# INJURIES OF THE LOWER LEGS - FOOT, ANKLE JOINT, TIBIA; MECHANISMS, TOLERANCE LIMITS, INJURY - CRITERIA EVALUATION OF A RECENT BIOMECHANIC EXPERIMENT-SERIES
(Impact-tests with a Pneumatic-Biomechanic-Impactor)

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## Abstract

The purpose of a recent biomechanic experiment series*) of 24 cadaver tests was a claryfication of injurymechanisms and tolerancelimits of the lower legs, especially of the foot, ankle joint and tibia. Using a pneumatic coaxial-impactor, fresh, uninjured Post Mortem Human Subjects (PMHS) were exposed to an impact against the plantar foot surface.
The experimental set-up was designed to simulate a floorboard-foot impact, which occurs when the moving (intruding) footwell of a car hits the foot and viceversa in a frontal collision.
The independent variable was the velocity of the impacting mass. Each foot has been used for a separate experiment. Accelerations of the tibia were recorded from bone mounted accelerometers and impact forces as well as accelerations of the foot have been determined by transducers located in especially designed shoe integrated measurement (SIM).
Extent and pattern of post-impact injuries were detected by evaluation of x-rays and subsequent dissection of the knee- and ankle joint.
The same test set-up was used for two subsequent series of a total of 60 dummy tests, using a dummy H III. In the first series (20 tests) the dummy was equipped with instrumented legs, in the second series (40 tests) with an advanced lower leg.
The results of this study contribute to

- injury-mechanisms and tolerance-limits as a function of the test variables
- correlation of PMHS - and dummy test-results
- discussion of injury- and performance-criteria
- discussion of measurements on dummies lower legs as predictors for lower leg injuries.

## 1 Introduction

Advanced integrated retention-system design in passenger cars leads to a decreasing number of severe head and chest injuries. Due to this the frequency of painfull and expensive lower leg and foot ankle injuries in car crashes is increasing relatively. The evidence of this fact is known from accident research, but in the field of traumatomechanics there is still necessity to clarify injury-mechanisms and tolerance limits of the lower legs. The purpose of this study therefore was to determine the critical threshold for lower extremity injuries in a fresh, intact human cadaver by subjecting the plantar foot surface to an isolated force generated by a pneumatic coaxial-impactor. The experimental set-up is designed to model the floorboard-foot interaction which occurs in a car frontal collision when the legroom compartment crashes on primary impact.

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For the tests the selected impact velocity was determined by adjusting the pressure within the impactor at the point of impact with the foot of a post mortem human subject (PMHS). Each leg was used for a separate experiment. The extent of post-impact injuries was detected by evaluation of roentgenograms and subsequent dissection and isolation of the calcaneus and talus.
Accelerations of the tibia were recorded by bone mounted accelerometers; impact forces and accelerations at the foot were determined using shoe integrated measurement (SIM).
Statistical analysis of the results was carried out as well as individual test-result discussion.
The main goal of this FAT-project is to find correlations within the entire data of the experiments and to use these as a basis for discussion to define lower extremity dummy-design and measurements which are able to predict injuries when doing performance tests.

## 2 Material and Methods

A sample of 24 plantar foot impacts were executed using the pneumatic coaxial-impactor (PCI) as presented by the poster at the 1990 international IRCOBI-conference (test set-up see fig.1). Each foot of 12 fresh PMHS (age between 24 and 67 years) was subjected to an impact mass of 38 kg and varying the impact velocity between 24 and 45 km/h as shown in fig. 2 (distribution of PMHS age and impact velocity).
The PMHSs were placed on an adjustable seat in a suspended pendulum within the steel rails. The adjustable seat allowed proper and defined positioning of the subjects, even with respect to individual body-sizes. From every test a high-speed-film was taken and analysed.

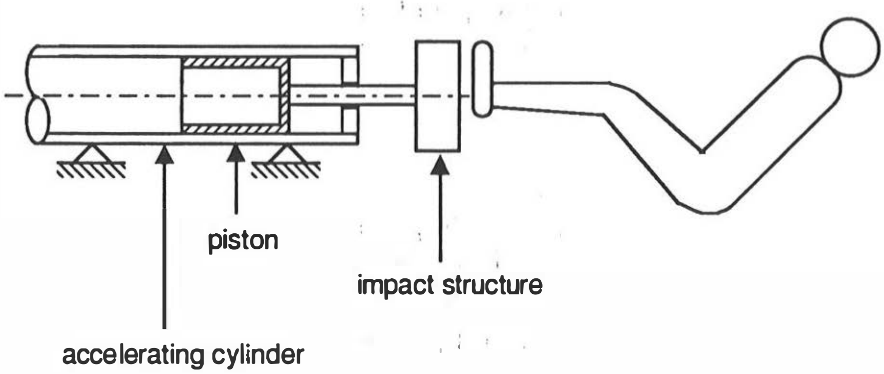


Figure 1 Plantar foot impacts: test set-up

Test Subject Preparation:

All PMHSs have been prepared as follows: body measurements (anthropometry) including individual data were taken followed by a series of roentgenograms (each AP and lateral, knee joint, foot). The pre-impact X-rays served as a status document (concerning signs of congential or acquired malformations) and as a control to compare with post-impact roentgenograms.

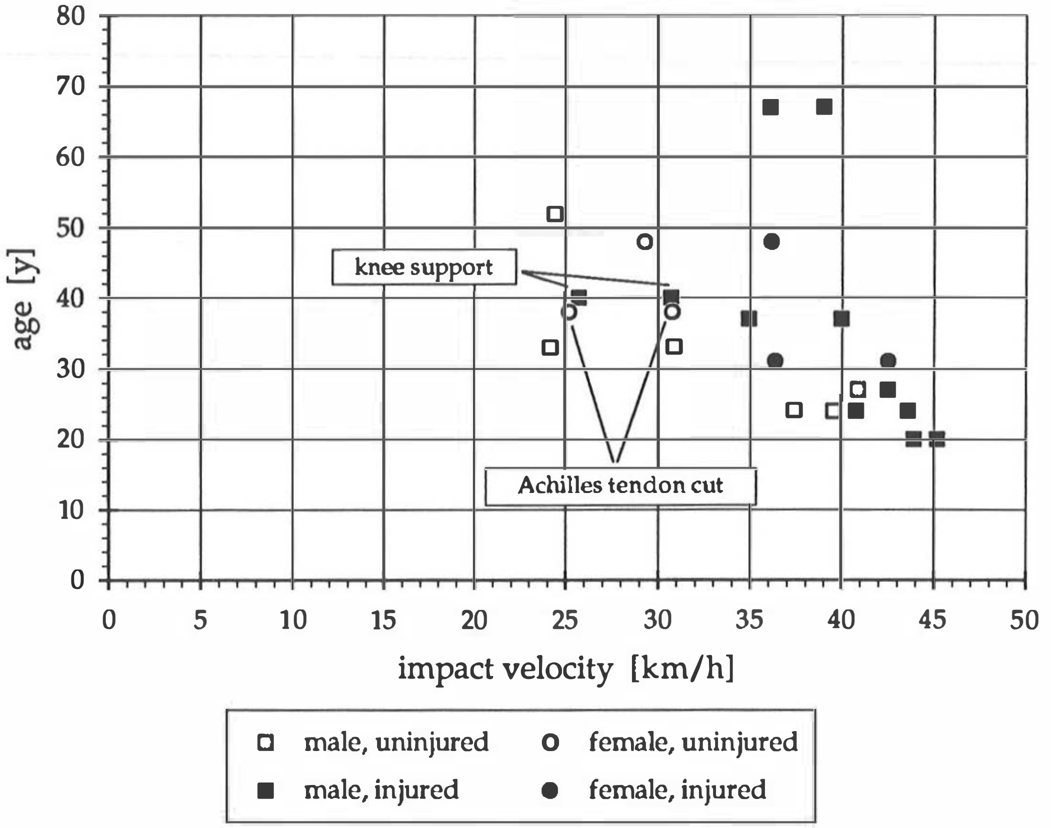


Figure 2 Plantar foot impacts: distribution of PMHS age and impact velocity

Application of transducers:

Bone-mounted biaxial accelerometers (sagittal and transversal planes) were attached to the tibia of the impacted lower leg between the tibial condyles and medial mallelous. For this an aluminium adapterbase was screwed into the tibia (slanted side facing laterally) and secured with two small allen wrench bolts. The PMHS was then transferred into the seat and fixed in proper position with one leg exposed for impact.

The especially designed shoes (SIM) equiped with six force transducers (sole and heel 3 directions each) and two accelerometers (sole and heel in z direction) were fitted onto the impact exposed foot and secured into place. The shoe was then suspended by a rope and moved into position for impact. A copper switch attached to the sole of the foot was demarcating first contact ($t_0$) between the impactor board and the foot.
All transducer signals were recorded by a reel to reel tape recorder. The impact was filmed by a high speed camera (1000 pictures per sec).

All functions of impactor and periphery such as initiation and sequence of the impact, the calibration of the accelerometer and force transducers, tape recorder and camera were managed by a memory programmable control device.

After both impacts post-impact roentgenograms were taken and special dissection and preparation of the feet, knee and hip-joint were executed to detect the pattern and extent of injuries. Mainly the calcaneus and talus were subsequently removed and examined for patterns of fracture. Any evidence of injury has been documented and classified according to AIS `90.

A statistical analysis made evident, that in a multivariate model the results became instable if more than two variables were included in the model (regression equation). Therefore an analysis was performed in three steps:

- correlation analysis
- analysis of possible predictor variables
- risk analysis

## 3 Results and Discussion

### 3.1 PMHS Experiments

All data also used for statistical analysis are shown in the table of the annex. These data contain the measured values and individual data of all tests.

In the statistical evaluation the correlation analysis was performed at first.

In order to measure the degree of association, the Pearson correlation coefficient r ($-1 \leq r \leq 1$) was calculated. The corresponding p-value indicates the error probability in order to postulate an association between the two variables if these variables are in fact independent.

Table 1 shows the correlation between the adjustable input characteristic ($v_{imp}$) and the surrogate variables.

| | | $a_{imp}$ | $a_{ll}$ | $a_{sole}$ | $F_{sole}$ | $I_{sole}$ | $a_{heel}$ | $F_{heel}$ | $I_{heel}$ |
|---|---|---|---|---|---|---|---|---|---|
| $v_{imp}$ | r= | *0,44* | 0,01 | *0,52* | *0,67* | 0,17 | 0,2 | *0,48* | *0,61* |
| | p= | *0,047* | 0,96 | *0,026* | *0,002* | 0,48 | 0,41 | *0,037* | *0,005* |

Table 1: adjustable input characteristic ($v_{imp}$) versus surrogate variables

Table 2 (see next page) shows the correlation between the surrogate variables.

Table 3 shows the correlation between the surrogate variables and individual characteristics.

In this table an additional individual characteristic is introduced named "body index". The body index indicates the relationship of body weight and body height. This characteristic was introduced to proof the influence of the individual body build.

The mass of the lower extremities is calculated using the anthropometric data. A combination of homogen cylinders and truncated cones was used in a model of thigh and lower leg.

| | | $a_{imp}$ | $a_{ll}$ | $a_{sole}$ | $F_{sole}$ | $I_{sole}$ | $a_{heel}$ | $F_{heel}$ | $I_{heel}$ |
|---|---|---|---|---|---|---|---|---|---|
| $a_{imp}$ | r= | 1 | ***-0,41*** | ***0,46*** | 0,24 | 0,34 | 0,05 | 0,12 | 0,08 |
| | p= | 0 | ***0,063*** | ***0,052*** | 0,32 | 0,15 | 0,84 | 0,62 | 0,73 |
| $a_{ll}$ | r= | ***-0,41*** | 1 | -0,31 | 0,34 | -0,0 | -0,33 | -0,01 | 0,22 |
| | p= | ***0,063*** | 0 | 0,21 | 0,16 | 0,99 | 0,17 | 0,96 | 0,36 |
| $a_{sole}$ | r= | ***0,46*** | -0,31 | 1 | 0,33 | ***0,41*** | -0,03 | -0,21 | -0,11 |
| | p= | ***0,052*** | 0,21 | 0 | 0,18 | ***0,092*** | 0,89 | 0,4 | 0,65 |
| $F_{sole}$ | r= | 0,24 | 0,34 | 0,33 | 1 | 0,36 | -0,06 | 0,28 | 0,34 |
| | p= | 0,32 | 0,16 | 0,18 | 0 | 0,13 | 0,81 | 0,24 | 0,15 |
| $I_{sole}$ | r= | 0,34 | -0,0 | ***0,41*** | 0,36 | 1 | ***-0,5*** | -0,19 | -0,09 |
| | p= | 0,15 | 0,99 | ***0,092*** | 0,13 | 0 | ***0,03*** | 0,43 | 0,71 |
| $a_{heel}$ | r= | 0,05 | -0,33 | -0,03 | -0,06 | ***-0,5*** | 1 | ***0,57*** | ***0,41*** |
| | p= | 0,84 | 0,17 | 0,89 | 0,81 | ***0,03*** | 0 | ***0,011*** | ***0,081*** |
| $F_{heel}$ | r= | 0,12 | -0,01 | -0,21 | 0,28 | -0,19 | ***0,57*** | 1 | ***0,72*** |
| | p= | 0,62 | 0,96 | 0,4 | 0,24 | 0,43 | ***0,011*** | 0 | ***0,0005*** |
| $I_{heel}$ | r= | 0,08 | 0,22 | -0,11 | 0,34 | -0,09 | ***0,41*** | ***0,72*** | 1 |
| | p= | 0,73 | 0,36 | 0,65 | 0,15 | 0,71 | ***0,081*** | ***0,0005*** | 0 |

Table 2: correlation analysis - surrogate variables versus surrogate variables

| | | $a_{imp}$ | $a_{ll}$ | $a_{sole}$ | $F_{sole}$ | $I_{sole}$ | $a_{heel}$ | $F_{heel}$ | $I_{heel}$ |
|---|---|---|---|---|---|---|---|---|---|
| age | r= | -0,14 | ***-0,4*** | 0,23 | ***-0,66*** | -0,02 | -0,14 | ***-0,65*** | ***-0,69*** |
| | p= | 0,55 | ***0,069*** | 0,35 | ***0,002*** | 0,94 | 0,56 | ***0,0028*** | ***0,001*** |
| body height | r= | ***0,47*** | -0,09 | 0,28 | ***0,42*** | 0,03 | 0,37 | ***0,69*** | ***0,68*** |
| | p= | ***0,033*** | 0,69 | 0,25 | ***0,074*** | 0,9 | 0,12 | ***0,0011*** | ***0,0015*** |
| body weight | r= | -0,11 | -0,13 | -0,24 | 0,04 | -0,2 | ***0,41*** | ***0,56*** | ***0,42*** |
| | p= | 0,64 | 0,56 | 0,33 | 0,87 | 0,41 | ***0,077*** | ***0,013*** | ***0,075*** |
| body index | r= | -0,27 | -0,1 | -0,34 | -0,1 | -0,22 | 0,31 | 0,35 | 0,21 |
| | p= | 0,24 | 0,66 | 0,17 | 0,7 | 0,36 | 0,19 | 0,14 | 0,38 |
| size of foot | r= | -0,07 | 0,08 | 0,04 | 0,31 | -0,18 | ***0,45*** | ***0,76*** | ***0,69*** |
| | p= | 0,77 | 0,72 | 0,88 | 0,2 | 0,45 | ***0,056*** | ***0,0001*** | ***0,0012*** |
| length of crotch | r= | ***0,57*** | 0,01 | 0,26 | ***0,41*** | 0,09 | 0,22 | ***0,52*** | ***0,52*** |
| | p= | ***0,0075*** | 0,97 | 0,3 | ***0,08*** | 0,71 | 0,36 | ***0,024*** | ***0,023*** |
| dist. butt.-knee | r= | ***0,51*** | 0,22 | 0,1 | ***0,54*** | 0,26 | 0,02 | ***0,47*** | ***0,56*** |
| | p= | ***0,017*** | 0,34 | 0,69 | ***0,018*** | 0,27 | 0,92 | ***0,042*** | ***0,013*** |
| dist. knee-sole | r= | ***0,63*** | -0,1 | 0,38 | 0,36 | 0,06 | 0,28 | ***0,45*** | ***0,53*** |
| | p= | ***0,0022*** | 0,66 | 0,12 | 0,13 | 0,79 | 0,25 | ***0,055*** | ***0,019*** |
| mass lower extr. | r= | -0,06 | 0,15 | -0,2 | ***0,52*** | -0,17 | ***0,45*** | ***0,7*** | ***0,61*** |
| | p= | 0,81 | 0,53 | 0,43 | ***0,022*** | 0,47 | ***0,055*** | ***0,0008*** | ***0,0053*** |
| mass lower leg | r= | -0,14 | 0,05 | -0,03 | ***0,41*** | -0,32 | ***0,51*** | ***0,59*** | ***0,55*** |
| | p= | 0,57 | 0,85 | 0,9 | ***0,082*** | 0,18 | ***0,026*** | ***0,0073*** | ***0,014*** |
| mass thigh | r= | -0,03 | 0,19 | -0,25 | ***0,54*** | -0,11 | ***0,4*** | ***0,71*** | ***0,61*** |
| | p= | 0,91 | 0,44 | 0,31 | ***0,017*** | 0,66 | ***0,089*** | ***0,0006*** | ***0,0058*** |
| period p. m. | r= | ***-0,38*** | 0,2 | ***-0,67*** | -0,25 | -0,06 | -0,1 | 0,26 | 0,13 |
| | p= | ***0,093*** | 0,39 | ***0,0023*** | 0,3 | 0,82 | 0,69 | 0,29 | 0,61 |

Table 3: correlation analysis - surrogate variables vs. individual characteristics

Analysis of Possible Predictor Variables

In order to analyse possible predictor variables, the means of the two groups (uninjured and injured) were compared by use of the t-test.

The corresponding p-value indicates the error probability in order to postulate a difference between the two means if in fact this is not true.

| | UNINJURED | | | INJURED | | | p-value |
|---|---|---|---|---|---|---|---|
| | n | mean | SD | n | mean | SD | (t-test) |
| $a_{imp}$ | 10 | 129,1 | 65 | 13 | 157,3 | 42,1 | 0,25 |
| $a_{ll}$ | 10 | 212,1 | 48,6 | 13 | 221 | 51 | 0,67 |
| $a_{sole}$ | 8 | 596 | 277,3 | 12 | 1093,7 | 333,3 | ***0,003*** |
| $F_{sole}$ | 8 | 10 | 5,1 | 13 | 16,3 | 6,6 | ***0,032*** |
| $I_{sole}$ | 8 | 25,6 | 7,4 | 13 | 38,1 | 21,7 | ***0,074*** |
| $a_{heel}$ | 8 | 1138 | 238 | 13 | 1026 | 403,9 | 0,46 |
| $F_{heel}$ | 8 | 14,1 | 3,9 | 13 | 13,7 | 4,4 | 0,81 |
| $I_{heel}$ | 8 | 46,1 | 15,5 | 13 | 54,3 | 13,6 | 0,22 |

Table 4: analysis of possible predictor variables - surrogate variables

| | UNINJURED | | | INJURED | | | p-value |
|---|---|---|---|---|---|---|---|
| | n | mean | std.-dev. | n | mean | std.-dev. | (t-test) |
| $v_{imp}$ | 10 | 30,7 | 6,5 | 14 | 38,4 | 5,5 | ***0,005*** |
| age | 10 | 36,9 | 10,8 | 14 | 36,6 | 15,3 | 0,96 |
| body height | 10 | 170,6 | 5,7 | 14 | 174,9 | 7,6 | 0,15 |
| body weight | 10 | 73,9 | 10,6 | 14 | 66,9 | 11,3 | 0,14 |
| size of foot | 10 | 24,2 | 1,9 | 14 | 24,2 | 1,5 | 0,97 |
| length of crotch | 10 | 77,5 | 6,5 | 14 | 80,5 | 5,7 | 0,24 |
| dist. butt.-knee | 10 | 56,4 | 2,6 | 14 | 58,1 | 2,8 | 0,12 |
| dist. knee-sole | 10 | 52,2 | 3,2 | 14 | 54,1 | 2,7 | 0,13 |
| mass lower extr. | 8 | 6,8 | 1,3 | 14 | 6,2 | 1,7 | 0,35 |
| mass lower leg | 8 | 2,1 | 0,4 | 14 | 1,9 | 0,5 | 0,3 |
| mass thigh | 8 | 4,8 | 0,9 | 14 | 4,3 | 1,3 | 0,4 |
| period p.m. | 10 | 73,8 | 26,4 | 14 | 54,1 | 28,2 | 0,1 |
| body index | 10 | 43,4 | 6,5 | 14 | 38,1 | 5,4 | ***0,04*** |

Table 5: analysis of possible predictor variables - input characteristics (adjustable and given)

Risk Analysis

Calculating the relative risk according to algorhythmically defined ranges for four possible predictor variables significantly increased values (i. e. lower limit of the 95%-confidence interval (CI) ≥ 1) were found.

| predictor variable | range | RR | 95%-CI |
|---|---|---|---|
| $v_{imp}$ | < 35 km/h | 1,0 | - |
| | ≥ 35 km/h | 2,6 | 1,0 - 7,0 |
| $a_{sole}$ | < 1000 g | 1,0 | - |
| | ≥ 1000 g | 2,4 | 1,1 - 5,5 |
| $F_{sole}$ | < 15 kN | 1,0 | - |
| | ≥ 15 kN | 2,5 | 1,1 - 5,6 |
| body index | > 42 kg/m | 1,0 | - |
| | ≤ 42 kg/m | 2,7 | 1,0 - 7,0 |

Table 6: predictor variables for the relative risk

Table 6 shows the four predictor variables as well as the range of values which indicate significantly a relative risk of leg injuries as follows :

- impact velocity ≥ 35 km/h
- sole acceleration ≥ 1000 g
- sole force ≥ 15 kN
- body index ≤ 42 kg/m

As a result of the statistical analysis the lower leg acceleration (tibia, z-direction) was not significant as predictor variable.
However, the mean values of acceleration maxima in both samples with or without injuries are very close (221 g and 212 g).
The consequence at this time leads to the hypothesis that injuries are limitating this value at a level of 200-250 g.
Furthermore various aspects of this foot impact series lead to the question of the influence of bone injuries of the foot concerning measurement values above the location of injuries.

## 3.2 Dummy Tests

In addition to the PMHS experiments two series of dummy tests (series I - 20 tests; series II - 40 tests) were executed using the same test set-up.
For series I (17 tests with SIM, 3 tests with "normal" shoes) the dummy (type Hybrid III) was equipped with instrumented legs.
Series I was divided into 3 different groups of impact exposures as follows:

a) 9 tests comparable to the PMHS foot impacts, 2 of these with "normal" shoes
b) 3 tests as plantar impacts simultaneus against both feet, 1 of these with "normal" shoes
c) 8 tests in oblique position (e.g. eversion, inversion, dorsiflexion) of the feet to the impacting surface.

All tests were executed at values of the impact velocity between 25 and 30 km/h.

A total of nine channels per lower leg was collected:

| | |
|---|---|
| upper tibia: | lateral and antero-posterior bending moments |
| knee: | left and right axial condyle force, knee force |
| lower tibia: | lateral bending moment, axial force and lateral shear force |
| foot: | acceleration |

In addition biaxial accelerometers were taped on the dummies´ skin in medial tibia position.
The reason for the large number of low velocity impacts has to be seen in the fact, that very high measured values became evident starting with the tests of the series. Not only the measurement but even the mechanical structure of the dummies lower legs were reaching the threshold of destruction.
In addition the repeatability of the tests using the instrumented leg was less satisfying than expected. The measured data were spreading in a wide range at the same test design and the same impact velocity.
An evaluation of the results of the dummy test series I concerning the validity of the tibia index (TI, Mertz) showed clearly that the tibia index measured in the dummy`s lower leg is not a sufficient predictor for the probability of lower leg injuries.
Although the calculated tibia index at impact velocity of 25 km/h lets assume a high risk of injury (calculated TI ≈ 1,8 at 25 km/h) no lower leg injuries occured in PMHS at the same load.
In addition the tibia compression force measured in the Hybrid III-(instrumented-) leg in the range of 16 kN is far beyond the limit for the tibia axial compression force given by Mertz with 8 kN for the 50 % Hybrid III dummy.
The acceleration of the lower instrumented leg however remained below 150 g which was defined in a first step as a limit value by drop tests with dummies in comparison with jumps of a voluntary test person from a height of 2 meters [Zeidler].
Due to the construction of the instrumented leg (e. g. no defined bending moment in the foot ankle) the movement of the feet in the tests with oblique position was limited by the ball and socket joints.
These main results show clearly the necessity of an improved dummy design concerning the lower legs.
For this reason, a complementary series II of 40 dummy tests was executed using a Hybrid III dummy with an advanced lower leg, designed by Viano.
The results of this series are published within the FAT-report Nr. 125/1995, [Schueler et al.].

## 4 Summary and Conclusions

24 PMHS and 20 dummy foot impact tests were performed using a pneumatic coaxial impactor. The measured values were analysed under the aspect of generated injuries. A main data set of the PMHS foot impact data was taken for statistical analysis (table of annex).
The injuries mainly occured in the bony structure of the foot (mainly fractures of the calcaneus).

As one result of the statistical analysis the relative risk of leginjuries and the significant ranges of values were calculated for the following predictor variables: impact velocity, sole acceleration, sole force and body index.

According to the statistical analysis the lower leg acceleration (tibia, z-direction) was not significant as predictor variable.
The fact that the main values of the tibia acceleration in both subsamples (injured and uninjured) were close together implicates the hypothesis that injuries limitate the tibia acceleration value at a level of 200-250 g in PMHS tests.
Various aspects of this foot impact series lead to the question of the influence of bone injuries of the foot concerning measured values above the location of those injuries.
Present design and measurements of the dummies' lower legs seem to be insufficient for injury prediction. Advanced designs have to take into account:

- kinematics of foot and knee joint
- mass distribution and relationship of bony and muscular structures
- location of measurement for injury prediction close to the point of impact.

Nevertheless the results show that the tibia index measured in the dummy's lower leg (series I/instrumented leg) is not a good predictor for the probability of lower leg injuries.
Although the tibia index calculated in the dummy-test series I lets assume a high risk of injury, no lower leg injuries were found in PMHS at the same load.
In addition the tibia compression force measured in the Hybrid III-(instrumented-) was twice as high as the limit for the tibia axial compression force given by Mertz with 8 kN for the 50 % Hybrid III dummy.
In addition the acceleration- and force-values of the sole (dummy test series I) remained far below the thresholds which were found to be significant for probability of lower leg injuries in the PMHS-tests.

From the results of the dummy test series I compared with the PMHS-tests we conclude that using the state of the art-dummy Hybrid III equipped with an instrumented leg the tibia index will give misleading results and consequently is at this time no reasonable injury criterion.

To gain better knowledge of injury mechanisms concerning the foot it is important to perform further PMHS experiments with oblique positions (e.g. eversion, inversion, dorsiflexion) of the foot at the moment of impact.

Abbreviation Index

| | | |
|---|---|---|
| $a_{imp}$ | impact mass acceleration | [ g ] |
| $a_{ll}$ | lower leg acceleration | [ g ] |
| $a_{sole}$ | sole acceleration | [ g ] |
| CCF | comminuted calcaneus fracture | |
| CF | calcaneus fracture | |
| CI | confidence interval | |
| f | female | |
| FAT | Forschungsvereinigung Automobiltechnik (Automobile Technique Research Association) | |
| $F_{heel}$ | heel force | [kN] |
| $F_{sole}$ | sole force | [kN] |
| $I_{heel}$ | heel impulse | [Ns] |
| $I_{sole}$ | sole impulse | [Ns] |
| KJI | knee joint injury | |
| LE | lower extremity | |
| LL | lower leg | |
| m | male | |
| MPC | memory programmable control | |
| p | p-value (statistical error probability ) | |
| p.m. | post mortem | |
| PMHS | post mortem human subjects | |
| r | Pearson correlation coefficient based on normaly distributed variables | |
| RR | relative risk | |
| SD | standard deviation | |
| SIM | shoe integrated measurement | |
| TF | talus fracture | |
| $v_{imp}$ | impact velocity | [km/h] |

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| T.-No. | Age | Sex | Height | Weight | Dist. Butt.-Knee | Dist. Knee-Sole | Lenght of crotch | foot size | Mass Thigh | Mass LL | Mass LE | Body Index | Period |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | [y] | | [cm] | [kg] | [cm] | [cm] | [cm] | [cm] | calc. [kg] | calc. [kg] | calc. [kg] | [kg/m] | p. m. [h] |
| 225 | 33 | 1 | 174 | 76 | 58 | 54 | 83 | 26 | m.v. | m.v. | m.v. | 43,68 | 80 |
| 226 | 33 | 1 | 174 | 76 | 58 | 53 | 82 | 26 | m.v. | m.v. | m.v. | 43,68 | 80 |
| 227 | 52 | 1 | 163 | 83,5 | 53 | 47 | 67 | 24 | 4,76 | 1,86 | 6,62 | 51,23 | 104 |
| 228 | 52 | 1 | 163 | 83,5 | 52 | 48 | 67 | 24 | 4,55 | 1,86 | 6,41 | 51,23 | 104 |
| 301 | 27 | 1 | 173 | 64 | 55,5 | 52,5 | 79 | 25,5 | 5,25 | 2,62 | 7,87 | 36,99 | 48 |
| 302 | 27 | 1 | 173 | 64 | 56 | 53 | 79 | 25 | 4,93 | 2,57 | 7,5 | 36,99 | 48 |
| 303 | 67 | 1 | 175 | 65 | 54,5 | 56 | 79,5 | 24 | 2,57 | 1,68 | 4,25 | 37,14 | 32 |
| 304 | 67 | 1 | 175 | 65 | 55 | 54 | 79,5 | 24 | 2,64 | 1,56 | 4,2 | 37,14 | 32 |
| 305 | 48 | 2 | 165 | 78 | 54 | 50 | 73 | 22 | 5,83 | 2,37 | 8,2 | 47,27 | 24 |
| 306 | 48 | 2 | 165 | 78 | 54 | 50 | 73 | 22 | 5,47 | 2,2 | 7,67 | 47,27 | 24 |
| 307 | 37 | 1 | 173 | 64 | 58 | 56 | 84 | 25 | 3,91 | 1,32 | 5,23 | 36,99 | 80 |
| 308 | 37 | 1 | 173 | 64 | 59 | 55 | 84 | 24 | 3,84 | 1,3 | 5,14 | 36,99 | 80 |
| 309 | 24 | 1 | 178 | 82 | 57 | 56 | 84 | 25,5 | 5,8 | 2,56 | 8,36 | 46,07 | 57 |
| 310 | 24 | 1 | 178 | 82 | 59 | 57 | 84 | 25,5 | 5,37 | 2,28 | 7,65 | 46,07 | 57 |
| 311 | 24 | 1 | 186 | 85 | 61 | 55 | 82 | 26 | 5,89 | 2,37 | 8,26 | 45,70 | 108 |
| 312 | 24 | 1 | 186 | 85 | 61 | 55 | 82 | 26 | 5,91 | 2,32 | 8,23 | 45,70 | 108 |
| 313 | 20 | 1 | 185 | 75 | 62 | 58 | 90 | 26 | 5,82 | 2,26 | 8,08 | 40,54 | 48 |
| 314 | 20 | 1 | 185 | 75 | 62 | 59 | 90 | 26 | 5,62 | 2,25 | 7,87 | 40,54 | 48 |
| 315 | 31 | 2 | 167 | 50 | 59 | 51 | 72 | 22 | 3,53 | 1,54 | 5,07 | 29,94 | 40 |
| 316 | 31 | 2 | 167 | 50 | 60 | 52 | 72 | 22,5 | 3,77 | 1,63 | 5,4 | 29,94 | 40 |
| 317 | 40 | 1 | 169 | 58 | 56,5 | 51 | 80 | 23 | 3,17 | 1,47 | 4,64 | 34,32 | 34,5 |
| 318 | 40 | 1 | 169 | 58 | 56 | 52 | 80 | 23 | 3,17 | 1,41 | 4,58 | 34,32 | 34,5 |
| 319 | 38 | 2 | 169 | 57 | 59 | 52 | 78 | 21,5 | 3,75 | 1,61 | 5,36 | 33,73 | 92 |
| 320 | 38 | 2 | 169 | 57 | 58 | 52 | 78 | 21,5 | 3,13 | 1,53 | 4,66 | 33,73 | 92 |



**Table: Main Data of PMHS Foot Impact Tests**

| T.-No. | Injuries | Injuries | $v_{imp}$ | $a_{imp}$ | Low. leg az | Sole az | Sole imp. | Sole Fz corr. | Heel az | Heel imp. | Heel Fz corr. |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | Text | AIS ´90 | [km/h] | [g] | [g] | [g] | [Ns] | [kN] | [g] | [Ns] | [kN] |
| 225 | no | 0 | 24,16 | -90,7 | -212,75 | m.v. | m.v. | m.v. | m.v. | m.v. | m.v. |
| 226 | no | 0 | 30,87 | -116,6 | -250 | m.v. | m.v. | m.v. | m.v. | m.v. | m.v. |
| 227 | no | 0 | 24,4 | -40,1 | -231,55 | 264,96 | 22 | 4,95 | 1233,04 | 44 | 15,18 |
| 228 | no | 0 | 24,36 | -46,4 | -250 | 293,22 | 18 | 5,27 | 847,1 | 46 | 10,57 |
| 301 | no | 0 | 40,91 | -69,8 | -239,14 | 694,4 | 21,1 | 14,2 | 1446,9 | 53,8 | 18,6 |
| 302 | CCF | 2 | 42,55 | -69,7 | -280 | 1072,4 | 19,6 | 22,8 | 850,7 | 45,7 | 12 |
| 303 | CCF | 2 | 39 | -161,4 | -117,8 | 1535,9 | 27,6 | 5,5 | 1621 | 43,3 | 8,3 |
| 304 | CF | 2 | 36,11 | -208,4 | -143,9 | 1623,3 | 38,2 | 4,7 | 766,7 | 32 | 12,7 |
| 305 | dist. tibia# | 2 | 36,14 | -138 | -239,7 | 1022,8 | 43,8 | 15,8 | 1096,7 | 54,9 | 13,3 |
| 306 | no | 0 | 29,29 | -208 | -141,2 | 1091,9 | 38 | 19 | 1194,8 | 18,2 | 10,8 |
| 307 | CCF | 2 | 34,93 | -168 | -228,7 | 740,9 | 20,6 | 12,5 | 1356,6 | 42,6 | 16,4 |
| 308 | CCF | 2 | 39,94 | -183,7 | -223 | 969,1 | 94,5 | 19,3 | 228,9 | 40,9 | 11 |
| 309 | no | 0 | 37,46 | -206,9 | -107 | 629,4 | 26,9 | 11,2 | 1603,9 | 67,1 | 20,4 |
| 310 | no | 0 | 39,53 | -188,9 | -237,7 | 822,5 | 24,5 | 12,3 | 1030 | 62,9 | 15,4 |
| 311 | TF | 2 | 40,81 | -168,5 | -215 | 853,1 | 58,4 | 18,4 | 1504,8 | 63,7 | 20,5 |
| 312 | TF | 2 | 43,62 | -151,6 | -159 | 1004,5 | 23,9 | 18,5 | 1169,4 | 61,6 | 20 |
| 313 | CF | 2 | 43,91 | -207 | -242 | 647,8 | 31,5 | 18,2 | 1394,6 | 68,8 | 18,2 |
| 314 | CF | 2 | 45,16 | -206,9 | -280,4 | 1326,4 | 30,2 | 25,1 | 1233,9 | 65,9 | 17,6 |
| 315 | CF | 2 | 36,36 | -164 | -236,7 | 1255,8 | 60,3 | 20,7 | 714,4 | 49,6 | 9,5 |
| 316 | CF | 2 | 42,49 | m.v. | m.v. | m.v. | m.v. | m.v. | m.v. | m.v. | m.v. |
| 317 | CCF | 2 | 30,68 | -104,3 | -237,5 | 1381,2 | 20,9 | 21,5 | 795,1 | 80,7 | 10,7 |
| 318 | KJI | 2 | 25,7 | -114 | -269,6 | 659,8 | 25,8 | 8,4 | 605,8 | 56,6 | 7,7 |
| 319 | no | 0 | 25,18 | -153,2 | -234,7 | 535 | 35,3 | 5,7 | 890,5 | 36,9 | 10,7 |
| 320 | no | 0 | 30,77 | -170,1 | -217,2 | 436,7 | 19 | 7 | 858 | 39,7 | 11,4 |



**Table: Main Data of PMHS Foot Impact Tests**