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Optimized lower leg injury probability curves from post-mortem human subject tests under axial impacts

Narayan Yoganandan,

Department of Neurosurgery, 9200 West Wisconsin Avenue, Medical College of Wisconsin, Milwaukee, WI

Mike W.J. Arun,

Department of Neurosurgery, 9200 West Wisconsin Avenue, Medical College of Wisconsin, Milwaukee, WI

Frank A. Pintar, and

Department of Neurosurgery, 9200 West Wisconsin Avenue, Medical College of Wisconsin, Milwaukee, WI

Aniko Szabo

Institute for Health and Society, Division of Biostatistics, 8701 Watertown Plank Road, Medical College of Wisconsin, Milwaukee, WI

Narayan Yoganandan: yoga@mcw.edu; Mike W.J. Arun: marun@mcw.edu; Frank A. Pintar: fpintar@mcw.edu; Aniko Szabo: aszabo@mcw.edu

Abstract

Objective—Derive optimum injury probability curves to describe human tolerance of the lower leg using parametric survival analysis.

Methods—The study re-examined lower leg PMHS data from a large group of specimens. Briefly, axial loading experiments were conducted by impacting the plantar surface of the foot. Both injury and non-injury tests were included in the testing process. They were identified by pre- and posttest radiographic images and detailed dissection following the impact test. Fractures included injuries to the calcaneus and distal tibia-fibula complex (including pylon), representing severities at the Abbreviated Injury Score (AIS) level 2+. For the statistical analysis, peak force was chosen as the main explanatory variable and the age was chosen as the co-variable. Censoring statuses depended on experimental outcomes. Parameters from the parametric survival analysis were estimated using the maximum likelihood approach and the dfbetas statistic was used to identify overly influential samples. The best fit from the Weibull, log-normal and log-logistic distributions was based on the Akaike Information Criterion. Plus and minus 95% confidence intervals were obtained for the optimum injury probability distribution. The relative sizes of the interval were determined at predetermined risk levels. Quality indices were described at each of the selected probability levels.

Results—The mean age, stature and weight: 58.2 ± 15.1 years, 1.74 ± 0.08 m and 74.9 ± 13.8 kg. Excluding all overly influential tests resulted in the tightest confidence intervals. The Weibull distribution was the most optimum function compared to the other two distributions. A majority of quality indices were in the good category for this optimum distribution when results were extracted for 25-, 45- and 65-year-old at five, 25 and 50% risk levels age groups for lower leg

fracture. For 25, 45 and 65 years, peak forces were 8.1, 6.5, and 5.1 kN at 5% risk; 9.6, 7.7, and 6.1 kN at 25% risk; and 10.4, 8.3, and 6.6 kN at 50% risk, respectively.

Conclusions—This study derived axial loading-induced injury risk curves based on survival analysis using peak force and specimen age; adopting different censoring schemes; considering overly influential samples in the analysis; and assessing the quality of the distribution at discrete probability levels. Because procedures used in the present survival analysis are accepted by international automotive communities, current optimum human injury probability distributions can be used at all risk levels with more confidence in future crashworthiness applications for automotive and other disciplines.

Keywords

Biomechanics; fracture; lower extremities; probability distributions; survival analysis; Weibull distribution

INTRODUCTION

Lower limb injuries from frontal impact crashes have received considerable attention from epidemiological, medical and biomechanical perspectives because of their associated impairments and long-term disabilities to motor vehicle occupants (Burgess et al., 1995; Estrada et al., 2004; Gloyns et al., 1979; Read et al., 2004; Seipel et al., 2001; Sherwood et al., 1999; Yoganandan et al., 1996; Yoganandan et al., 1997; Yoganandan et al., 2000). From an epidemiological perspective, the United States National Automotive Sampling System – Crashworthiness Data System (NASS-CDS) database has been queried to determine crash, vehicle and occupant factors for analyzing these injuries. For example, Morgan et al., analyzed this database for the years 1979 to 1986 in an initial effort and showed the incidence of lower extremity injuries to be approximately one-quarter of all, Abbreviated Injury Scale, AIS2+ injuries (AIS, 1990; Morgan et al., 1991). Another analysis of the NASS-CDS database files for the years 1991 to 2000 indicated that a majority of all lower limb injuries occur in frontal crashes and below the United States New Car Assessment Program (NCAP) maximum testing velocity (Crandall et al., 1996). There is currently no injury assessment criterion for the tibia/ankle (tibia force or tibia index) in the US NCAP or FMVSS 208, but the IIHS offset frontal test uses the tibia index.

The database for the years 1988 to 1996 was used to project occupant injuries in an all airbag fleet (Stucki, 1998). The cited study showed that risk of AIS2+ lower limb injuries is almost twice that of head and face, thorax or upper extremity injuries; and foot-ankle fractures were most common. Drivers in airbag equipped vehicles sustained ankle injuries most frequently, followed by the tibia/knee in frontal crashes. In an analysis of the same database for the years 1933 to 1999, with airbag equipped vehicles, lower extremities was found to be the most frequently injured body region in all types of frontal impacts (Kuppa et al., 2001). In a more recent analysis, Rudd et al. queried the NASS-CDS database for the years 1994 to 2007 (vehicle model years 1995 or higher) for front seat belted occupants in airbag equipped vehicles and found that occupants of newer vehicles sustain more foot-ankle and knee rather than pelvic injuries, thus providing a rationale to pursue more research

in this area (Rudd, 2009). Analyses of the Crash Injury Research and Engineering Network (CIREN) files have also revealed similar findings (Dischinger et al., 2004).

From a biomechanical perspective, researchers have advanced varying types of human cadaver lower leg experimental models to replicate field-observed/identified injuries and proposed tolerance metrics. For example, an earlier study in 1993 presented as a report to the US Centers for Disease Control and Prevention, examined injury mechanisms and tolerance of the foot-ankle joint using a lower leg Post Mortem Human Subject (PMHS) model (Roberts et al., 1993). A later study presented axial strength results of PMHS lower legs and behaviors of the calcaneo-fibular, talo-fibular and talo-calcaneal ligaments (Begeman and Aekbote, 1996). Although impact forces were reported in these two studies, attempts were not made to quantify the underlying injury probability distribution. In a study reported in 1996, intact PMHS lower legs subjected to axial loading by impacting the plantar foot surface produced calcaneus and distal tibia fibula complex fractures, typically seen in field data, discussed above (Yoganandan et al., 1996). Although these authors developed injury probability curves based on the peak impact force with an assumed risk function and combined impact force and injury data from previous experiments, the efficacy of the distribution including confidence intervals were not described. The Association des Constructeurs Européens d'Automobiles from Europe supported the efforts of the International Standards Organization's (ISO) Technical Committee 22, for developing a detailed methodology for 'constructing' injury probability curves for crashworthiness applications and assist in global technical regulations for motor vehicle and pedestrian safety. The developed methodology has been applied to derive risk curves under side impact loads using sled and pendulum tests (Petitjean et al., 2011). Such an analysis has not been done for lower leg injuries. Consequently, the objective of the present study was to apply this methodology and develop optimized lower leg injury probability curves from the above described PMHS lower leg experiments under axial loading to describe human tolerance and obtain the most efficacious injury probability curves.

METHODS

As indicated above, biomechanical data were obtained from an earlier publication (Yoganandan et al., 1996). In this study, experiments consisted of subjecting intact PMHS foot-ankle tibia-fibula complex specimens to axial loading at velocities ranging from 2.2 to 7.6 m/s. The subject selection criteria included an evaluation of medical records and radiographs to ensure the absence of pre-existing degenerative disease or trauma, and screening for human immunodeficiency virus and hepatitis. The preparation of the specimen included disarticulation at the knee such that the entire lower extremity distal to the knee remained intact. The proximal tibia was fixed rigidly in polymethyl-methacrylate. The distal region of the foot-ankle complex was left intact. Steinmann pins were transversely passed through the proximal tibia complex for securing the fixation. Pre-test alignment of the shank for axial loading was defined in the coronal plane from the tip of the lateral malleolus to the insertion site of the posterior cruciate ligament and in the sagittal plane from the center of the insertion of the Achilles tendon into the calcaneus distally to the posterior cruciate ligament insertion proximally. The impact load application to the specimen, accomplished using a pendulum, was such that the line between the second toe and the center of the heel

was held vertical and the plantar surface of the foot was upright. The resting position of the pendulum was used to align the plantar surface of the foot to contact the flat portion of the impacting surface. The specimen was fixed to the mini-sled consisting of precision ground stainless steel rails attached to a steel frame. The plantar aspect of the foot, which defined the distal end, was loaded axially by the pendulum impact surface. The preparation was stabilized to remain in the chosen position without creating dorsiflexion before impact by taping the toe region of the foot to the anterior tibia. Figure 1 shows a schematic of the test setup used in these experiments. The impact load was oriented such that the line between the second toe and center of the heel was held vertical and the plantar surface of the foot was held upright. The centerline of the pendulum was aligned with the shank such that off-axis forces were minimal. The impacting surface was such that no focal edge load was imparted to specimen. These procedures were obtained from preliminary tests.

Biomechanical data included the use of maximum axial forces from the tibia load cell, located at the proximal end (knee end) of the specimen. In other words, pendulum loads were not used in the analysis. Injuries were identified based on x-rays and dissections from these experiments. During the development of injury risk curves, the authors combined data from two studies to develop risk curves, assuming a simple approach (Yoganandan et al., 1996). In contrast, to determine the optimum distribution, a more detailed survival analysis was followed in the present study, and force was chosen as the main explanatory variable and the age of the specimen was included as a co-variable. The censoring status for the force was assigned as follows. If only one test was conducted on a specimen, the impact force was coded as right or left censored based on whether it remained intact or sustained calcaneus or distal tibia fracture after loading. In contrast, the impact force was coded as interval-censored in tests when the specimen was repeatedly loaded, with the lower bound of the interval representing the force from the non-injurious test and the upper bound representing the force sustained during the injury test. Reasons for selecting this approach are expanded in the discussion section. The parameters of the parametric survival analysis were estimated using the maximum likelihood approach. The Weibull, log-normal and log-logistic distributions, routinely used in impact biomechanics were considered in the analysis. The dfbetas statistic, used to identify the overly influential samples, was determined by eliminating one observation in the ensemble at a time and the best fit from these probability distributions was based on the corrected Akaike Information Criterion, AIC. It is based on the likelihood parameter of the statistical analysis, and in addition, it is an indicator of parsimony as it takes into account the number of variables used in the statistical model. The distribution with the lowest criterion value represented the best-fit optimum fracture function. Plus and minus 95% confidence intervals for the optimum injury probability distribution were obtained, and the relative size of the interval was determined at predetermined risk levels. It was defined as the width at a given injury probability level relative to the value of the mean force at the same injury probability. In this study, the width was calculated at five, 25 and 50% probabilities. Based on the width of the interval, quality indices were identified as good (0 to 0.5), fair (0.5 to 1.0), marginal (1.0 to 1.5) and unacceptable (greater than 1.5) at each of the selected probability levels.

RESULTS

There were 52 samples available for conducting the analysis. The mean age, stature and weight were 58.2 ± 15.1 years, 1.74 ± 0.08 m and 74.9 ± 13.8 kg, respectively. Out of the 52 samples, 27 were fractured and 25 were non-fractured data points. The mean age, stature and weight of all non-fractured and fractured data points were 51.4 years, 1.79 m and 74.6 kg, and 65.7 years, 1.71 m and 75.2 kg, respectively. Peak forces for non-fracture and fracture tests were 5.3 ± 2.4 and 8.5 ± 2.2 kN. The test matrix was such that some specimens underwent one impact test without injury, some sustained injuries with one loading, and in some specimens multiple tests were conducted, initially at sub-failure loads with the final test resulting in fracture. Based on the dfebtas statistic metric, five out of the 52 tested samples were determined to be overly influential and therefore were removed from further processing to represent the most rigorous statistical analysis. In addition, since nine out of the 52 tests contained only proximal forces (instead of distal, discussed later) in the dataset, to be consistent, these data were also removed from the ensemble. This process resulted in a sample size of 38 tests. Figure 2 shows the mean Weibull injury probability distribution as a function of force along with 95% upper and lower confidence intervals for this sample size (estimation included data from all ages but the prediction was specifically obtained for the mean age). It should be noted that the Weibull distribution responded with the lowest magnitudes of the AIC metric and hence, it was determined to be the most optimum function. Details of the metric for this dataset from the 38 points for the Weibull, log-normal and log-logistic functions are included (see Appendix). Figure 3 shows the injury probability curves from the sample size of 38 for the 25-, 45- and 65-year-old age groups based on the Weibull risk function. The prediction was based using the estimated Weibull function and incorporating these three ages to obtain age-specific risk curves. For 25, 45 and 65 years, peak forces were 8.1, 6.5, and 5.1 kN at 5% risk; 9.6, 7.7, and 6.1 kN at 25% risk; and 10.4, 8.3, and 6.6 kN at 50% risk, respectively. A majority of quality indices were found to be in the good category at various injury probability levels and age groups for this sample size of 38 tests (Table 1).

DISCUSSION

As indicated in the Introduction, the objective of the study was to develop optimized human injury probability curves under axial loading of the human cadaver lower legs using published data. As also indicated, previous data were not processed using parametric survival analysis, although such methods have been used in other scientific disciplines. While not resorting to such analysis process is a limitation of the results from the previous study, the dataset was amenable to higher level statistical processes as the sample size was large ($n=52$) and both injury and non-injury data points were included in the ensemble along with repeated tests from the same specimen. This experimental design permitted the use of different censoring schemes for the present analysis. As described earlier, the analysis methods used in the current study followed methods recommended by the automotive community around the world through the auspices of the ISO as it was based on consensus of experts including the authors of this study who were involved in the process. The following criteria were met for determining the optimum injury probability curves. The study used relevant data from axial loading experiments and adopted force as the main

explanatory variable and age as a co-variable and checked for different injury mechanisms. Appropriate censoring status was assigned based on no injury, fracture and repeated tests on the same specimen. Parameters of the three selected distributions were determined using the survival method. Overly influential tests were identified. The distribution assumption was checked using quintile-quintile plots. The probability distribution with the best statistical fit was chosen. The 95% Confidence intervals and their widths were computed at pre-chosen risk levels. Quality indices at discrete fracture risk levels were selected based on crashworthiness studies used in automotive research. It should be noted that these critical steps have not been followed in previous lower leg studies although probability curves have been presented (Begeman and Aekbote, 1996; Funk et al., 2002; Yoganandan et al., 1996). From these perspectives, outcomes of human injury probability curves should be considered as robust and more appropriate in the current context of improving automotive safety, designing crash tests dummies and establishing human tolerance, and as a first step these curves can be used in other environments such as underbody blast loading for military applications as such events impart dynamic axial loads to the lower leg due to improvised explosive devices and landmines (Owens et al., 2007; Radonic et al., 2004; Van der Horst et al., 2005). This is one of the reasons for selecting the three distinct age groups to represent the younger military (25 years), commonly used automotive (45 years) and ageing populations (65 years) for future crashworthiness studies (Kuppa et al., 2003; Yoganandan et al., 1996).

Another reason to choose the axial loading mode for the human lower leg is the importance of this vector in current motor vehicle environments. A recent study on frontal impacts has shown that lower leg injuries to three-point belted drivers occur from contacts within the vehicle component and higher levels of intrusion are associated with greater percentages of trauma to this body region (Austin, 2012). This study used the NASS-CDS database for the years 1997 through 2009, with vehicle model years 1998 through 2010 (sample size 7,284), the latest available analysis of United States field data, to the best knowledge of the authors of this study. The authors included the latest definition of a frontal small overlap impact (SOI), which used the NASS' Collision Deformation Classification and crush profiles (Halloway et al., 2011). For all frontal crashes, the odds of experiencing a lower leg injury with intrusion were twice the odds without intrusion. In full frontal crashes and left offset and SOI impacts, lower leg injury odds ratios with intrusion increased to seven. Each additional centimeter of intrusion increased the odds by 14% in full frontal impacts and 5% in left offset and SOI crashes. As intrusion compromises the occupant compartment space and induces contact loading to the lower leg, the present study which included fractures to the calcaneus and/or distal tibia complex has relevance to current automotive environments.

The present statistical analysis of data consisted of using data from the 52 samples/tests from three sources as explained in the original publication (Yoganandan et al., 1996). The whole ensemble constituted peak proximal tibia forces from 43 samples and applied forces from nine samples. The previous study grouped all these data and this selection may have biased earlier outcomes. In order to test the robustness of the current survival analysis with varying sample sizes, iterations were conducted by removing the nine tests from the dataset, which reported only peak applied forces, and this reduced the sample size to 43 tests. Excluding the five overly influential tests from this reduced dataset, constituted another

dataset for parametric survival analysis, and this process resulted in a sample size of 38 tests. Figure 4 compares fracture forces at different probability levels for all three age groups used in the literature with outcomes from present survival analysis. Literature outcomes were obtained from the Yoganandan et al. study as follows (1996). The two-parameter risk function consisting of force and age was used to derive the probability of injury with respect to force for specific ages. As can be seen, differences in the forces were generally low between the two methods at the 50% probability level, suggesting that either procedure can be used for this dataset when the injury criterion is based on mid-level risk. However, variations were found to be more pronounced at lower probabilities with the present survival analysis and this was true for all three age groups (Figure 4). As robust injury criteria specifications are required at lower probability levels for crashworthiness advancements, it is important to obtain the most efficacious data at such levels (Prasad et al., 2010). Because the present survival analysis is based on both robust statistical and biomechanical considerations, the distributions at lower probabilities represent improvement in injury criteria assessments for the lower leg under axial loading.

Force data were not normalized in this study in order to compare the present survival analysis output with a previous study which used the same data. However, data normalization is appropriate if PMHS results data are applied to specific anthropometry. Because the mid-size male dummy is frequently used in crashworthiness tests and development of Federal Standards, as a first step, present data were normalized to this anthropometry using the equal stress equal velocity approach (Eppinger, 1976; Maltese et al., 2002; Yoganandan et al., 2014). The present study analyzed peak forces at the proximal end of PMHS specimens. This dataset does not contain distal tibia forces. Hybrid III and THOR-LX are capable of recording distal tibia loads and these are more predictive of foot-ankle injuries. Matched pair tests with these devices should be conducted to develop a transformation function in order to apply present results to the distal tibia and this is considered as a future research topic. The injury risk function based on normalized peak force is shown (Figure 5). Lower leg injuries in automotive collisions and corresponding injury mechanisms vary due to irregular geometry of the floor pan, intrusion, posture and demographics of the occupant and pedal interactions. These variables can induce off-axis modes of injury such as inversion/eversion and dorsiflexion/plantar flexion. These modes were not considered in the present analysis and from this perspective this is a limitation of current probability curves. Because these parameters can influence human injury tolerance, axial force alone may not be the only metric required to accurately assess injury risks in all modes. Additional studies are therefore necessary to account for these injuries, injury mechanisms and injury risk functions. Another issue is the applicability of the present results to all lower leg injuries, injury mechanisms and tolerance. A discussion of this aspect is included in the Appendix.

CONCLUSIONS

The study derived axial loading injury risk curves based on survival analysis to describe human lower leg tolerance. Axial loading PMHS data from a large group of specimens were re-examined to derive injury probability curves using peak force and specimen age. This was accomplished by adopting different censoring schemes, considering overly influential

samples in the analysis and assessing the quality of probability distributions at discrete risk levels. The Weibull distribution was found to be the most optimum function. Results were extracted for 25-, 45- and 65-year-old specimens at five, 25 and 50% injury probability levels. Excluding all overly influential tests resulted in the tightest confidence intervals. The quality indices were in the good category for a majority of cases. While forces at the 50% fracture risk level were similar when data from the present survival analysis were compared with previous analysis, they were different at lower risk levels and this was true for all ages. Because procedures used in the present survival analysis are accepted by international automotive, current optimum human injury probability distributions can be used at all risk levels with more confidence in future crashworthiness applications.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

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REFERENCES

- AIS. Association for the Advancement of Automotive Medicine. Des Plaines, IL: 1990. The Abbreviated Injury Scale.
- Austin, RA. National Center for Statistics and Analysis. Washington, DC: National Highway Traffic Safety Administration; 2012. Lower extremity injuries and intrusion in frontal crashes.
- Begeman, PC.; Aekbote, K. Axial load strength and some ligament properties of the ankle joint. In: Grimm, MJ., editor. 6th Injury Prevention Through Biomechanics Symposium. Detroit, MI: Wayne State University; 1996. p. 125-135.
- Burgess AR, Dischinger PC, O'Quinn TD, Schmidhauser CB. Lower extremity injuries in drivers of airbag-equipped automobiles: clinical and crash reconstruction correlations. *J Trauma*. 1995; 38:509–516. [PubMed: 7723088]
- Crandall, J.; Martin, P.; Bass, C.; Pilkey, W.; Dischinger, P.; Burgess, A.; O'Quinn, T.; Schmidhauser, C. Foot and Ankle Injury: The Roles of Driver Anthropometry, Footwear, and Pedal Controls; 40th Annual Proceedings of the Association for the Advancement of Automotive Medicine; 1996.
- Dischinger PC, Read KM, Kufera JA, Kerns TJ, Burch CA, Jawed N, Ho SM, Burgess AR. Consequences and costs of lower extremity injuries. *Annu Proc Assoc Adv Automot Med*. 2004; 48:339–353. [PubMed: 15319134]
- Eppinger, RH. Prediction of thoracic injury using measurable experimental parameters. Proceedings of the International Conference of Experimental Safety Vehicles; NHTSA; Washington, DC. 1976. p. 770-779.
- Estrada LS, Alonso JE, McGwin G Jr, Metzger J, Rue LW 3rd. Restraint use and lower extremity fractures in frontal motor vehicle collisions. *J Trauma*. 2004; 57:323–328. [PubMed: 15345980]
- Funk JR, Crandall JR, Tournet LJ, MacMahon CB, Bass CR, Patrie JT, Khaewpong N, Eppinger RH. The axial injury tolerance of the human foot/ankle complex and the effect of Achilles tension. *J Biomech Eng*. 2002; 124:750–757. [PubMed: 12596644]
- Gloyns, PF.; Hayes, HRM.; Rattenbury, SJ.; Thomas, PD.; Mills, HC.; Griffiths, DK. Lower limb injuries to car occupants in frontal impacts. 1979 International IRCOBI Conference; International Research Council on the Biomechanics of Impact; Bron, France. 1979. p. 105-121.

- Halloway, D.; Saunders, J.; Yoganandan, N.; Pintar, F. Society of Automotive Engineers, World Congress. Warrendale, PA: SAE International; 2011. An Operational Definition of Small Overlap Impact for Published NASS Data.
- Kuppa S, Eppinger RH, McKoy F, Nguyen T, Pintar FA, Yoganandan N. Development of Side Impact Thoracic Injury Criteria and Their Application to the Modified ES-2 Dummy with Rib Extensions (ES-2re). *Stapp Car Crash J.* 2003; 47:189–210. [PubMed: 17096250]
- Maltese MR, Eppinger RH, Rhule HH, Donnelly BR, Pintar FA, Yoganandan N. Response corridors of human surrogates in lateral impacts. *Stapp Car Crash J.* 2002; 46:321–351. [PubMed: 17096232]
- Morgan, RM.; Eppinger, RH.; Hennessey, BC. Ankle joint injury mechanism for adults in frontal automotive impact. 35th Stapp Car Crash Conference; Society of Automotive Engineers; Warrendale, PA. 1991. p. 189-198.
- Owens BD, Kragh JF Jr, Macaitis J, Svoboda SJ, Wenke JC. Characterization of extremity wounds in Operation Iraqi Freedom and Operation Enduring Freedom. *J Orthop Trauma.* 2007; 21:254–257. [PubMed: 17414553]
- Petitjean A, Trosseille X. Statistical simulations to evaluate the methods of the construction of injury risk curves. *Stapp Car Crash J.* 2011; 55:411–440. [PubMed: 22869316]
- Prasad P, Mertz HJ, Dalmotas DJ, Augenstein JS, Diggs K. Evaluation of the field relevance of several injury risk functions. *Stapp Car Crash J.* 2010; 54:49–72. [PubMed: 21512903]
- Radonic V, Giunio L, Biocic M, Tripkovic A, Lukcic B, Primorac D. Injuries from Antitank mines in Southern Croatia. *Military medicine.* 2004; 169:320–324. [PubMed: 15132237]
- Read KM, Kufera JA, Dischinger PC, Kerns TJ, Ho SM, Burgess AR, Burch CA. Life-altering outcomes after lower extremity injury sustained in motor vehicle crashes. *J Trauma.* 2004; 57:815–823. [PubMed: 15514536]
- Roberts, D.; Donnelly, B.; Severin, C.; Medige, J. Injury mechanisms and tolerance of the human ankle joint. Atlanta, GA: Centers for Disease Control; 1993.
- Rudd, RW. Updated Analysis of Lower Extremity Injury Risk in Frontal Crashes in the United States. 21st International Technical Conference on the Enhanced Safety of Vehicles; Stuttgart, Germany. 2009.
- Seipel RC, Pintar FA, Yoganandan N, Boynton MD. Biomechanics of calcaneal fractures: a model for the motor vehicle. *Clin Orthop Relat Res.* 2001:218–224. [PubMed: 11451123]
- Sherwood C, O'Neill B, Hurwitz SR. Lower extremity causation in frontal crashes. International Research Council on the Biomechanics of Impact. 1999
- Stucki, L. Determination of frontal offset test condition based on crash data. 17th International Technical Conference on the Enhanced Safety of Vehicles; Windsor, Canada. 1998.
- Van der Horst, M.; Simms, C.; van Maasdam, R.; Leerdam, P. Occupant lower leg injury assessment in landmine detonations under a vehicle; IUTAM Symposium on Impact Biomechanics: From Fundamental Insights to Applications: Springer; 2005. p. 41-49.
- Yoganandan N, Arun MW, Pintar FA. Normalizing and scaling of data to derive human response corridors from impact tests. *J Biomech.* 2014; 47:1749–1756. [PubMed: 24726322]
- Yoganandan, N.; Pintar, FA.; Boynton, M.; Begeman, PC.; Prasad, P.; Kuppa, SM.; Morgan, RM.; Eppinger, RH. Dynamic axial tolerance of the human foot-ankle complex. 40th Stapp Car Crash Conference; Society of Automotive Engineers; Warrendale, PA. 1996. p. 207-218.
- Yoganandan N, Pintar FA, Kumaresan S, Boynton M. Axial impact biomechanics of the human foot-ankle complex. *J Biomech Eng.* 1997; 119:433–437. [PubMed: 9407282]
- Yoganandan N, Pintar FA, Seipel R. Experimental production of extra- and intra-articular fractures of the os calcis. *J Biomech.* 2000; 33:745–749. [PubMed: 10807996]
- Yoganandan N, Pintar, Gennarelli TA, Seipel R, Marks RM. Biomechanical tolerance of calcaneal fractures. *Annu Proc Assoc Adv Automot Med.* 1999; 43:345–356.
- Yoganandan N, Stemper BD, Pintar FA, Maiman DJ. Use of postmortem human subjects to describe injury responses and tolerances. *Clin Anat.* 2011; 24:282–293. [PubMed: 21433078]

Figure 1. Schematic of the setup used for axial loading of the lower leg using PMHS (see text for details, from (Yoganandan et al., 2011).

Figure 2. Injury probability curves (mean and 95% confidence intervals) as a function of force from the survival analysis.

Figure 3.
Injury probability curves as a function of age from the survival analysis.

Figure 4.
Comparison of peak force at three ages at different fracture probabilities.

Figure 5.
Estimated Weibull injury probability risk function based on the normalized data.

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Table 1

Comparison of quality indices

Age (years)	Risk level	Quality index (N=52)	Quality index (N=38)
25	0.05	0.71	0.704
25	0.25	0.512	0.608
25	0.5	0.477	0.582
45	0.05	0.606	0.454
45	0.25	0.324	0.309
45	0.5	0.242	0.268
65	0.05	0.634	0.377
65	0.25	0.335	0.208
65	0.5	0.231	0.157