On Predicting Lower Leg Injuries for the EuroNCAP Front Crash

Thomas Hofer, Altair Engineering GmbH

Peter Karlsson, Saab Automobile AB

Niclas Brännberg, Altair Engineering AB

Lars Fredriksson, Altair Engineering GmbH

Summary:

Validation of occupant lower leg injury performance is a difficult procedure due to the complex interaction between occupant and vehicle structure. As a starting point, a carefully validated structural model is crucial to ensure the accurate load of the occupant model in terms of acceleration and applied forces. However, even after a tedious validation of structural performance and occupant environment, the calculated tibia values might still deviate from the test results. Some of these deviations may be caused by restrictions in the occupant model fidelity. This becomes evident in an offset-crash simulation (EuroNCAP), since the complex force behaviour (x, y, and z- components) do not seem to be reproduced by existing occupant models to 100% satisfaction. Especially the dummy joint representation for the ankle, knee and pelvis might cause deviations between the occupant model and the test. Modifications of joint parameters were done to demonstrate a significant potential in the improvement of the fidelity of the occupant model and to bring the tibia injury criteria closer to the test results.

This paper presents a detailed numerical analysis to point out the discussed difficulties and proposes possible approaches for a more realistic prediction of tibia values in the case of the EuroNCAP front crash. The proposed changes in this paper will not replace the need to permanently improve the standard FE dummies, but should be seen as a part of the discussion in order to improve the fidelity of the standard dummies in the future.

Keywords:

occupant simulation, lower leg injuries, tibia index, EuroNCAP, front crash

1 Introduction

Nowadays, crash simulation results are decisive for the car manufacturing industry to get a fast turn-around time between model changes and to end up with a reduced number of real prototypes. To meet this requirement, a well validated and stable simulation model is required to predict a realistic behaviour of both structure and occupant. Otherwise, simulation results might be misleading, when the impact of model changes have to be assessed or the development is driven by simulation instead of doing a real test. The evaluation of every vehicle crash comprises the structural behaviour of the car and the occupant injuries involved. The structural behaviour like dynamic deformation, material failure or vehicle deceleration are directly affecting the occupant values during the crash. A detailed correspondence of structural performance between test and analysis is of special importance when the interaction between structure and occupant is not filtered through the seat, seat belt and the airbag. Lower leg behaviour and the interaction between feet and fire wall is such a case. This makes the prediction of lower leg injuries a particularly difficult task. Although specific occupant values at pelvis, chest or femur are close to given test results, the tibia values might still deviate in an unsatisfactory manner. The off-set crash (EuroNCAP) raises such issues, since the force behaviour caused by intrusions and vehicle rotation is considerably more complex compared to a 100% overlay crash. In most cases the tibia index is not calculated satisfactory due to possible deficiencies of the occupant model. The investigations in this paper point out such difficulties and propose possible approaches for a more realistic prediction of the tibia index in the case of the EuroNCAP front crash. During this project it becomes apparent, that especially the ankle and knee joint do not always have the ability to predict a realistic behaviour in the case of a complex load. Modifications in this area have been done to test their influence to tibia values and to show their potential to obtain values closer to test results.

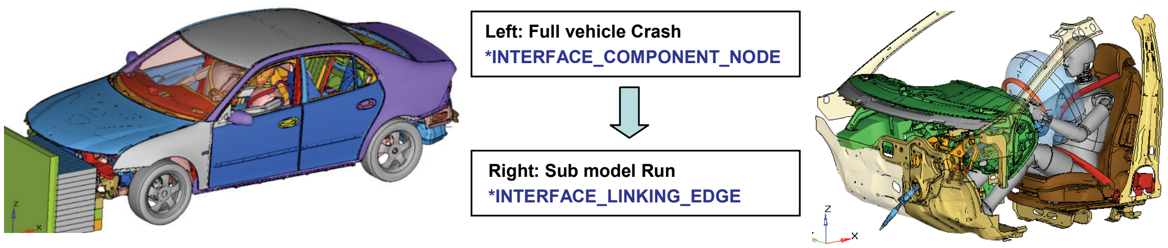


Figure 1: Full vehicle crash and reduced sub model for fast analysis runs

As shown in Figure 1, a sub model technique is used to reduce the simulation time and to run studies or Design of Experiments (DoE) in a timely manner. The occupant values are directly comparable. However the sub model is limited, since the displacements at defined interface nodes are prescribed and changes inside the sub model do not affect the global vehicle behaviour. If a full vehicle crash is required, it can be done quickly by using modular modelling techniques. The investigations in this paper were mainly performed using the standard FTSS 50th percentile Hybrid III model, version 5.1. Comparisons were also performed using the PDB dummy model, version 5.0a.

2 Evaluation of Occupant Values

Compared to a structural model, occupant analysis needs significantly more effort in modelling. Figure 2 (left) shows a common occupant environment. Basically every structural part having contact to the dummy during a crash has to be considered. To describe stiffness and kinematic properly such critical

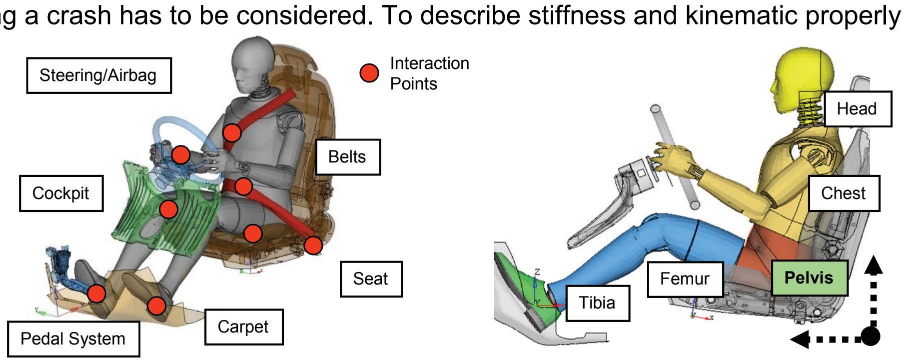


Figure 2: Left: driver environment and contacts; Right: Validation procedure of occupant values

parts require a proper mesh, accurate material data and a detailed reproduction of all connections and joints. As a consequence, this is costly and the calculation time is increasing considerably. Among structural properties, a proper positioning of feet, legs and pelvis has high influence on the results. For validation of occupant values, a detailed dummy positioning protocol is indispensable and additional pictures or videos are most helpful to rule out the possibility of a wrong occupant position. As shown in Figure 2 (right) every validation should start with the motion of the pelvis, before looking at the chest and head or at the femur and tibia data.

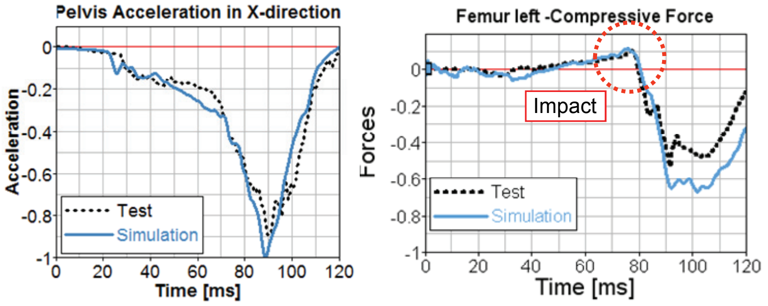


Figure 3: EuroNCAP: Validation of the pelvis kinematic and the corresponding femur forces left/right

Figure 3 (left) shows a comparison of the pelvis acceleration in simulation vs. real test. Initially the pelvis motion is influenced by the deceleration of the seat structure, the contact of the dummy relative to the seat foam and the belt forces respectively displacements. This kinematic behaviour should be validated carefully, since small deviations to the test might subsequently cause different impact conditions to the environment and therefore a different force loading of the lower and upper legs. Figure 3 (right) shows a comparison of the femur forces between simulation and physical test. Timing and absolute values are strongly influenced by the pelvis motion and the impact location of the lower leg at the cockpit panel. The impact time usually depends both on the pelvis motion and a possible intrusion of the cockpit caused by deformations of the firewall and A-Pillar. The absolute values, especially the main peak are given by the impact behaviour of the impacted parts, for instance the knee bolster. To reproduce the cockpit stiffness properly, all material properties (e.g. foams), but also connections or material failure should be modelled accurately. At this point it is helpful to have real world colour prints showing the impact location of the lower leg at the cockpit and a possible knee sliding during contact.

3 Lower Leg Assessment – General Considerations

The evaluation of the tibia index represents a weighted combination of the compressive force Fz and the resulting moments Mx (inversion, eversion movement) and My (dorsiflexion, plantar flexion movement). The calculation formula for the tibia index is defined as

$$TI = M_R(M_x, M_y) / 225\text{ Nm} + |F_z| / 35.9\text{ kN},$$

whereas both forces and moments have to be predicted well for a realistic estimation of the tibia index. Figure 5 (left) shows the definitions of the required forces and moments at the lower tibia above the ankle joint and at the upper tibia below the knee and illustrates the common situation in the case of a EuroNCAP load case. The tibia forces Fz are mainly activated by external forces caused by intrusions of the firewall and footrest. The resulting force level at the foot is normally damped by the carpet and pedal stiffness, for what reason an accurate modeling of these parts is essential.

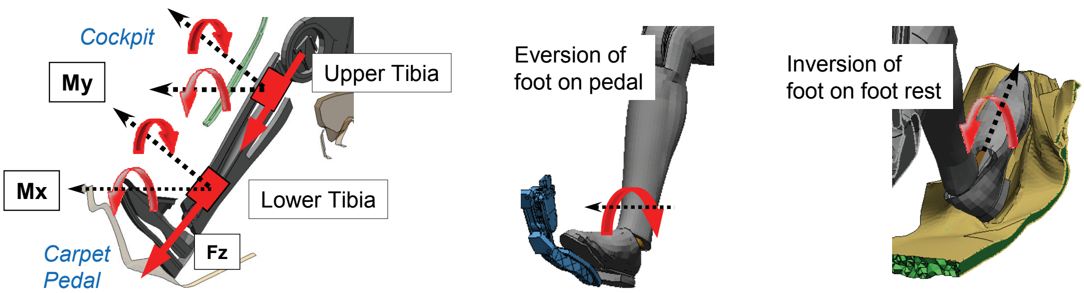


Figure 5: Left: Tibia definitions; Middle: Right foot on gas pedal; Right: Left foot on foot rest

The right foot is positioned on the pedal, while the pedal system at the firewall and the floor below the foot heel is intruding. The left foot is positioned on the foot rest, at which due the offset of the deformable EuroNCAP barrier, complex force directions occur. The corresponding moments (Mx/My) are causing inversion, eversion or dorsiflexion movements of the ankle joint.

4. Validations of Tibia against Existing Data Set

The following sections 4.1 and 4.2 explain the validation procedure used to validate a simulation model against a physical data set and describes the remaining deviations between test and analysis.

4.1 The Compressive Tibia Forces Fz

The evaluation of the compressive forces Fz requires a well validated structural model in terms of dynamic intrusions, a proper modeling of the dynamic stiffness during the interaction between foot and pedal/footrest and an accurate start position of the foot. Figure 6 shows influences to the lower tibia forces, if specific parameters are changed during the evaluation. At the left leg the compressive tibia forces are sensitive to the foot position as well as to the stiffness of the carpet. The carpet acts like a damper of the external forces caused by intrusions of the foot rest. Figure 6 shows a comparison between two simulations, when fitting the material data of the carpet. Mainly the peak values in the time range [70-80ms] are reduced and get closer to the test data.

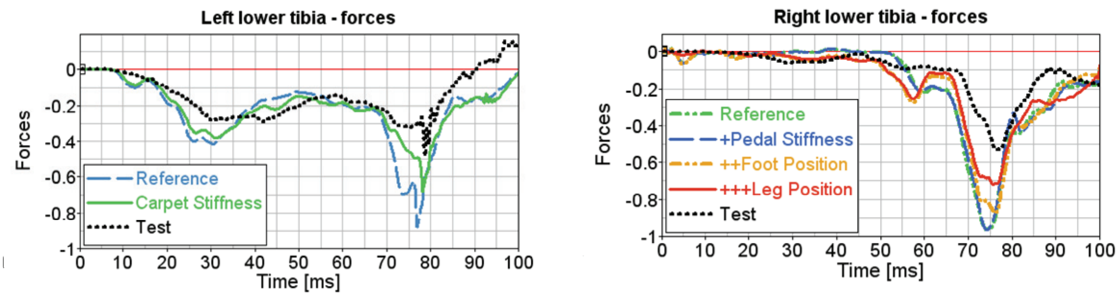


Figure 6: Variation of the lower tibia force, when changing sensitive parameters

At the right leg the foot position on the pedal is causing a problematic situation, since the interaction between foot and pedal is quite complex in general. Before starting the actual validation, the overall correspondence was checked by comparing the videos of the physical test to the animation as shown in Figure 8. At this point a significant difference could be observed. The right foot tended to slide off sideward's from the gas pedal during the simulations. This phenomenon was not observed in any of the physical tests and was generally insensible to foot positions or other means of changing the model. This phenomenon would only be corrected by changing the ankle joint characteristics, i.e. by increasing the friction. This is physically motivated through the following reasoning: Friction is normally proportional to the normal force acting on the friction surface. In the case of the ankle joint, this would imply that the friction moment should be proportional to the axial force through the ankle joint. The FTSS friction model for the ankle joint, however, includes a constant force not depending on the axial force Fz. At this stage of validation the friction force was simply stepwise increased until a stable ankle joint behaviour could be noticed.

Once the ankle joint is stable, the influence parameters to the compressive force can be analysed. Figure 7 demonstrates exemplary three of these sensitive parameters, which influences the lower tibia force Fz. The corresponding force curves are plotted in Figure 6 (right). First the pedal stiffness is reduced by using a finer mesh (left), which yields to a slightly higher deformation. As a result the foot remains more stable on the pedal and the deformation indicates now a possible material failure, which fits to the test. However, the force values in Figure 6 are comparable to the reference run, since the differences in foot behaviour do not occur before 80ms and therefore after the time of the peak value of the tibia forces. An additional reposition of the foot (middle) changes the foot kinematic. The yellow heel stays stable on the carpet and the foot is pushing the pedal through, without sliding too much over the carpet compared to the blue position. An additional rotation of the upper leg (red) in horizontal y-direction supports this situation even more, which results in clearly lower tibia values. This combination of changes leads step by step to tibia forces, which are closer to the test.

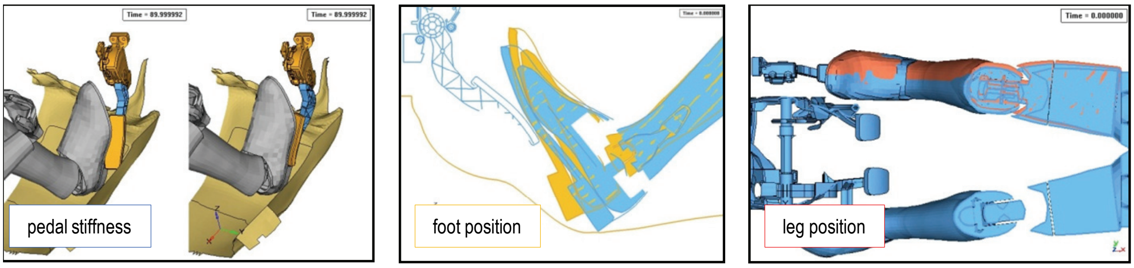


Figure 7: Steps during the evaluation of the right lower tibia force (Tibia Forces are plotted in Fig.6)

All investigations demonstrate that the compressive forces at femur and tibia strongly correlate with the dynamic stiffness of the contact interface (pedal/carpet) and the foot and leg positioning. A change of the contact stiffness or dummy position shows a high sensitivity of these parameters and enables thus a quite good validation and a realistic prediction of the compressive forces at femur and tibia. For the right foot, it is essential that the foot stays on the gas pedal and does not twist as observed initially.

4.2 The Tibia Moments Mx/y

The evaluation of the tibia moments Mx/My is highly sensitive to both the force level and the force direction. The dynamic intrusion of the foot well in conjunction with the current foot position defines the direction of the external force and the thereby resulting moments at the lower leg. Therefore a comparable foot movement between test and simulation during the crash impact is crucial to achieve realistic moment values. At this point the real world videos of the foot well showing the foot position and the foot kinematics during the impact should be checked thoroughly.

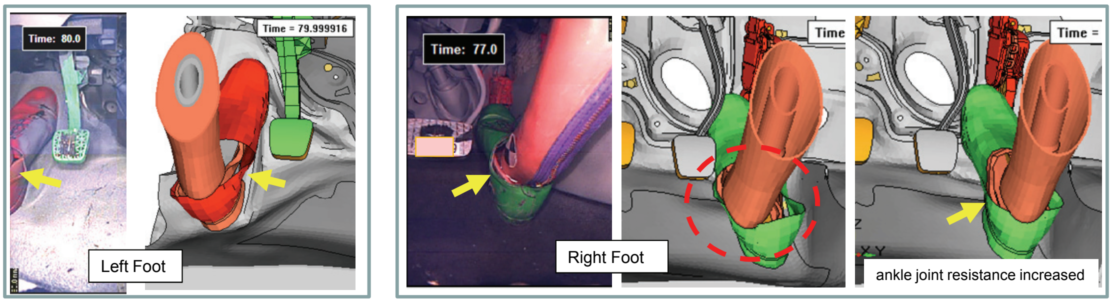


Figure 8: Test video compared to analysis: Left (at 80ms) and right foot (at 77ms) behaviour

Figure 8 (left) shows the left foot on the foot rest at the time of 80ms. The foot position is comparable between test and simulation and the shoe deformation looks similar, which indicates a similar loading of the foot. At the right foot the test video clarified, that the foot remains stable on the gas pedal and pushes it through without a visible side-slip. In the simulation on the other hand the ankle joint of the current FTSS dummy model is twisting strongly (right/middle). This phenomenon was already observed and discussed in chapter 4.1. As a consequence such a foot kinematic would cause high moments Mx at the lower tibia, which do not occur in the test data. This means the modification of the friction force at the ankle joint introduced in chapter 4.1 is as well crucial to achieve realistic tibia moments Mx. In Figure 8 (right) the stabilised foot remains stable on the pedal and the shoe deformation looks quite well. This stability allows the foot now to push the gas pedal through, whereby the resulting dorsiflexion movement and therefore the lower tibia moment values My fit closer to the test data.

At this stage of the validation the motion of the upper leg, the impact position of the lower leg at the instrument panel and the behaviour of the foot on the pedal resp. footrest are comparable to the test. Therefore the tibia moments should also fit to the test data, but they partly do not. In Figure 9 for example the moment values of the left upper tibia are plotted against the test data and the compliance is poor. The peak area during the time range [70-90ms] is far away from the test results.

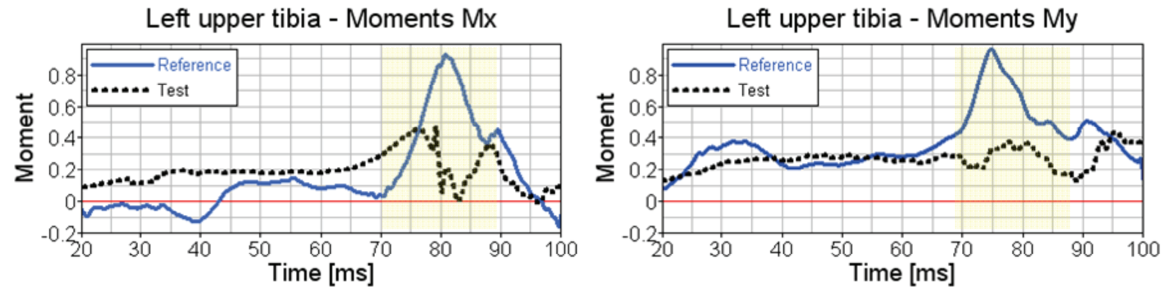


Figure 9: Upper tibia moments in torsion Mx and shear My for the left leg

4.3 Investigation of the Remaining Deviations

During the analysis several studies were performed to detect a set of parameters, which are showing high sensitivity to the system. Changing one of these parameters is directly influencing the force response depending on its range of sensitivity. Otherwise when looking at the tibia moments, especially the high peak area remained steady during all the studies. Therefore additional studies were performed to influence this area. For instance, at the left foot a set of completely different foot positions was tested. Figure 10 shows two exemplary positions. Normally this variation should lead to different results, but when looking at the moment curves especially the peak area is not influenced.

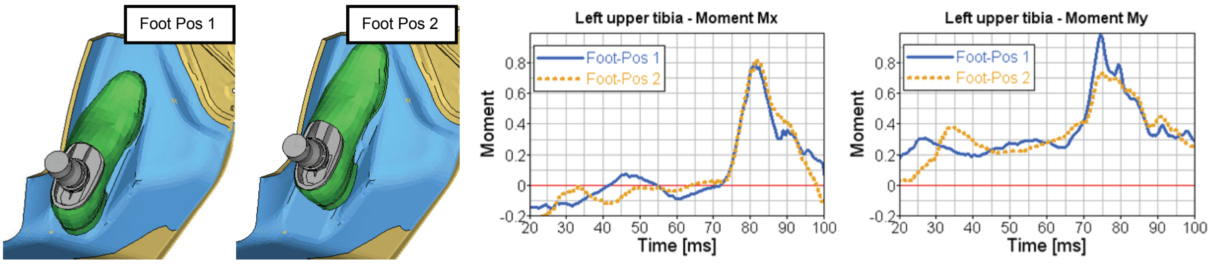


Figure *10: Example of two different foot positions left and the resulting upper tibia moments*

All those variations of the setup made it clear that there had to be one or more dominating error sources in the model and such “ruling phenomena” make the model insensible to other changes. The ankle twist appeared to be one visible evidence of such errors, but correcting this was not enough to be able to validate the lower leg model properly. Two further main sources for the mentioned systematic error were conceivable:

- The validation of the structural behaviour of the foot well is not satisfactory.
- The occupant model still fails to reproduce the physical test behaviour satisfactory and therefore gives the wrong sensor values.

Since a large numbers of investigations including DOE studies were performed to check the sensibility of results by changing the structural model, the stiffness of interacting parts and the occupant position and all these investigations did not yield to the desired effect on the tibia moments, further attention was focussed on the occupant model.

One obvious characteristic of the critical peak area in Figure 9 is that it constantly occurs in the time range [70-90ms]. When looking at the femur force the upper leg comes in contact with the cockpit panel at about 70ms and the force rises up to its peak value exactly during this critical time range. The observation indicates a possible correlation between the high moment values in the simulation and the hard contact between the lower leg and the structure. From 70ms on, the upper tibia cell stays in contact with the cockpit panel and is therefore locked, while the upper leg and therefore the knee moves freely. As shown in Figure 11 the upper tibia cell is loaded by the femur force and by the force distribution of the intruding foot well, which is acting partly lateral due to the offset-crash. This force directions are causing the torsion and shear moments Mx/My at the upper and lower tibia load cells. Due to the modelling of the clevis joint in the knee the lower leg has no flexibility, while the upper tibia is locked at the panel. This configuration is causing high moment values until ca. 77ms, when the knee impacts at the cockpit and releases the upper tibia load cell. In a real world dummy a slight rotation of the lower leg relative to the knee can be observed and gives so the necessary flexibility to avoid high and therefore unrealistic moment values.

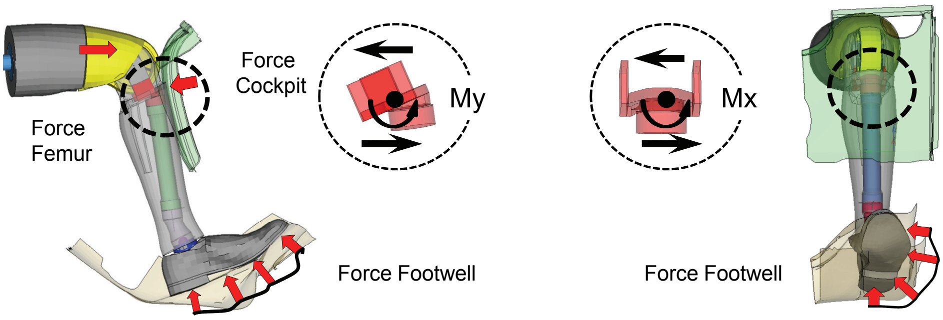


Figure 11: Force Loads to the left leg in case of a EuroNCAP front crash load case

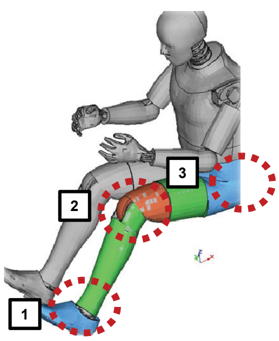
5. Approach to Improve the Behaviour

The idea of changing the LS-Dyna FTSS dummy joint representation is based on the observation that the critical moments occur during the hard contact between lower leg and cockpit. Accordingly a slight flexibility of the leg, which is observed in hardware dummies, should have the potential to reduce these high moment peaks.

The first change, increasing the friction moment of the ankle joint, was already performed to achieve a reasonable general behaviour. As further experiment, the generalized-stiffness-definition at pelvis and knee were deleted just to look at the effects onto the moments. As might be expected this modification leads to a general reduction of the torsion moments Mx due to the gained flexibility of pelvis and leg. Important at this point is the fact, that this modification has nearly no influence to the compressive tibia forces. However this overly freedom of movement is changing the leg kinematic, which results in a wrong impact position at the cockpit panel and therefore different femur forces compared to the test. An erasure of the generalized stiffness definition at pelvis and knee points to the right direction, but is certainly not a solution. The goal is to find an appropriate combination of changes, which is reducing the high tibia moments but without changing the global dummy kinematic. By doing this, the modifications should have a physical background. All changes must be able to explain from the aspect of real possible deviations between the current FE models and the physical occupant models.

The following set of changes to the ankle joint, knee and pelvis is put together to test the behaviour of the lower leg and its capability to reduce the high moment peaks:

[1] Modification to the ankle joint definition (section 4.1/4.2)
A stable foot kinematic was only achievable by adding a defined frictional resistance to the ankle joint. This observation between test and simulation was made when comparing the kinematic behaviour of the right foot positioned on the gas pedal. In LS-Dyna this can be done quickly by defining an appropriate value in the generalized-stiffness card of the joint definition. The optional parameter is defined as <FMPH> and can be considered as an elastic-plastic spring. This modification is just for testing since a final and correct solution requires that the frictional force depends on the current axial force, which in particular means that the friction should increase with a higher load of the ankle.



[2] Modification to the knee joint definition (section 4.3)
Due to the ideal revolute joint in the knee there is no flexibility between lower and upper leg. In a real world dummy a slight flexibility in the knee can be observed. To test this fact, the generalized-stiffness definition in the clevis joint is deleted and the corresponding penalty stiffness is reduced. Therefore the knee cap can have a slight rotation relative to the upper tibia, which should avoid the unrealistic moments during the hard contact between the lower leg and the cockpit panel. Again this modification is just to test the influence, because a final solution requires an accurate modelling and testing of the physical behaviour of the real world dummy.

[3] Modification to the pelvis joint definition
At the pelvis the frictional resistance of the generalized-stiffness definition is slightly reduced, which should give some additional freedom of movement but keeps the dummy kinematic stable. In comparison to the modifications at ankle and knee this change shows only a small influence to the results.

Figure 12 shows a front view of the knee behind the cockpit panel at the critical time of 80ms for the reference run (left) and for the approach using the described set of modifications (right). A slight rotation of the upper tibia relative to the knee cap can be clearly detected. This means the intended flexibility between the upper and lower leg works well and will also be used during the critical time range of the high moment peaks.

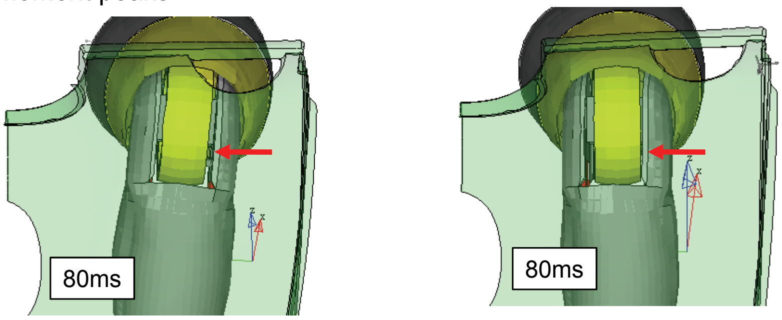


Figure 12: Left: left leg of the current dummy, Right: left leg with the described set of modifications

Figure 13 shows the corresponding moment values at the upper tibia of the left leg. The moment values in torsion and shear are significantly reduced during the discussed time range of [70-90ms], which proves that the test was successful and the additional flexibility inside the knee describes a significant step in the right direction.

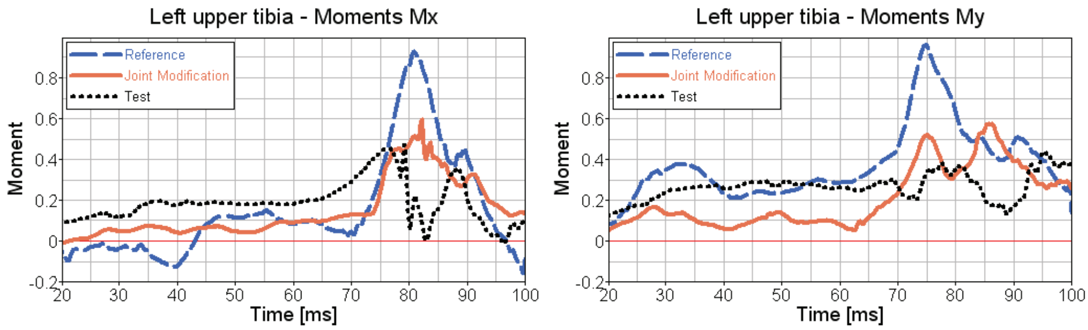


Figure *13: Moment values for the upper tibia with and without changing the knee and pelvis joint*

5. Conclusion

The investigation during this project detected “ruling phenomena”, which are dominant to the tibia moment values in torsion and shear. In this case, sensitivities to the moment values are hidden by unrealistic high peak values, which make any assessment regarding tibia index to a difficult task. The results from e.g. a DOE-study might be misleading, since the evaluation pretends, that the varied parameters do not have a significant influence to the stability of the system.

Observations based on the hardware dummy and the corresponding test data indicated a weakness in the joint representation of ankle, knee and pelvis. This issue appears especially in the case of an offset front crash due to a complex force direction in conjunction with a structural contact. To support this observation test-modifications in the joint definition have been performed, whereby the results clearly demonstrate that the unrealistic moment values can be eliminated. Intention of this approach is not to provide a final or correct solution but to show that there is a straight potential to avoid such unrealistic moment values by improving the lower leg model on physical basis. Every evaluation of lower leg injuries would become more reliable.

All studies were performed using the "FTSS Hybrid III 50Th - Version 5.1" dummy. The "FTSS Hybrid III 50Th - PDB Version 5.0a" was also tested and this model can be considered as a good starting point. In this version the translational joint in the knee slider is replaced by a cylindrical joint combined with a rotational spring. This enables the lower leg to rotate slightly around the local z-direction of the upper leg if a force is applied to the foot in local y-direction. However, the discussed effects are mainly observed in an offset crash, where the force direction but also the structural contact seems to be more complex as considered by the current component tests. In such a test first of all the ankle joint should be analysed under comparable load conditions (e.g. foot on pedal) and improved by adding a dependency between axial and frictional force to achieve a realistic resistance. Afterwards the flexibility between lower and upper leg should be analysed in detail and tested within component tests. These test configurations should consider realistic boundary conditions to represent an offset crash like the EuroNCAP. The suggestions made in this paper should be seen as a part of the discussion in order to improve the fidelity of the standard dummies in the future development.