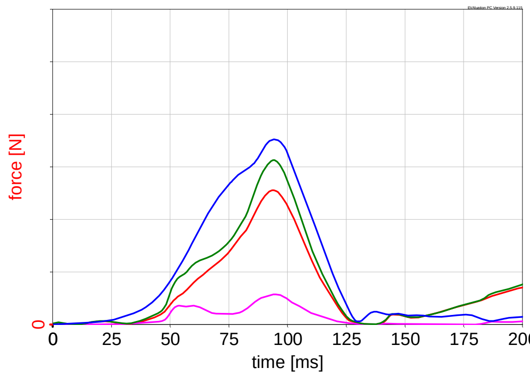

Fig. 16 Right shoulder forces

Fig. 15 and Fig. 16 show forces of dummy and human model in the shoulder area. The resultant forces of clavicle and T2 bolts are comparable and show a good correlation. The shape of the signals and the time of peak are identical. The later rise of the T2 forces are caused by the slim upper body of the dummy (Fig. 17). As shown in Fig. 15 and Fig. 16, the main loads are taken by the T2 bolts. The bolts at T4 (left) and T5 (right) take only a minor share of the loads.

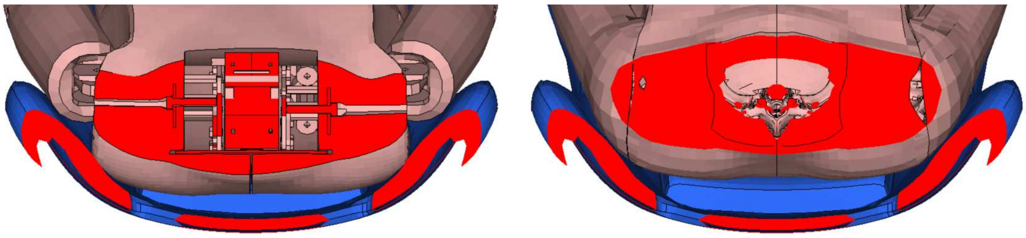

Fig. 17 Section-cut at the T2 level of BioRID-II and THUMS

In conclusion, the T2 bolts of the BioRID-II hold the shoulders in place (Fig. 6) and transfer external loads to thoracic spine. Such a direct load path does not exist in the human body. The clavicles that have a similar functionality like the T2 bolts when looking at the forces, transfer loads to the front of the rib cage (sternum). There is no direct and rigid connection from sternum to the thoracic spine (Fig. 29, Fig. 30).

6.2 Standard vehicle seat

6.2.1 Overall kinematics

The findings of the set-up with the carbon fibre seat can be transferred to the set-up with standard vehicle seat.

6.2.2 Distribution of the shoulder loads

Fig. 18 depicts the contact force distribution of BioRID-II and THUMS at 100 ms. The pelvis is taking most of the loads similar to the carbon fibre seat. The shoulder area is only slightly loaded because the seat's backrest does not cover the shoulders of dummy and human. The torso of the BioRID-II is compressed at its left and right side and the THUMS not.
The absolute difference between the shoulder compression of dummy and human model is low again (Fig. 19) but the compression's characteristics is different. It is probably caused by the more flat shape of the backrest. It does not provide the same support to the torso like the carbon fibre seat. However, the maximum shoulder compression is reached at approximately 100 ms by both occupant models.

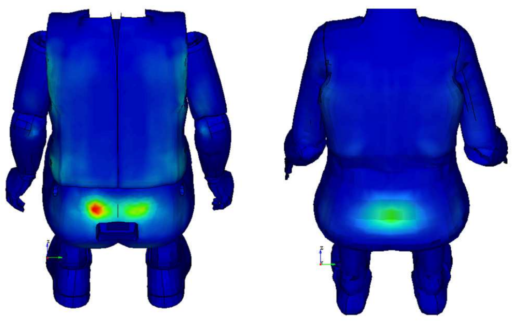

Fig. 18 Contact pressure between occupant and vehicle seat

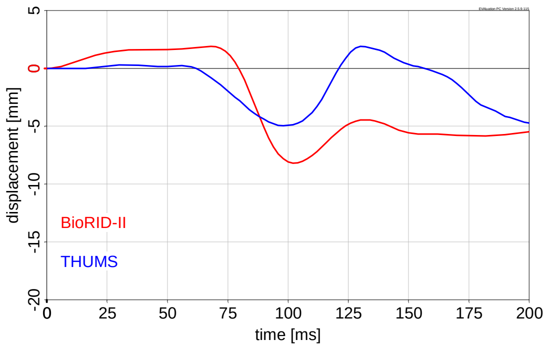

Fig. 19 Lateral compression of the shoulders

Contrary to the carbon fibre seat, the dummy's T2 bolt loads are lower than the clavicle loads of the THUMS (Fig. 20 and Fig. 21). The correlation of the right T2 bolt and the right clavicle is similar to that in the carbon fibre seat. There is also almost no delay in the raise of the force between dummy and human model. There was no sufficient explanation found for the different shape of the left T2 bolt force. The drop of the force occurs a few milliseconds before the contact between head and headrest.

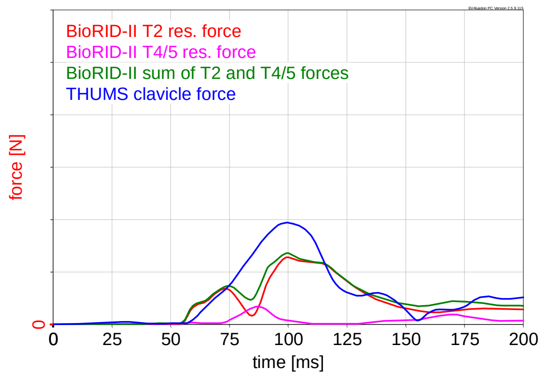

Fig. 20 Left shoulder forces

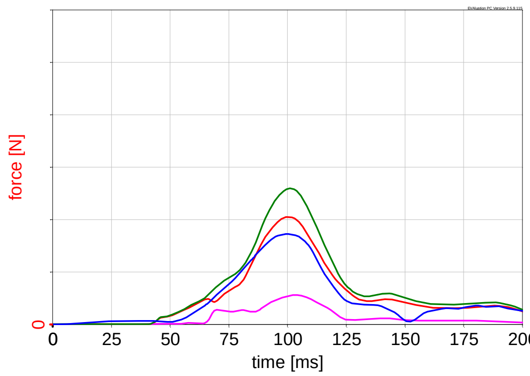

Fig. 21 Right shoulder forces

In summary, the shoulders are not compressed directly in this seat. Therefore, the absolute shoulder compression as well as the analysed forces are lower than in the carbon fibre seat.

6.3 EvaRID and downscaled THUMS

The findings of the simulation runs with BioRID-II and THUMS in both seats can be transferred to EvaRID and downscaled THUMS. So the longitudinal accelerations correlate well, the EvaRID tends to slide upwards by straighten up its spine, and the downscaled human model is pushed into the seat without significant vertical movement.

The difference in width of the torso of EvaRID and downscaled THUMS is smaller than that of the 50^{th} percentile occupants. Therefore, the upper bodies are pressed deeper into the seat, resulting in a higher compression of the shoulders (Fig. 23). The shoulder area of the EvaRID is smaller than that of the downscaled THUMS (Fig. 22). Consequently, EvaRID's shoulder compression is higher.

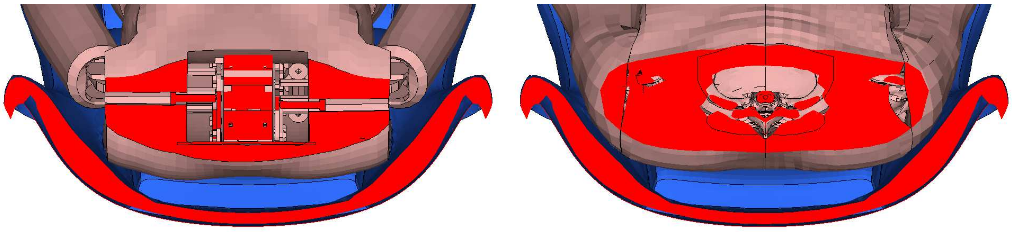

Fig. 22 Section-cut at the T2 level of EvaRID and downscaled THUMS

The flat shape of the standard vehicle seat does not induce significant compression of the shoulders (Fig. 24).
The clavicle forces and the forces of the T2 bolts are also analysed. There is almost no correlation between both forces because of the rudimental modelling of the EvaRID shoulders. A simulation with the BioRID-II release 2, which has the same simple shoulder design like the EvaRID, confirmed this assumption.

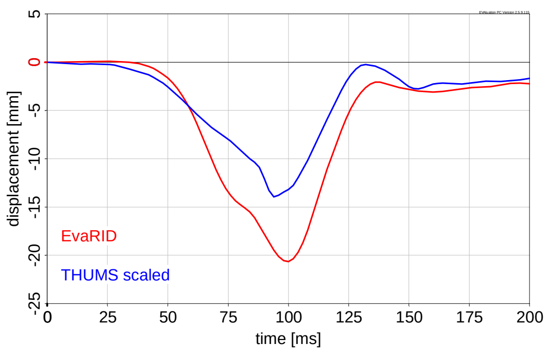

Fig. 23 Lateral compression of the shoulders (carbon fibre seat)

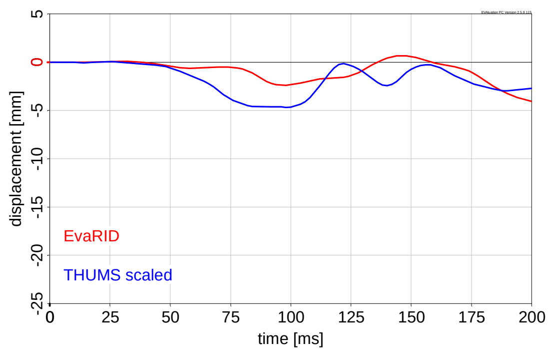

Fig. 24 Lateral compression of the shoulders (standard vehicle seat)

6.4 Analysis of the shoulder load path

It was shown in the previous sections that the bolts at the T2 level can distribute external shoulder loads like the clavicles of a human. The significance of the shoulder load path depends on the guidance that the seat's backrest provides to the upper torso. Tests with the BioRID-II showed that the these bolts influence the upper neck shear force.
The neck forces of a dummy model are measured by a beam that connects two rigid bodies. It measures the force in the skeleton and there is usually no other load path (e.g. soft tissue) that bypasses this loadcell. Such a design cannot be transferred to a human model. The spine is covered by soft tissue and the head is supported by ligaments. So the force between two rigid vertebrae would represent only a portion of neck loads. A section force that includes soft tissue, ligaments and

vertebrae must be defined. This section force was implemented in the THUMS but there is no correlation between dummy and human body model. Therefore, simulations with the THUMS cannot help to evaluate the dummy's neck forces with and without T2 bolts.

The simplest option to minimise or disable the influence of the T2 bolts on the neck forces is the removal of these bolts. In this case the inner shoulder plates are only hold by the bolts at T4 (left) and T5 (right) level (Fig. 6). This removal has almost no effect on the dummy accelerations but the shoulder area is less stable. It results in a higher compression of the shoulders. The absolute compression increases from approximately 20 mm with bolts to 25 mm without these bolts. As shown in Fig. 25 and Fig. 26, the T4/5 bolts take the loads in the modified BioRID-II model. They have now the same function like the T2 bolts in the non-modified dummy.
The removal of the T2 bolts does not eliminate the shoulder load path completely because the T4 and the T5 bolts are rigidly fixed to the spine too and are still influencing the spine.
All of these findings are also valid when using the standard vehicle seat, or EvaRID and downscaled THUMS.

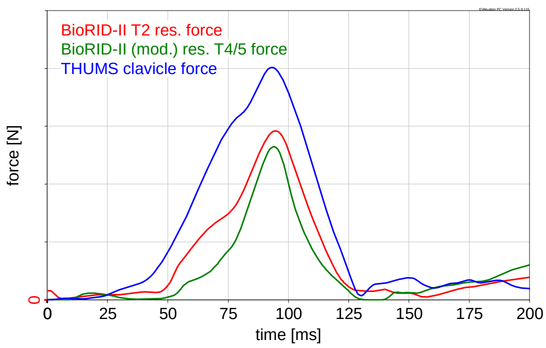

Fig. 25 Left shoulder forces (carbon fibre seat)

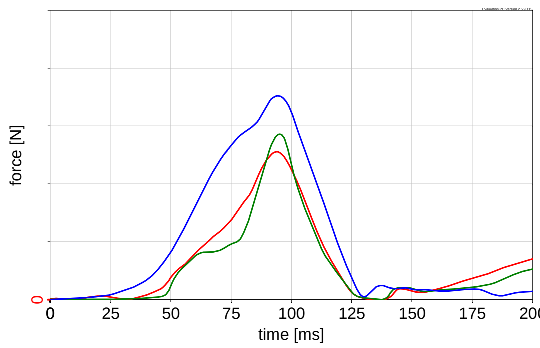

Fig. 26 Right shoulder forces (carbon fibre seat)

To visualise the influence of the T2 bolts on the neck forces in a more general way, a differential upper neck shear force is calculated (Fig. 27). It is the differential curve between the curves of upper neck shear force with T2 bolts and without these bolts. The higher the magnitude of this differential curve, the more relevant is the influence of the T2 bolts on the neck shear force.
Fig. 27 shows that the influence of the T2 bolts on the neck is lower in the standard vehicle seat than in the carbon fibre seat. It also correlates with the lateral compression of the shoulders. The results are similar when looking at the EvaRID (Fig. 28). The difference in shoulder compression between both seats is higher than for the BioRID-II. Consequently, the relative difference between the differential shear force curves is higher, too.

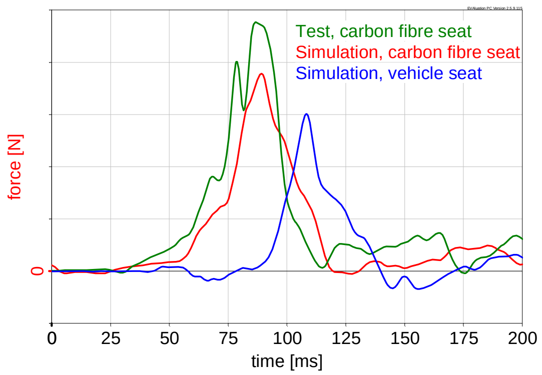

Fig. 27 Differential upper neck shear force (BioRID-II)

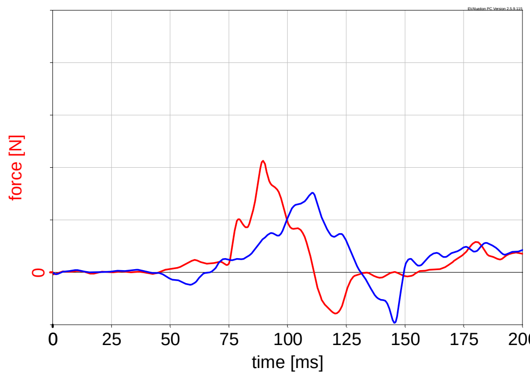

Fig. 28 Differential upper neck shear force (EvaRID)

The difference of test and simulation curve of the BioRID-II (Fig. 27) is caused by the suboptimal correlation of the upper neck loads. The correlation of the accelerations between test and simulation is significantly better.
The different timings of the differential curves in the set-ups with the carbon fibre seat and the standard vehicle seat are caused by the different kinematics of the dummies in these seats.

7 Conclusion and summary

A dummy is always a simplified model of a human. Biofidelity is only one aspect of a dummy development. Robustness and usability are important design targets, too. A very biofidelic dummy which is damaged in almost every test and which measurements are not repeatable nor reproducible cannot be seriously considered for the use in vehicle development processes. So there is always a balance required between biofidelity, robustness, and usability.
The study shows that the design of the shoulder area of the BioRID-II differs significantly from a human. Bolts that are directly fixed to the spine partly take functions of the human shoulder. It is also shown that the bolts at the T2 level have similar functionality like the clavicles when looking at the distribution of external shoulder loads. Compared to the dummy's T2 bolts (Fig. 29), the clavicles are not directly linked to the thoracic spine (Fig. 30). Both clavicles transfer load from the shoulder joints to the sternum. The vertebrae are solely indirectly loaded and the connections between the bones are elastic.

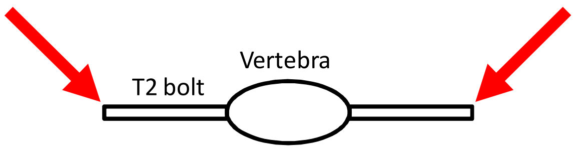

Fig. 29 Schematic diagram of the distribution of BioRID-II shoulder loads

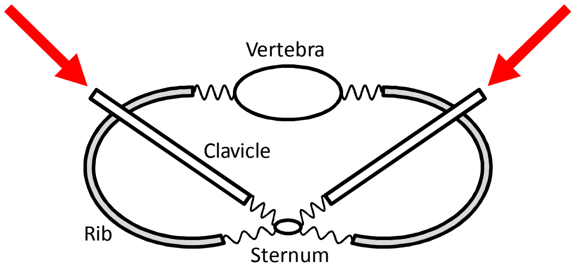

Fig. 30 Schematic diagram of the distribution of shoulder load in a human body

The loads that are taken by the BioRID-II's T2 bolts are directly transferred to the thoracic spine. The presence of these bolts can be detected in the upper neck loads. The intensity of this shoulder artefact depends on the type of seat that is used. Seats with a more flat and soft backrest seems to be less affected. Stiff sport seats with lateral guidance of the upper body can enable this shoulder load path. Consequently, the assessment of the upper neck loads in a rear impact depends also on the lateral guidance of the shoulders by the seat.
The hypothesis that the removal of the bolts changes the overall kinematics of the dummy and affects almost all dummy responses can be disproven with the whiplash performance criteria NIC and N_{km}. The NIC, that assesses the relative accelerations and velocities of head and T1, changed by only 2% when removing these bolts, whereas the N_{km}, that assesses neck forces and moments, changed by 11% at the same time.

The BioRID-II was originally designed for the analysis of the kinematics in rear-end crashes. The measurement of forces and moments was introduced afterwards. There was probably no need to look at the secondary function of the bolts that hold the shoulders in place when the dummy was designed.

The removal of the T2 bolts demonstrates the redirection of the forces in the shoulder area but it is definitely not the right technical solution to solve the problem. The T2 bolts are required to stabilise the shoulders and a permanent removal would probably reduce the durability of the dummy.

This study also shows the potential and limitations of a human body model. It is a very helpful tool to support the evaluation of a dummy design. A human model is probably not always telling the full truth but it can give ideas of inconsistencies in the dummy's behaviour.
The correlation of the kinematics between dummy and human model was never a problem in this study. The comparison of a bone's section force with the corresponding dummy loadcell (e.g. clavicles and T2 bolts) is possible. The analysis of section forces that contains bones, soft tissue material, and

ligaments seems to be difficult. There was no correlation between the upper neck dummy loads and the corresponding section forces in the human model. It is not clear yet if it is a numerical or mechanical problem. A numerical problem could probably be solved by a software update. A mechanical problem needs further investigations. It must be clarified which type of load in the human neck corresponds with the neck loads of a dummy.

8 Limitations

The THUMS that was used in this study was not validated for low severe rear-end crashes. Especially the neck may not show the right kinematics. However, the kinematics of the neck was not of interest in this study. The relative displacement between head and upper thoracic spine is relatively small in the chosen test set-up. So the model's weakness in whiplash configurations have only limited influence on the results.

The correlation of the dummy's neck loads between test and simulation should be improved. It is probably a problem of the dummy hardware, too. It was found that the reproducibility of the BioRID-II's neck forces and moments is a serious problem in some test configurations [2]. As long as the cause of these problems is not fully identified and solved, it is difficult develop a model that is universally validated. The validation of a dummy model is always linked to a specific dummy specimen or a small group of dummies.

9 General remarks

From the user's point of view the human model that was used in this study cannot be compared with a dummy model. Firstly, the preparation of an input deck is very time consuming because of the multistep pre-simulations that are necessary to position the human model. State of the art dummy models require pre-simulations too but this process is less complicated and it is sometimes automated by scripts. For instance the repositioning of the arms of the THUMS from the drivers to the passengers position required a two-step pre-simulation and the re-mesh of the ligaments that connects the upper arm bones with the shoulder. This is not acceptable when using the human model in standard vehicle development processes.
Secondly, the numerical robustness of human models is sometimes an issue. The used THUMS was numerically stable in the low severe rear-end crash environment of this study. Nevertheless, a few ligaments that are fixed to first rib caused some problems. This problem was solved by the definition of some nodal rigid bodies.

A human model is a very helpful tool to get answers to very specific questions but right now it is probably not the right tool for daily use.

10 Acknowledgments

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11 Literature

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