Annex E – SUPPLEMENTAL INFORMATION ON LOWER LEG INJURY ASSESSMENT

E.1 INTRODUCTION

The loading mechanism acting on the lower leg during an AV blast mine strike is comparable to the ones generated by frontal car crashes or anti-personnel (AP) blast landmines. In these cases, an important axial force is transmitted to the lower leg, which may result in disabling injuries to the foot/ankle complex. A literature review on lower leg injury criteria was performed [Keown, 2003] in order to select the most appropriate one(s) for AV blast landmines testing. A few researchers performed dynamic axial impact tests on Post Mortem Human Surrogate (PMHS) lower legs in order to study the influence of different parameters on foot/ankle injury tolerance. The ones of interest used PMHS data to develop injury risk equations predicting the probability of foot/ankle fracture as a function of tibia axial force response. These models were the ones of Yoganandan et al., [Yoganandan, 1996], Griffin et al., [Griffin, 2001], Kuppa et al., [Kuppa, 2001a], Seipel et al., [Seipel, 2001] and Funk et al., [Funk, 2002b] are described, compared and analysed in the present annex. Other relevant lower leg injury criteria, which are the Tibia Index, the Lower Leg Threshold (LLth) and the ankle moment injury risk models, were found and are briefly described in this document. Finally, this annex also includes lower leg surrogates information and some discussions on the effect of boot, and leg positioning. It should be noted that this annex focus on the 10% risk of AIS 2+ injuries as has been agreed upon by STANAG 456. The reader is referred to the main report (Chapter 3) for anatomy of the lower leg as well as for more general information on the injury assessment method.

The present annex is divided in 8 sections:

- Section E.1 – Introduction
- Section E.2 – Foot/Ankle Injury Risk Models for Pure Axial Loading
- Section E.3 – Other Lower Leg Injury Criteria
- Section E.4 – Lower Leg Surrogates
- Section E.5 – The Effect of the Boot on Lower Leg Protection
- Section E.6 – The Effect of Leg Positioning on Tibia Response
- Section E.7 – Conclusion
- Section E.8 – References

E.2 FOOT/ANKLE INJURY RISK MODELS FOR PURE AXIAL LOADING

E.2.1 Yoganandan Model

The objective of Yoganandan et al. [Yoganandan, 1996] study was to develop a quantitative relationship between biomechanical parameters such as specimen age, tibia axial force and injury. Dynamic axial impact tests were conducted at the Medical College of Wisconsin (MCW). Twenty-six (26) intact adult lower legs were tested under axial loading using a mini-sled pendulum device. As shown in Figure E.1, the entire lower extremity distal to the knee (lower leg) was installed in a neutral position and ballasted by a 16 kg pendulum. A six-axis load cell was installed behind the potting material in order to record the proximal tibia axial force.

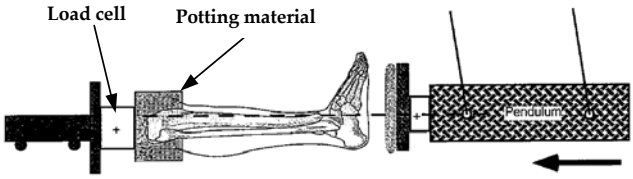

Figure E.1: Yoganandan Experimental Set-up (Modified from [Yoganandan, 1996]).

The results of MCW tests were combined to the ones obtained from similar studies at Wayne State University (WSU) and Calpan Corporation (Caplan), giving a sample size of 52 specimens having an age range of 27 to 85 years old. The whole set of experimental data (MCW, WSU and Caplan) was then used to derive two risk equations using the Weibull technique. The first one expresses the probability of foot/ankle fracture as a function of the tibia axial force and the second one expresses the probability of foot/ankle fracture as a function of tibia axial force as well as the subject age. Because military personnel are relatively young compared to the specimens used in this study (average age was 59 years old), the second injury risk model was the one of interest. Figure E.2 shows the probability distribution for foot/ankle injuries as a function of age and tibia axial force (peak value). Plus/minus one standard deviation limits are shown in dotted lines and solid circles represent the 'fracture' and 'non-fracture' data points. Fractures of the foot/ankle complex (distal tibia and calcaneus) were reported.

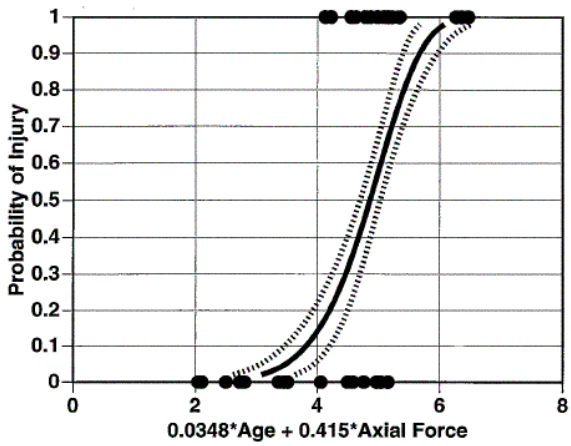

Figure E.2: Risk of Foot/Ankle Injury as a Function of Age and Tibia Axial Force [Yoganandan, 1996]. The injury criterion along the x-axis is expressed in kN.

Based on the relation given on Figure E.2, the probability of foot/ankle fracture can be expressed as follows:

$$P = 1 - \left[\exp\left\{ -\left(\frac{0.0348 * A + 0.415 * F}{5.13076} \right)^{7.42582} \right\} \right]$$

where:

- P is the probability of foot/ankle fracture;
- A is the age (in years); and
- F is the tibia axial force (in kN).

Using this Weibull probability equation presented above, the risk of foot/ankle fracture, as a function of tibia force, can be computed for any age. Figure E.3 presents foot/ankle injury risk curves for 25, 45 and 65 years old subjects. Based on these curves, the tolerance value for 10% risk of foot/ankle fracture for 25, 45 and 65 years old, are respectively 7.0, 5.4 and 3.8 kN representing 10% risk of foot/ankle fracture (AIS 2+). To protect most of the population in military vehicles (having an estimated age range of 20 to 45 years old), the tolerance value of 5.4 kN (for 45 years old) was chosen by the TG-25. Because most of the specimens used by Yoganandan were male (39 on 52) and the average specimen's weight was 75 kg, this tolerance value is applicable for mid-size males or large females [see Chapter 4, Figure 4.1 and Figure 4.2].

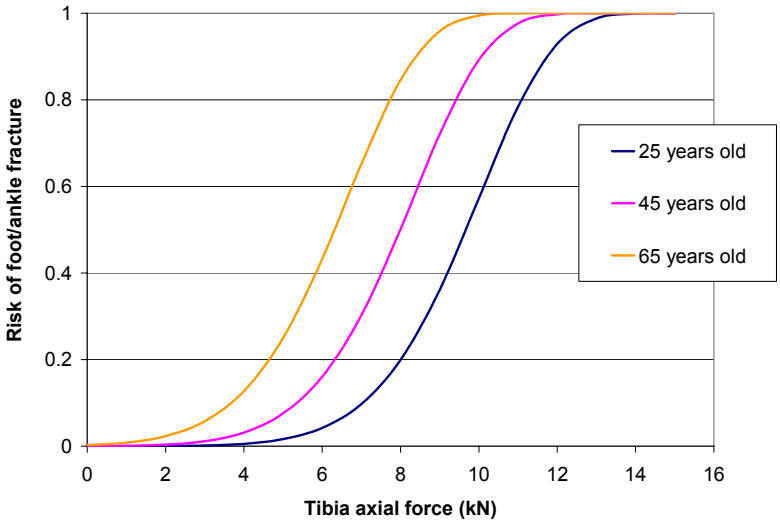

Figure E.3: Yoganandan Risk Curves for Different Subject Ages.

E.2.2 Griffin Model

The objective of Griffin et al., [Griffin, 2001] study was to evaluate the performance of different AP mine protective boot models for a direct contact blast load. Twenty (20) full human cadavers were subjected to the detonation of AP mines, which generated lower extremity injuries. The age range of the cadavers was 37 to 96 years old and the average weight was 73 ± 14.1 kg (close to a mid size male). Specimen gender was not mentioned. A load cell was installed at the proximal end of the tibia to record the axial force transmitted during the mine strike. Fractures in the foot/ankle complex (calcaneus, talus, cuboid, navicular and/or pilon) were reported. It was found that the significant predictors of pilon fracture were the tibia axial force and loading rate. Pilon fracture data points were used to derive the injury following risk equation, expressing the probability of fracture as a function of tibia peak axial force and loading rate.

$$P = \frac{1}{1 + \exp\left(-8.39 - 0.078R + 0.073W - 5.2X10^{-4}F\right)}$$

where:

- P is the probability of pilon fracture;
- F is the tibia axial force (in N);
- R is the tibia loading rate (in kN/ms); and
- W is the subject body weight (in lbs).

Based on this risk equation, probability curves were plotted (Figure E.4) for a 75 kg subject submitted to different loading rates.

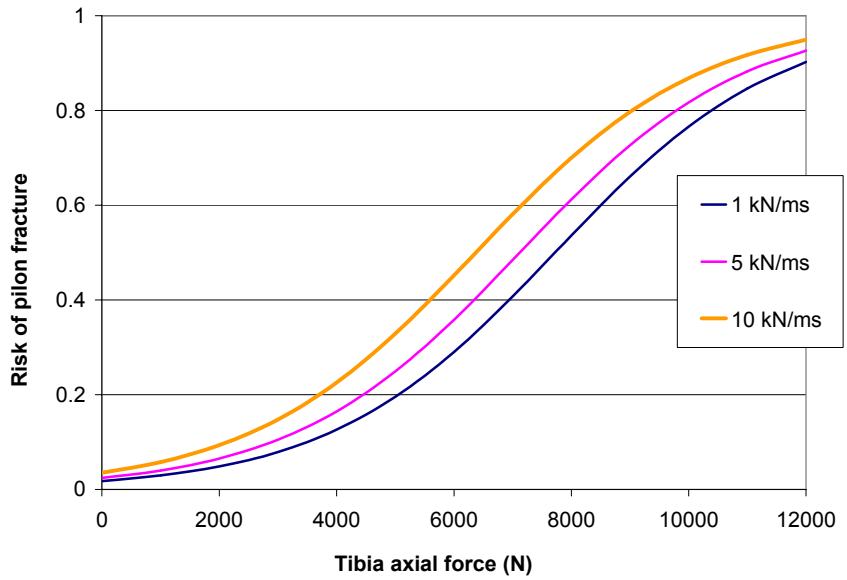

Figure E.4: Griffin Risk Curves for a 75 kg Subject and Different Loading Rates.

On 38 tested legs, 37 sustained foot/ankle fractures, but only 25 sustained pilon fractures. All the injured legs had calcaneal fracture. The injury data showed that calcaneal fracture is the primary injury mode under axial impact and may occur without pilon fracture. For this reason, Griffin model is limited for the study of lower leg injuries resulting from AV blast landmine strikes in which calcaneus fracture is a predominant injury. On 38 tests, only 25 were performed with a tibia load cell and used to derive the injury risk equation presented above. The second limitation of the model is that it was developed with tibia loading rate data ranging from 5.2 to 116.8 kN/ms. The validity of the model for loading rates below 5 kN/ms, being more representative of AV blast mine loadings, is then questionable.

E.2.3 Kuppa Model

Kuppa et al., [Kuppa, 2001a], used other authors PMHS experimental data to derive different lower extremity injury risk functions. The data set of Yoganandan et al., [Yoganandan, 1996], was used by Kuppa to develop the following risk equation:

$$P = \frac{1}{1 + \exp(4.572 - 0.670F)}$$

- P is the probability of foot/ankle fracture; and
- F is the tibia axial force (in N).

In contrast to Yoganandan, the risk equation developed by Kuppa does not include the subject age. For example, the tolerance value for 10% risk of fracture is 3.6 kN (Kuppa used Yoganandan data, so same age range) when using Kuppa and 5.4 kN when using Yoganandan for a 45 years old subject. This indicates the need of including the age factor in the definition of the tolerance level.

E.2.4 Seipel Model

Seipel et al., [Seipel, 2001], simulated axial lower leg injuries secondary to vehicular frontal impacts with the use of a mini-sled pendulum (same set-up as Yoganandan et al., [Yoganandan, 1996], shown in Figure E.1). The study focussed on calcaneus fracture, being the most frequent lower leg injury resulting from an axial impact. The pendulum impacted the surface of the foot of 22 unembalmed cadaver lower extremity specimens. Of the 22 specimens, 21 were males. The specimen age range was 27 to 74 years old. The 16 kg pendulum velocity ranged from 2.2 to 7.6 m/s to produce non-injurious and injurious impacts. A probability distribution was generated with the 'fracture' and 'nonfracture' data points. Only limited information is available on the injury details. Based on the injury risk curve derived from a logistic regression analysis, the threshold value (based on peak tibia axial force) for 10% and 50% risk of calcaneus fracture are respectively 2.4 and 5.5 kN. The equation developed in this study was not mentioned by the authors, but the probability graph was shown. The first limitation of this study is that the sample size was relatively small (22), which gives a low confidence in the injury risk equation accuracy. The second limitation is that the model does not include the specimen age effect, which, as shown by Yoganandan model, has a significant influence on the foot/ankle injury tolerance. The tolerance values given by Seipel injury model are then too conservative to be applied to military vehicle occupants.

E.2.5 Funk Model

The objectives of Funk et al., [Funk, 2002b] study were to investigate the effect of Achilles muscle tension on fracture mode and to develop an empirical model of the axial loading tolerance of the foot/ankle complex. Funk developed, using a multivariate Weibull regression model, a risk equation to predict the probability of foot/ankle fracture as a function of the tibia axial force, specimen age, gender and weight, and Achilles tension. Achilles tension was applied on the lower leg specimens to simulate the leg muscle tension prior to a frontal car impact. In the case of AV blast mine detonation, muscle pre-tension is not considered because the vehicle occupants do not 'expect' the impact. Also the process is so fast that muscle contraction will probably not respond in time to have any influence on the injury response.

As shown on Figure E.5, thirty (30) cadaveric lower extremity specimens were subjected to dynamic axial impacts by a footplate attached to a transfer piston. The foot was in contact with the footplate prior to the impact and the footplate velocity reached approximately 5 m/s during the impact. The leg specimens were sectioned at mid-femur to preserve knee joint and leg musculature. Fifteen tests (15) over thirty (30) were done without Achilles tension. All the tested legs sustained foot/ankle fracture. Calcaneus, pilon, talus, malleolus, fibula and tibial plateau fractures were reported. On 30 tested legs, 25 sustained calcaneus fractures, showing again that calcaneus is the most vulnerable foot/ankle bone when subjected to axial impact. The tibia load cell, in contrast with the previous studies, was inserted into the tibia.

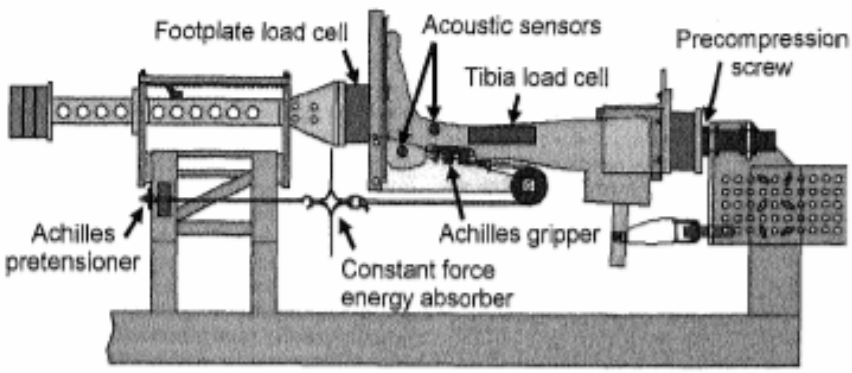

Figure E.5: Funk Experimental Set-up [Funk, 2002].

The risk equation developed by Funk is the following:

$$P = 1 - \left[\exp\left\{ -\exp\begin{bmatrix} 4.99\ln(F) - 43.7 - 0.964G + 0.0793A \\ -0.0552W - 0.473AT \end{bmatrix} \right\} \right]$$

where:

- P is the probability of foot/ankle fracture;
- F is the tibia axial force (in N);
- G is the subject gender (=1 if male; =0 if female);
- A is the subject age (in years);
- W is the subject body weight (in kg); and
- AT is the Achilles tension (in N).

This model allows the study of the effect of different specimen parameters. For example, the Figure E.6 shows the effect of the age on the tolerance to fracture for mid-size males and females, when there is no Achilles tension. These curves, as the ones of Yoganandan, show the strong effect of the specimen age on the tolerance to fracture. They also show that males have a stronger tolerance to fracture than female. According to Funk model, 45 years old mid-size female lower leg could be less resistant than 65 years old mid-size male lower leg.

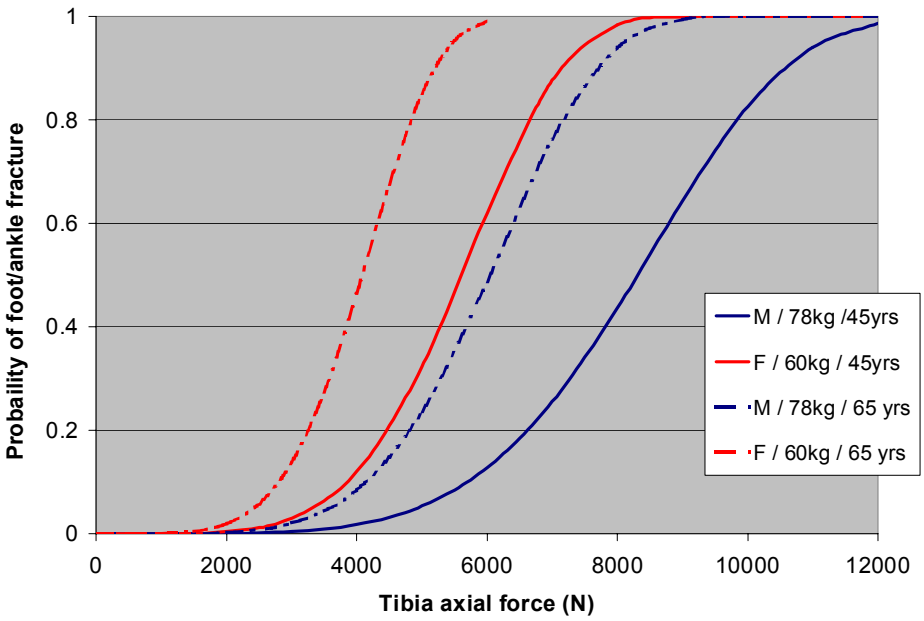

Figure E.6: Funk Risk Curves for Different Subject Age and Weight.

The injury risk model developed by Funk is complete because it gives the possibility to predict the risk of fracture for a large range of human population. On the other hand, the model can represent some complications when defining NATO standards because the model requires the specification of gender, weight and age. The average weight and age might be different for the different NATO countries, rendering the definition of these parameters difficult. The second limitation of Funk model is that its validity for age below 40 years old is questionable because the specimen age range was 41 to 74 years old.

E.2.6 Hirsch

In 1964 Hirsch [Hirsch, 1964] presented a tolerance curve (Figure E.8) for **a standing man** with stiff legs exposed to shock motion of short duration. The shock was represented by an acceleration square pulse with 1 – 100 ms duration and 20 – 800g amplitude. The tolerance curve is a typical "iso-injury" curve meaning that for every point on this curve the same injury/damage will occur (here tolerance). For points over and to the right of the curve more injury/damage will occur and consequently less injury/damage when under and to the left. For other shapes of the acceleration pulse and other targets, different iso-injury curves must be used.

Hirsch has a vertical asymptote for durations of > 24 ms implying that for pulse amplitude of 20g and increasing the pulse duration will have the same tolerance level. The value 20g is based on the crushing load for the two lower legs of 13340N for a 72.5 kg heavy man. A horizontal asymptote of 3 m/s velocity change is for pulse durations < 10 ms. The tolerance level can be something between severe discomfort to fracture on foot or lower leg.

Hirsch gives in his Figure E.7 an example of shock-motion terminology used in the evaluation of a velocity – time history. Assuming that the acceleration – time history is measured at the place on the floor where you can expect to have a man standing stiff-legged with both feet on the floor, the acceleration – time history can be integrated to velocity – time as in his Figure E.8.

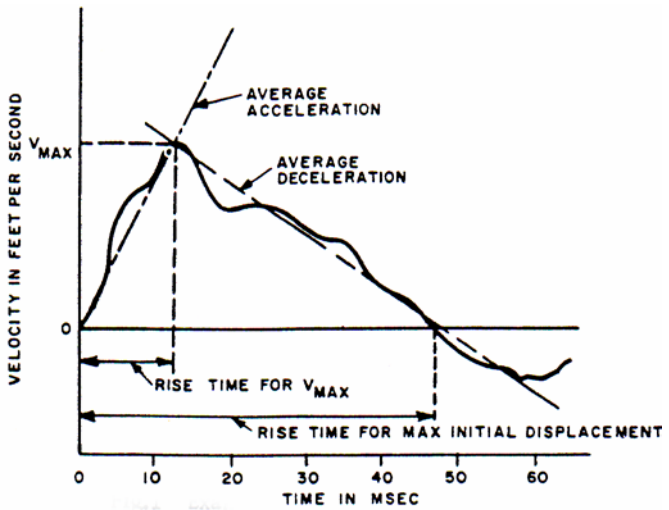

Figure E.7: Example of Shock-Motion Terminology [Hirsch, 1964].

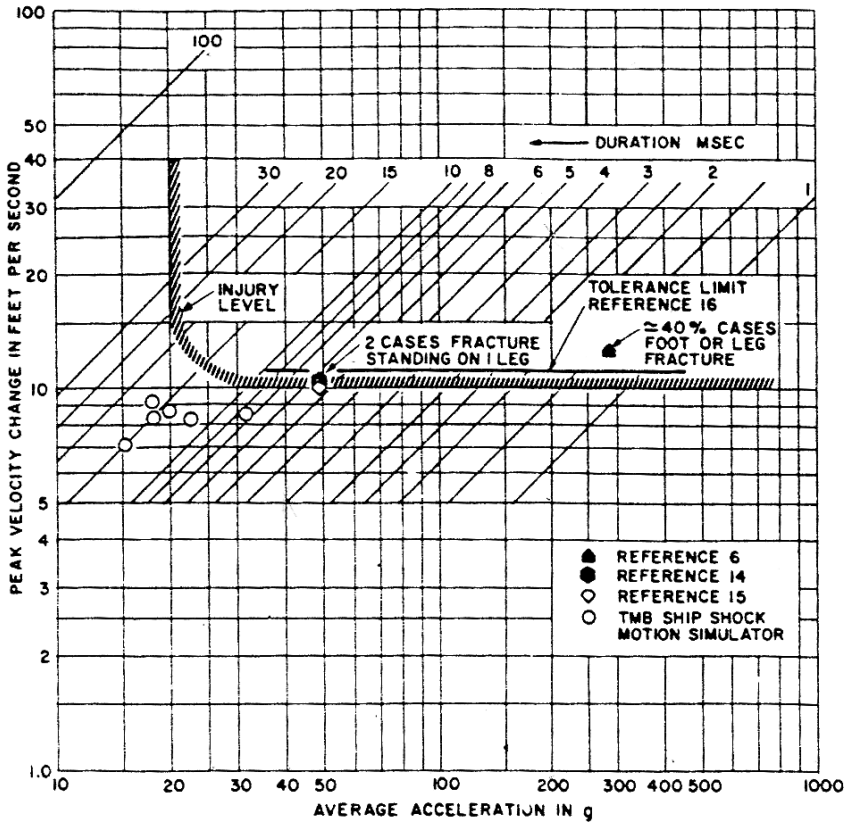

Figure E.8: Tolerance of Stiff-Legged Standing Men to Shock Motion of Short Duration [Hirsch, 1964].

The velocity increases almost linear up to a peak velocity change = Vmax, reached after a time Δt (= rise time for Vmax). Δt is called duration in his Figure E.7. Vmax/Δt = average acceleration and is the constant acceleration level in the square pulse.

Two out of the three quantities

- Max velocity change (Vmax)
- Duration/rise time for Vmax
- Average acceleration

can be used to assess if the shock pulse is on the safe side or not of the tolerance curve.

Some advantages with the Hirsch model are

- Use of PMHS, human volunteers and war experience for evaluation of the tolerance curve;
- Measurements can be made on where the feet are positioned (floor, foot-rest, etc.) and the model is still relevant; and
- Inexpensive method.

Some disadvantages are

- It is still a technical challenge to measure the acceleration on a shock loaded steel plate;
- The model is valid for only one shape of acceleration pulse; and
- The model is not applicable to a sitting man.

Most wanted is a simple mathematical model (like the DRI model) of the lower leg for calculating the response to all kinds of acceleration – time histories.

E.2.7 The Lower Leg Threshold (LLth)

The Lower Leg Threshold (LLth) is a foot/ankle injury risk model, which was developed by WTD-91 (DEU). The idea of the model was to correlate the probability of foot/ankle fracture with shock pulse duration and amplitude. Data from Hirsch [Hirsch, 1964], (for the standing man), were used to develop the injury tolerance curve shown in Figure E.9. The tolerance curves implies that any acceleration-duration data points falling below the curve, represents a risk of less than 5% or 10% of sustaining foot/ankle fracture (AIS 2+). Using the acceleration-duration data points of Hirsch, and Yoganandan [Yoganandan, 1997,1998], the force-duration injury tolerance curve (10% risk of foot/ankle fracture) was developed (Figure E.10) without considering the age of the population. In Figure E.10, the actual injury threshold (5.4 kN, representing 10% risk of fracture) is drawn to compare both tolerance curves.

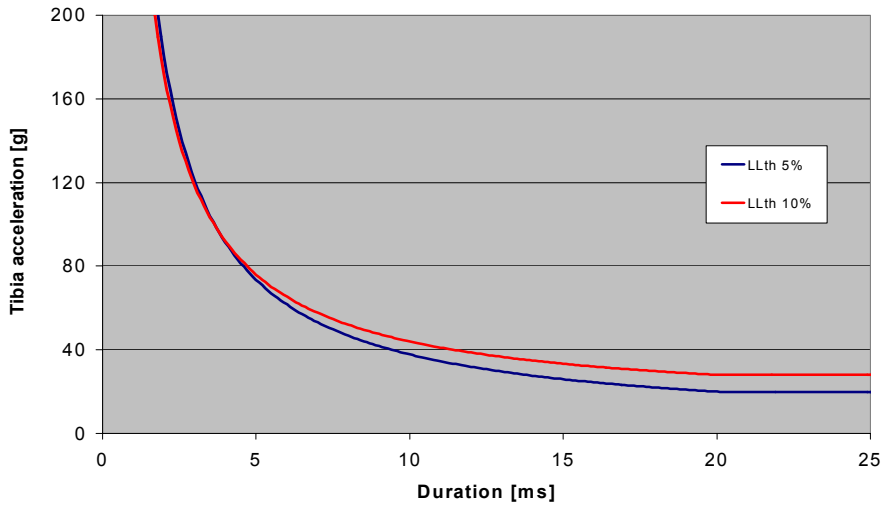

Figure E.9: The LLth Acceleration-Based Injury Tolerance Curve.

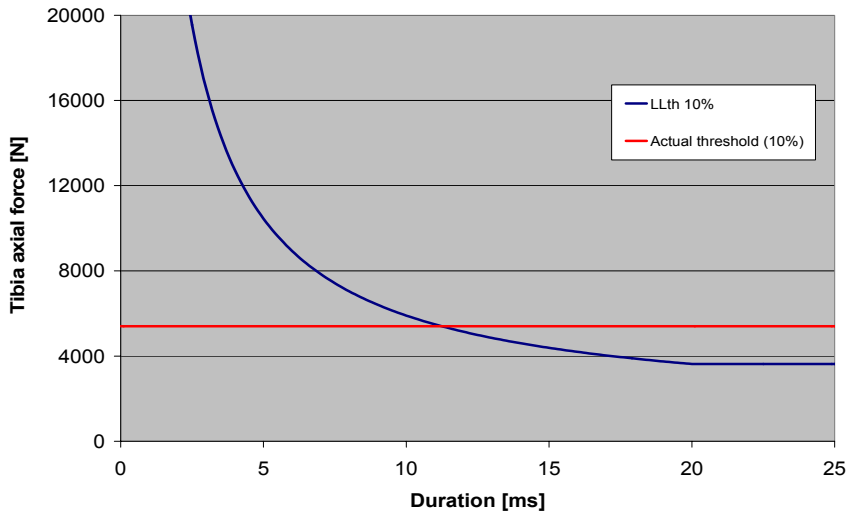

Figure E.10: The LLth Force-Based Injury Tolerance Curve.

The typical tibia loading duration expected during a mine strike is approximately 10 msec. As shown on Figure E.9, it can be said that the Lower Leg Threshold is in accordance with the proposed tolerance value for loading durations of approximately 10 to 12.5 ms. For shorter durations, the proposed tolerance value of 5.4 kN would be very conservative compared to the LLth. The LLth gives the possibility to assess risk of foot/ankle fracture as a function of an important parameter, which is the loading duration. This parameter is very important because AV mine strikes are usually shorter events than car crashes, which are the loading simulated to develop most of the injury models presented in the open literature. Additionally to the loading duration, the loading rate, as shown by Griffin model seems to have a significant influence on the tolerance to fracture. The ultimate foot/ankle injury models would take the loading duration, rate and amplitude into consideration, as well as important epidemiologic parameters such as the age and the gender. However, the LLth is a good starting point for the development of injury risk model specific to special loadings such as the ones generated by AV blast landmines.

E.2.8 Summary, Analysis and Discussion

The following tables summarize the important information belonging to each foot/ankle injury risk model discussed in this part. Table E.1 presents the specimen characteristics, Table E.2 shows the parameters considered in each study to develop the injury risk equation (Achilles tension is not mentioned) and Table E.3 summarizes the relevant advantages and shortcomings of the models. This information was used to achieve a comparative analysis to select the best model. Table E.4 presents the tolerance value (based on tibia axial force) for 10% and 50% risk of foot/ankle fracture (AIS 2+), for each model. The parameters of the models were specified such that the models can be compared together as best as possible. The age was set to 45 years old for Yoganandan and Funk models. The weight was set to 75 kg for Funk and Griffin based on the average specimen weight of Yoganandan study. The gender was set to 'male' for Funk because the majority of the specimens used in the other studies were males. A loading rate of 1 kN/ms was used in Griffin model, which is in the range of the tibia loading rate measured in Seipel and Funk study.

Table E.1: Specimen Characteristics

Model	Number of Specimens	Number of Males	Average Weight (kg)	Average Age (range) (yrs)	Force Measurement Location
Yoganandan (and Kuppa)	52	39	75 ± 15	56 ± 15 (27-85)	Proximal tibia
Griffin	25	?	73 ± 14	75 ± 17 (37-96)	Proximal tibia
Seipel	22	21	78 ± 11	49 ± 16 (27-74)	Proximal tibia
Funk	30	15	68 ± 14	63 ± 9 (41-74)	Middle tibia

Table E.2: Parameters Included in the Injury Risk Equations

Model	Tibia Axial Force	Tibia Loading Rate	Age	Gender	Weight
Yoganandan	•		•		
Griffin	•	•			•
Kuppa	•				
Seipel	•				
Funk	•		•	•	•

Table E.3: Relevant Advantages and Shortcomings of the Models

Models	Advantages	Shortcomings
Yoganandan	Includes subject age.	
Griffin	Includes subject weight and tibia loading rate.	Validity for loading rate < 5 kN/ms is unknown. Only pilon fracture is considered.
Funk	Includes subject age, gender and weight: complete model.	Validity for age < 40 years old is unknown.

Table E.4: Tolerance Levels for the Different Models

Model	Injured Region	Tolerance Value (kN)		Specifications or Remarks
		10%	50%	
Yoganandan	Foot/ankle	5.4	8.0	For a 45 years old subject.
Griffin	Tibia pilon	2.7	6.9	For a 75 kg subject and a loading rate of 1 kN/ms.
Kuppa	Foot/ankle	3.6	6.8	
Seipel	Calcaneus	2.4	5.5	Taken from the original graph.
Funk	Foot/ankle	5.5	8.0	For a 75 kg and 45 years old male, no Achilles tension.

The tolerance values presented in Table E.4 quantify the effect of the subject age on the injury tolerance of the foot/ankle complex. Seipel, Kuppa and Griffin models give lower tolerance values than Yoganandan and Funk models for similar conditions. Because military vehicle occupants are relatively young, Funk and Yoganandan models are more suitable for the vehicle mine protection assessment. As shown in Table E.4, both models give almost the same results for a 45 years old mid-size male, but the consistency between both models is not so good for age different from 45 years old (see Figure E.11). The models are

relatively consistent for 65 years old, but are less consistent for 25 years old, which was expected because this age is outside the validity level of Funks model.

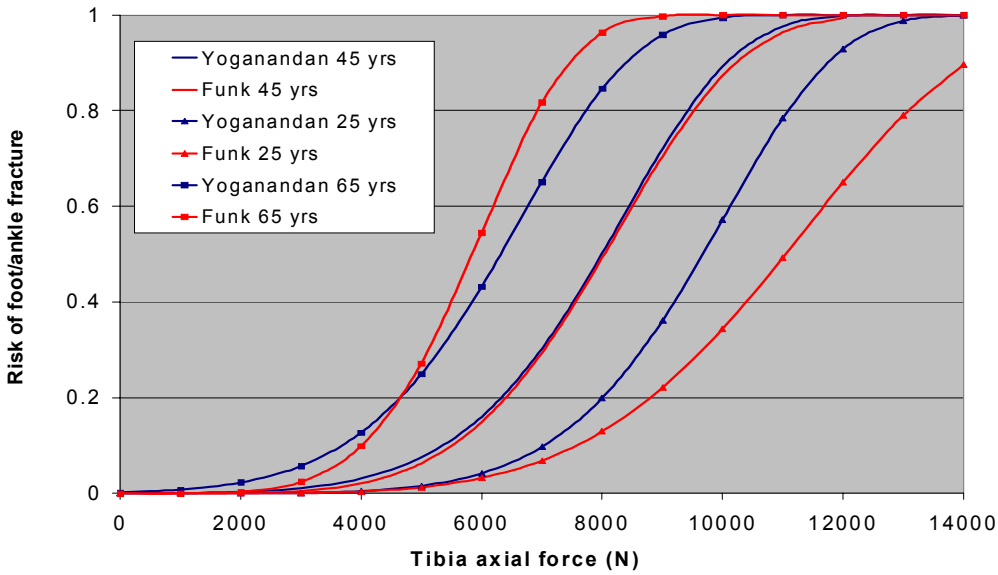

Figure E.11: Comparison between Yoganandan and Funk Models.

Based on these findings, the HFM-090/TG-25 has recommended the use of Yoganandan injury risk models to be included in NATO standards for vehicle mine testing assessment. The TG-25 established the lower leg threshold value to 5.4 kN, representing 10% risk of foot/ankle fracture for a 45 years old subject. In order to protect most of the military occupants (having an estimated age range of 20 to 45 years old), the age of 45 was chosen. The Yoganandan model, as well as the other foot/ankle injury models presented above, has four important limitations for the application of AV blast mine testing:

- The model was developed for pure axial impact on the base of the foot. In some cases, the foot may be loaded differently depending on the protection system and seating configuration.
- In some PMHS test conditions the foot is impacted by a mass, whereas in case of an AV mine strike the foot is always in contact with the floor, and this floor will accelerate. It needs to be studied in detail whether this difference in set-up has influence on the injury.
- The loading regime for which the model was developed is not available anymore, but is believed to be different than the one generated by an AV mine strike, being usually faster than the ones generated by frontal car crashes. However, based on other studies the loading conditions for a car crash is not deviating that much from lower legs loads measured in a well protected vehicle.
- The established tolerance level is to be applied to the Hybrid III instrumented tibia, which has different mechanical properties than the one of the human tibia, as discussed in Section E.4.

E.3 OTHER LOWER LEG INJURY MODELS

The previous described injury models focus on a pure axial impact, whereas in reality the lower leg will be subjected to a combination of loadings (compression, bending, shear, etc.), depending on the orientation of the leg on the bottom plate. So far, HFM-090/TG-25 did not study the injury criteria for these different loading conditions. However, a short description of two other injury lower leg models is given below.

E.3.1 The Tibia Index (TI)

The Tibia Index is used in some qualification trials of car crash safety systems [Kuppa, 2001a]. The TI has been developed to assess tibia and fibula shafts fracture, but does not include foot/ankle injury assessment. The Tibia Index was developed from tests on cadaveric leg specimens (without foot/ankle) that were subjected to a direct impact on the tibia shaft and axially compressed at the same time. The Tibia Index (TI) is expressed as follows:

$$TI = \frac{F_z}{F_c} + \frac{M}{M_c}$$

where:

- F_z is the axial compression force (N);
- M is the resultant bending moment $(M_x^2 + M_y^2)^{1/2}$ (Nm);
- F_c is the critical axial compression force (constant value); and
- M_c is the critical bending moment (constant value).

The Revised Tibia Index (RTI) involves the use of new critical values, established by Kuppa [Kuppa, 2001a] with the use of experimental data from other authors. The axial force and bending moment critical values recommended by Kuppa are respectively 12 kN and 240 Nm. Based on the risk equation developed by Kuppa, the recommended RTI threshold value is 0.75, representing 10% risk of tibia/fibula fracture (AIS 2+). When using the standard Hybrid III instrumented lower leg (described in Section E.4), the bending moment My has to be corrected as specified in [Welbourne, 1998].

The following injury risk equation (developed by Kuppa) can be used:

$$P = 1 - \left[\exp\left\{ -\exp\left[\frac{\ln(RTI) - 0.2728}{0.2468} \right] \right\} \right]$$

where:

- P is the probability of tibia/fibula fracture; and
- RTI is the Revised Tibia Index.

Because direct impact on the tibia is not one of the expected primary injury mechanisms occurring during mine strikes, the Tibia Index was not part of the mandatory injury criteria recommended by the TG-25.

E.3.2 Ankle Rotation Injury Risk Models

Especially during frontal car crashes, the ankle joint may rotate in dorsiflexion and/or inversion or eversion modes (Figure E.12), which may result in soft tissue injuries and/or ankle bone fractures. Even if this type of loading mechanism is not the first one expected during AV mine, ankle rotation injury assessment may be required in cases where the foot is placed on a pedal or a foot rest, resulting in load transfer via the fore foot. Kuppa et al., [Kuppa, 2001a] developed, with the use of other author experimental data, ankle joint injury risk equations based on dorsiflexion and eversion/inversion moments. Based on the risk equations developed by Kuppa, the recommended ankle moment threshold values are 40 Nm for dorsiflexion and 27 Nm for inversion/eversion, representing 10% risk of AIS 2+ ankle injuries. The ankle moment cannot be directly measured in the dummy lower legs. An equation to calculate the ankle moment, when using the Thor-Lx leg model (described in Section E.4), is given by [Kuppa, 2001b]. Similar relation can be used for the standard Hybrid III leg.

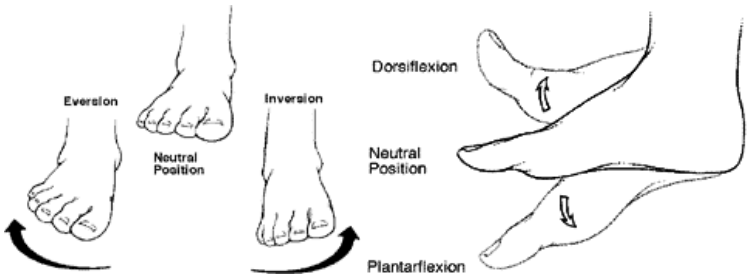

Figure E.12: Ankle Joint Dorsiflexion and Inversion/Eversion Rotation Modes.

E.4 LOWER LEG SURROGATES

The injury assessment method proposed by the HFM-090/TG-25 involves the use of the standard Hybrid III instrumented lower leg (see Chapter 4). The standard Hybrid III lower leg model has a 45º rotation foot whereas the original version had a 30º foot. Even if the current Hybrid III lower leg biofidelity has been improved by the 45º foot, its tibia axial force response is not excellent in biofidelity [Owen, 2001]. The standard Hybrid III lower leg is equipped with an instrumented tibia called the Denton leg [Denton, 1984]. The Denton leg (shown in Figure E.13) is a simple steel shaft with lower and/or upper tibia load cells.

Figure E.13: Thor-Lx (left) and Standard HIII Denton Lower Leg (right) [Kuppa, 2001b].

A more biofidelic model of the human lower leg is the Thor-Lx (see Figure E.13), which was designed with the use of recent biomechanical data [Kuppa, 2001b]. It can be used together with the Hybrid III ATD, or with the original THOR frontal ATD (Test device for Human Occupant Restraint).

The Thor-Lx is the more biofidelic mechanical lower leg actually available [Kuppa, 2001b; Owen, 2001]. It is unique in that the design includes an Achilles tendon coupled with the straight tibia shaft to simulate passive resistance of musculature. This was shown to have a considerable influence in axial force response. The tibia includes a rubber element for to improve axial compression biofidelity and the shaft is straight. This is unlike the standard Hybrid III shaft, which is offset at the knee clevis and is known to introduce bending moments under pure axial loading conditions [Kuppa, 2001b; Welbourne, 1998]. The Thor-Lx is available as a retrofit for the Hybrid III 50th percentile dummy. More information on Denton leg and Thor-Lx, and their instrumentation is given in [Kuppa, 2001b].

E.4.1 Frangible Synthetic Lower Legs Surrogates: CLL and FSL

The Canadian Lower Leg (CLL) was developed by a team including DRDC to evaluate lower leg injuries sustained by anti-personnel (AP) mines and assess protective boot systems [Williams, 2002; Biokinetics, 2003; RTO-TR-HFM-089, 2004]. The CLL, shown in Figure E.14, is comprised of polymeric bones (that represent tibia/fibula, talus, and calcaneus), a nylon tendon, silicone rubber cartilage pads, a silicone rubber heel pad, ballistic gelatin (representing the flesh), and a latex skin. Since the objective of the CLL was to model the injury path up through the heel into the tibia, the forefoot is not considered and the leg has two calcaneus. When subjected to an impact, the CLL sustains damage comparable to real injuries sustained by a human leg. Figure E.15 shows typical CLL damage after AP mine testing (direct blast).

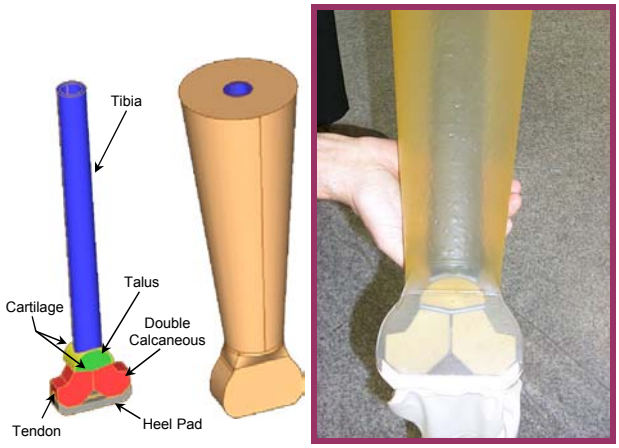

Figure E.14: The Canadian Lower Leg (Picture courtesy of DRDC).

Figure E.15: Typical CLL Injuries (Picture courtesy of DRDC).

A similar synthetic leg, called the Frangible Synthetic Leg (FSL), was developed at the Defence Science and Technology Organization (DSTO) in Australia to evaluate AP mine protection system performance [RTO-TR-HFM-089, 2004]. The FSL is a geometric reproduction of the human leg using materials that react to blast in a manner similar to human tissue. The bones are made from mineralized plastic and the flesh (soft tissue and muscles) from ballistic gelatin. As opposed to the CLL, which is a below-knee leg surrogate, the FSL is a representation of the whole lower extremity (upper and lower legs). The lower part of the FSL, the FSLL (Frangible Synthetic Lower Leg), is shown in Figure E.16.

Figure E.16: The Frangible Synthetic Lower Leg (FSLL), Without (left) and With (right) Gelatine.

The CLL and the FSL are biofidelic frangible human surrogates for axial loading conditions generated by AP mines [RTO-TR-HFM-089, 2004]. Australia performs AV mine strike tests using the FSL [Wang, 2001] and the CLL performance is currently evaluated for axial impacts generated by the vehicle floor intrusion caused by the detonation of AV blast landmines [Manseau, 2005a, 2005b, 2005c]. Both CLL and FSL are considered good research tools for AV mine protection studies when PMHS testing is not available, however so far validation of these models for the AV mine loading conditions are not available.

E.4.2 Post Mortem Human Subjects

The HFM-090/TG-25 wrote a white paper to perform Post Mortem Human Subjects (PMHS) tests to study the lower leg response during AV mine strikes and to generate validation data for the mechanical, synthetic and numerical models [Bir, 2006; Geurts, 2006a, 2006b]. Recently tests are performed and preliminary results were published [Barbir, 2005, Bir, 2006]. More tests will be performed in the future.

E.4.3 Comparison between Hybrid III Lower Leg and Thor-Lx

WTD 91 (DEU), IABG (DEU) and TNO (NLD) performed together experimental tests to compare the axial force response measured by the Thor-Lx and the standard Hybrid III lower leg [Nies, 2005]. These tests were done using the TROSS™ (Test Rig for Occupant Safety Systems, developed by IABG), which was designed to assess seat and restrain systems in the field of vehicle mine protection. It also has the capacity to simulate footplate displacement to replicate lower leg loadings seen during full-scale mine trials. The TROSS™ was developed to use scaled detonations and provide the same input to an occupant as during a full-scale test. The loading produced by small charges detonated under the TROSS™ is comparable to a real mine (2 to 10 kg TNT) detonation under a military (light or heavy) vehicle. The TROSS™ offers the possibility to provide well-defined and reproducible loads by the detonation of small explosive charges under an elastic deformable membrane bottom plate. Figure E.17 shows the exterior and interior views of the TROSS™. The test rig is closed by a box (in grey), which is de-coupled from the membrane plate and thus, isolated from the shock of the detonation.

Figure E.17: Exterior (left) and Interior (right) View of TROSS™ Set-up (Pictures courtesy of IABG).

Figure E.18 shows the tibia axial force measured by the standard Hybrid III leg (Denton leg) and the THOR-Lx, both subjected at the same time to loadings generated by small charges detonated under the TROSS. The ratio between the tibia axial force measured on the Hybrid III and the Thor ranged from 1.4 to 2.1. These results correlate well with the ones of Owen [Owen, 2001], for which the ratio between Hybrid III and THOR-Lx was approximately 1.43 (Figure E.18).

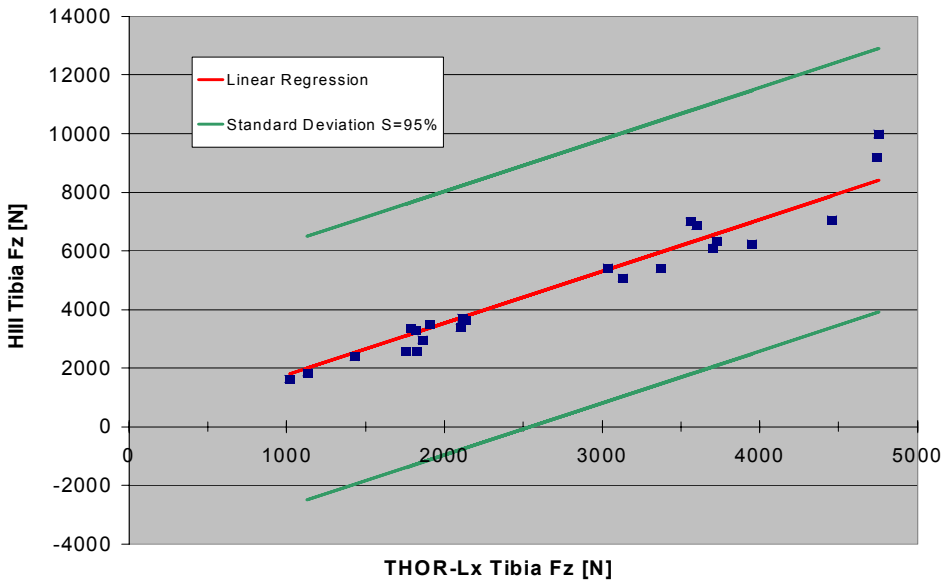

Figure E.18: Comparison between Hybrid III and Thor-Lx Tibia Axial Forces (TROSS Tests) [Nies, 2005].

E.5 THE EFFECT OF BOOTS ON LOWER LEG PROTECTION

WTD 91 and IABG (DEU) and TNO (NLD) used the TROSS set-up to perform preliminary tests on the CLL, which was attached to a whole Hybrid III dummy (Figure E.19) [Horst, 2003]. Tests with and without military boot showed that the boot is offering a considerable protection to the foot when subjected to an axial impact [Manseau, 2005a; Nies, 2005, Geurts, 2006a].

Figure E.19: TROSS Tests on the CLL With (left) and Without (right) Boot (Pictures courtesy of TNO).

Laboratory axial tests were also performed by CA, on CLL and Hybrid III, in order to evaluate the effect of the military boot on the tibia loading response and the injury severity [Manseau, 2005b]. In both TROSS and laboratory testing, wearing the military boot avoided calcaneal fracture, a disabling lower extremity injury. Figure E.20 shows CLL results after being submitted to laboratory axial impact with and without boot. The CLL with a boot (shown on the left side) only sustain soft injuries (heel pad and talus cartilage damage) and the CLL without boot (shown on the right side) sustained an important calcaneus fracture. Finally, Figure E.21 show Hybrid III tibia loading resulting from tests with and without boot, which quantify the effect of the boot on the injury severity. In that case, the presence of the boot reduced the peak tibia axial force value of approximately 30%.

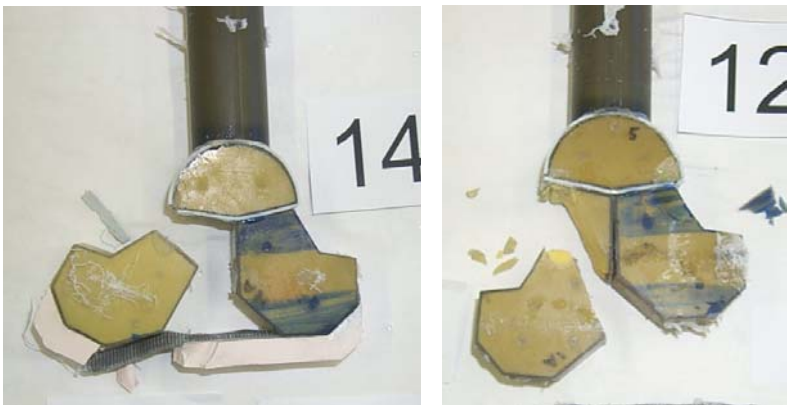

Figure E.20: Results of Laboratory Axial Tests on the CLL With (left) and Without (right) Boot [Manseau, 2005b].

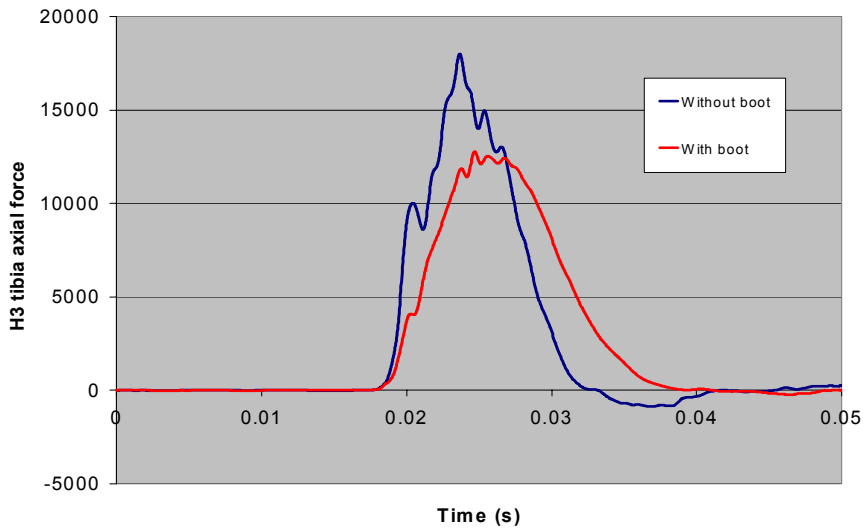

Figure E.21: Example of Hybrid III Tibia Axial Force for Axial Impact Tests With and Without Boot [Manseau, 2005b].

E.6 EFFECT OF LEG POSITIONING

TNO studied the influence of the initial lower leg position on the forces, moment and accelerations using the MADYMO computer model of the Hybrid III 50th percentile male ATD [Horst, 2005]. As shown in Figures E.22 and E.23), four initial positions (A, B, C and D) and two loading conditions (db1 and db2) were simulated.

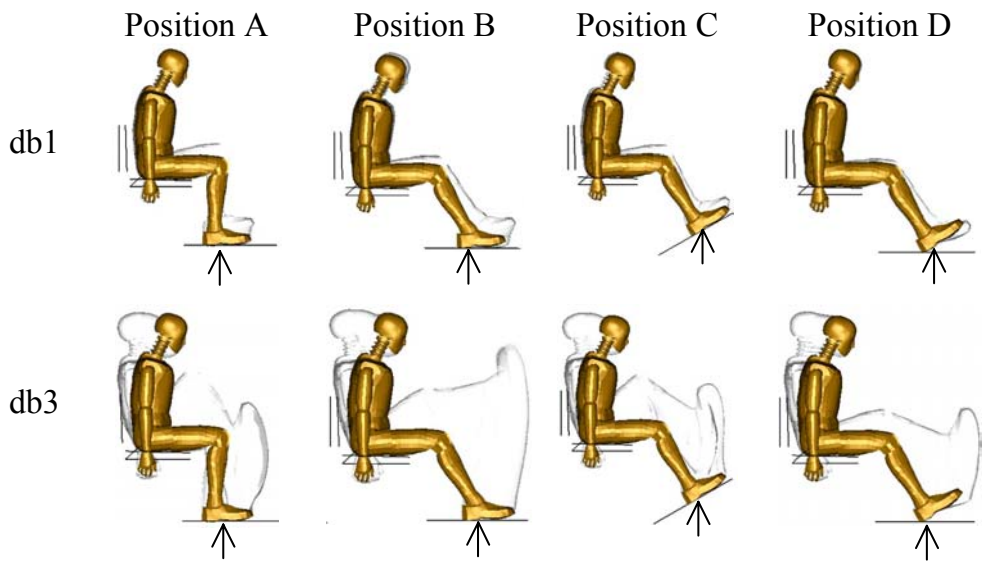

Figure E.22: Tracing View Using Altair Hyperworks: Crash Dummy Motion during Pure Vertical Footplate Displacement for Four Initial Positions at Two Different Loading Conditions [Horst, 2005].

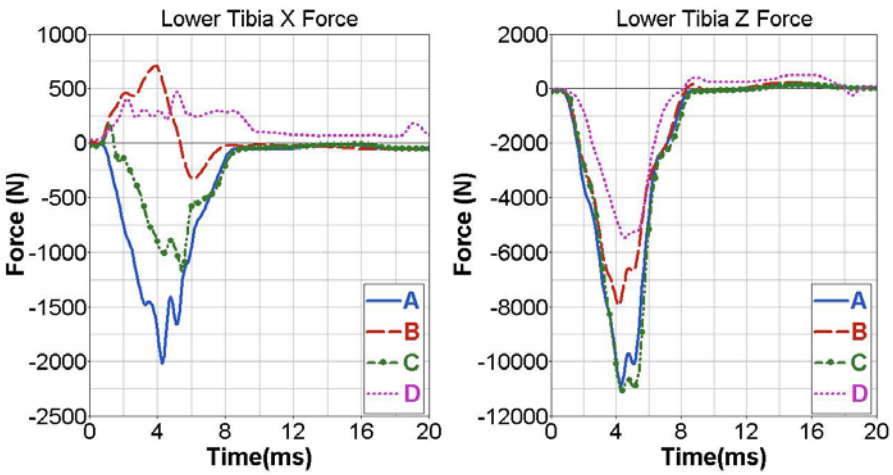

Figure E.23: Lower Tibia Axial Force (Fz) for MADYMO Simulation of Test db3 (Vertical Footplate Displacement) for Different Foot Positions [Horst, 2005].

The same trend was seen for the axial tibia forces (Fz) and accelerations (az) for the lower and higher loading conditions [Horst, 2005]. The highest values are seen for position A en C, while D shows the lowest values in all cases. The use of the tibia force as injury indicator is based on pure axial loadings of the lower leg. In case of position B and D the legs are orientated under an angle and there is no pure vertical loading. Although the calculated axial tibia values are low, there may be a risk of foot/ankle injuries for these different orientations.

Recently the numerical research for the lower leg loading conditions has been updated [Geurts, 2006 a,b].

E.7 CONCLUSION

Over the different injury risk models, [Yoganandan, 1996] and [Funk, 2002] models were the most suitable, since they include age effect. The Yoganandan model was chosen by the HFM-090/TG-25 since it was developed with a larger number of specimens with wider age range.

Actually, the threshold value of 5.4 kN might be too conservative because it is applied to the Hybrid III tibia, which is stiffer than the human tibia. For this reason, work is ongoing to evaluate the biofidelity of different existing mechanical legs [Bir, 2006] under pure axial impacts. Other loading configurations will also need to be studied in the future [Horst, 2005].

Finally, it was shown that the boot offers a considerable protection level and thus, should always be included in the qualification test protocol [Manseau, 2005b].

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