THE APPLICATION OF STATISTICAL METHODS IN BIOMECHANICAL RESEARCH

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ABSTRACT

As an introduction to the general theme of the IRCOBI conference 1988 this paper describes some biomechanical issues where the application of biometric approaches is necessary. The following problem areas are dealt with: population at risk, random sampling for in-depth studies, injury probability models (probit, logit, Weibull) and establishing of protection criteria of dummies. The general aim of the paper is to increase the awareness of the significance for a more intensive cooperation between biomechanics and biostatistics.

INTRODUCTION

Anyone who counts or measures is faced with the problem of drawing the valid conclusions from his observations and of making comparisons. Without comparisons, the results of his observations are no more than an establishment of magnitude; only comparisons enable the results obtained to be evaluated. The science concerned with the methodological questions of comparison is statistics. The reference point for selecting the appropriate statistical approach is always the definition of the particular problem for which the measurements or counts are performed.

Scientific questions in biomechanics are frequently concerned with the clarification of relationships: The link between mechanical loading during accidents and the injuries, and the relationships between observations made on cadavers and observations made on victims of road traffic accidents are often unclarified. It is not without reason that the relationship between the protection criteria measured on the dummy and tolerance levels for the human being is often questioned.

All observations in biology and medicine are characterized by the phenomenon of variation in the measured values. This applies also to studies of strengths in biomechanics. Biological structures such as tissues, organs and bones react differently to loads and stress as a result of known and unknown random influences. Statistics provides appropriate methods for the analysis of relationships, taking into consideration the spread of the characteristics.

As an introduction to the general theme of the IRCOBI Conference 1988, this paper is intended to present a number of aspects of statistical methods on the basis of a few selected problem areas in order to arouse and/or increase the awareness of the significance of biometric approaches for the solution of biomechanical problems. The paper is subdivided in accordance with Aldman's definition of biomechanical terms /1/.

1. Population at Risk

In 1987 8000 people died in road accidents in the Federal Republic of Germany.

From the point of view of the statistician, the road accident for an individual road user is a rare event. The enormous number of kilometres driven, i.e. the mobility of the population, is often underestimated. Every road user realizes and accepts the risk. Statistically, every car driver must expect to be involved in a serious accident on average every 20 years, to be injured on the road every 150 years and to be killed every 6500 years /2/.

If the number of persons killed are subdivided according to the type of road user, the following statistics are obtained for the Federal Republic of Germany for 1986.
This table of the official accident statistics shows clearly how low the frequencies can be in the individual categories. If only specific problem areas are examined, these figures become even smaller.

One example is the statistical breakdown of 32 rear seat passengers without seat belts in the centre seat position during head-on collisions taken from an accident study. The results are divided into 5 speed ranges and 4 MAIS classes. As a result of this technically justified differentiated breakdown, however, a generalized statement is scarcely possible from these case figures /3/.(see fig. 1)

Table: Persons killed according to the type of road user for one-party accidents, according to the type of accident opponent for accidents between two road users and according to accidents involving more than two parties 1986

Killed as		Drivers and passengers of							
Killed in	Pedestrian	Bicycles	Mopeds	Motor-cycles	Cars	Busses	Heavy Goods Vehicles	Other Vehicles[1] and Pers.	Number of Deaths
One-party accidents	—	92	30	302	1804	4	45	44	2321
Coll. with another road user	1763	670	211	525	2118	9	53	44	5393
With a:									
-Pedestr.	—	2	1	1	2	—	—	—	
-Bicycle	21	11	—	7	5	—	1	—	
-Moped	4	5	—	2	1	—	—	—	
-Motor-cycle	68	18	5	10	19	—	1	1	
-Car	1379	442	160	371	1360	4	11	25	
-Bus	47	14	1	13	66	—	4	—	
-Heavy goods veh.	167	144	36	77	567	5	34	17	
-Other veh. or other person	80	34	6	44	98	—	2	4	
Coll. with more than 2 road user	286	57	18	146	677	2	31	17	1234
All accidents	2049	819	259	973	4599	15	129	105	8948

[1] Tractors are included under "Other Vehicles"

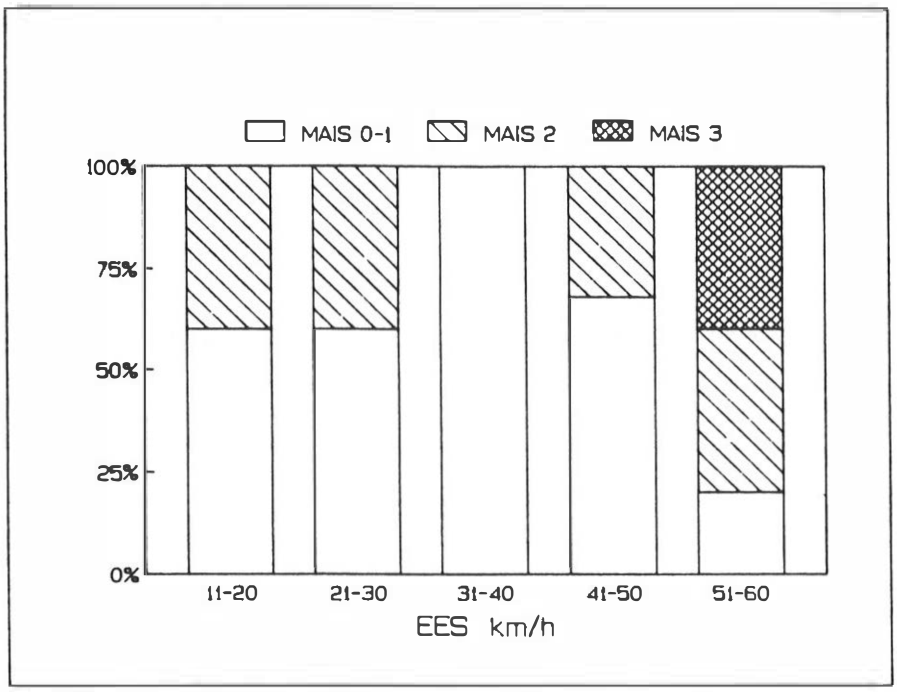

Fig. 1: MAIS breakdown of 32 rear seat passengers not wearing seat belts in the centre seat position during head-on collisions (from /3/)

"A key principle of epidemiology is to define the population at risk. The choice of an appropriate population depends on the use to which the information is to be put" (Bull in /4/). In order to assess passive accident protection, it is necessary to obtain information on persons injured or killed in accidents and persons involved in accidents who were not killed but who were subjected to the same or similar risk exposure. This can be achieved, for example, by studying all the occupants in vehicles in which at least one of them is injured. For the purposes of biomechanics, the population at risk must also be described with regard to age, sex, size and type of road use using appropriate exposure variables. Determination of the population to be protected required a scientific understanding of the problem and, last but not least, political guidelines.

In the analysis of accident data, statistical methods in the form of various types of probability models form a major part of the articles in the journal "Accident, Analysis and Prevention". In 1986, Haight concerned himself with the fundamental questions of risk definition in this journal /5/.

In recent years, "loglinear models" have proven to be a suitable method for analysis of qualitative data from accident studies /6/. During this year's conference, Brühning will be reporting on this method /7/.

The results of in-depth accident studies are of great significance for a wide range of biomechanical questions. But the restriction of this type of data collection to a spatially small survey area does not allow statements to be made, for example, on collision speeds in accidents between pedestrians and cars in the whole of the Federal Republic of Germany.

In one publication /8/, Tarriere pointed out how widely the cumulative frequency functions of the Δv in two in-depth studies in France and the Federal Republic of Germany vary as a result of different survey methods.

Representativity of the data is always necessary if conclusions are to be derived from these data which are valid for all accidents or for a defined sub-population of accidents. Representative conclusions can be derived from samples only if the sampling error can be quantified using random selection. In-depth studies are used primarily for analyzing the relationships between physical, technical and medical parameters. If the results are limited to "if-then" statements, the lack of representativity of local accident investigations must not necessarily be regarded as a limitation from the outset. However, statistical methods for analysing these relationships require a random sample, i.e. the accidents recorded by a survey team must represent a random sample from the population of the accidents in question within the particular survey area. Many in-depth accident studies fail to meet this demand.

For this reason, Hautzinger /9/ has developed a random sampling plan for performing this type of study at the Medizinische Hochschule in Hannover on behalf of the Federal Highway Research Institute (BASt). The population is taken as the total number of accidents involving personal injury reported to the survey team which occur within the survey area during the period of the investigation. In a 2-stage sampling process, the survey intervals are selected and individual accidents within these intervals.

2. Injury Severity, Injury Criteria and Human Tolerance Levels

The determination of human tolerance levels to mechanical loads is the central theme of biomechanics in the stricter sense. The parameters of the load causing the injury are already determined in the definition of the injury criteria using statistical terms: "... a physical parameter which correlates well with a scale of injury severity" (quoted from /1/).

An attempt is thus made to answer the question as to the cause by proving a statistical relationship. These relationships cannot be analyzed on the basis of accident data, since load parameters such as pressure, force, acceleration, area pressure, rigidity, elongation, bending, bending force and bending torque cannot be measured during the accident. In empirical investigations, these relationships are generally analyzed using surrogates for the human being. However, this method of procedure leads to a number of problems:

- The number of tests is generally only small, due to the limited availability of the test bodies (e.g. animals, cadavers, tissue sections, etc.)
- The understanding of biomechanical behaviour is patchy; this is true for both the cell level and the organ level, for bones, parenchymatous organs and vessels. Even more difficult is the assessment of complete parts of the body,such as the thorax or abdomen, which are made up of different organs,each with a different biomechanical behaviour
- The variation in the test results is generally large; age, sex, size, weight and previous damage affect the reactions of biological material. Test configuration, test result recording and data processing are other reasons for the spread of results
- In experimental tests, the loading exposure is often either too small or too excessive to cause a certain level of damage, e.g. to produce a bone fracture. Consequently, the loading measures are censored: In the group with observed fracture as well as in the group without fracture, the data are biased
- The change in the physical variables over time or distance must be described by appropriate parameters, e.g. in the form of a maximum or rate of onset, HIC, etc.
- The relationships discovered must be transformed for the human being or for the population at risk using correction factors or probability functions (transformation of damage criteria into injury criteria as defined in the terminology of /1/).

Let us now continue by examining a number of these problems using examples taken from relevant literature and to describe some statistical methods of solution.

2.1 Examples from Literature

The starting point for determining human tolerances is the assessment of the injury severity. As is known, this can be assessed in a number of ways. One internationally recognized method is scaling using the abbreviated injury scale (AIS) /1/.

Using the "six degrees of severity of this scale, the injury severity is ranked mostly on the criteria of threat to life" (quoted from /10/). In a study by Somers, a logistic regression analysis is used to try to determine the odds of death (as probability that the victim will die divided by the probability that the victim will not die) using various AIS codes. A new trauma score called the probability of death score is thus obtained from these statistical analyses and used in /11/ as a measure for use in planning and evaluating accident prevention.

The reference to these works is intended to indicate that statistical problems occur even during scaling of the injuries; in this respect, the overall assessment of multiple injuries should also be mentioned as a problem.

The following figure from a study by /12/ again shows clearly the wide spread, here on the basis of the relationship between static chest load and deflection.

The curves show a clear distinction between the results for volunteers and those for cadavers; the tests on volunteers in relaxed or tensed mode also show different results. The preparation of the cadavers also has an influence on the thorax response.

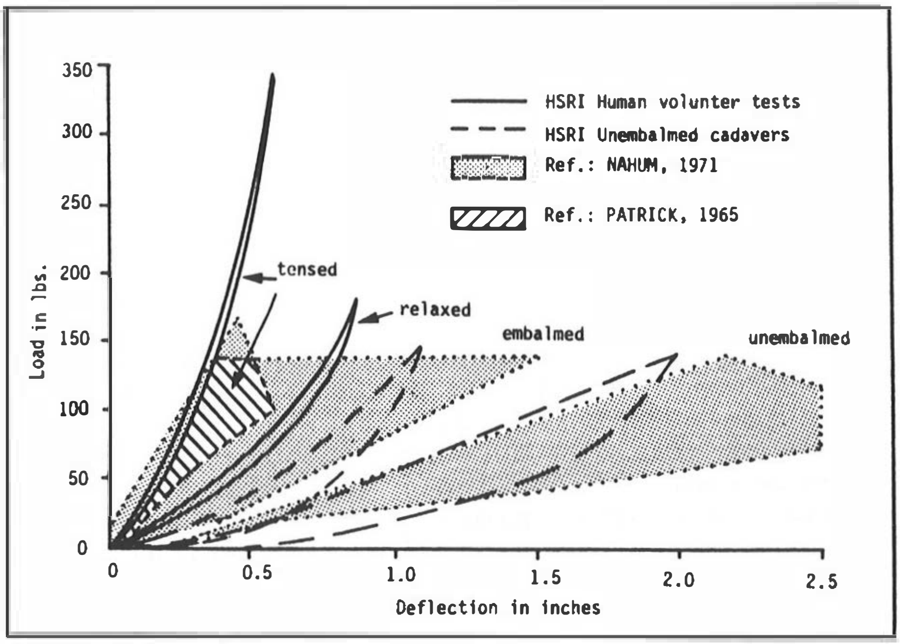

Fig. 2: Comparison of static chest load/deflection curves A-P (from /12/).

Methods of scaling and normalization are used to reduce the variation. The skull bone condition factor /13/ can be considered as an example for this kind of variation reduction. This factor has been obtained by means of factorial component analysis and takes simultaneously into account different parameters to characterize the anthropometry and resistance of the skull (e.g. head mass, mineralization of the skull cap, transversal diameters of the head). As an example of normalization, we can consider the formula of Eppinger /14/, which demonstrates that the number of rib fractures (NF) can be predicted quite well by

$$NF = -18.66 + 0.00955\ NBF + 0.327\ Age \text{ with } NBF = (\text{maximum upper torso belt force}) \text{ times } \left[\frac{165}{\text{mass of the subject}}\right]^{2/3}$$

The work of Eppinger and Marcus /15/ proposes that the mechanical load be characterized by a combination of several physical parameters instead of a single injury criterion: "The severity of injury produced in the thorax is proportional to the amount of specific energy that the thorax must absorb, inversely proportional to the area over which the energy is delivered and the length of time over which this is accomplished". Viano and Lau /16/ favour the concept of a viscous tolerance (deformation velocity and compression sensitive tolerance) as an injury criterion for the thorax. Using probit analysis, they estimate the probability of serious or fatal injuries as a function of the maximum viscous response.

Related literature contains a small number of other works which specify the probability of injury as a function of mechanical load parameters using statistical methods, see for example Ran /17/ and Haffner /18/. A separate report at this conference will be dealing with logit models as an aproach to determining injury predictors in side impacts /19/.

2.2 Statistical Methods

For a more abstract consideration of the above mentioned examples, the following individual steps can be used to develop injury prediction models (see also /20/):

- Study of relation between dependent (injury) and independent (mechanical) variables
- Review of scatter plots
- Development of models using statistical procedures
- Estimation of errors of fit of the data

In the study of statistical methods, a distinction is made between the following types of scale /21, 22/: Qualitative or categorial variables (nominal scale, e.g. sex and ordinal scale, e.g. AIS) and quantitative or metric variables (e.g. interval scale such as temperature, force, pressure). The following statistical methods are among the methods used for analysis and description of the effect of independent variables (x) on one or more dependent variables (y):

- Independent variable from any scale level, dependent variable metric:

    - Linear and non-linear simple regression (with one dependent and one independent variable)
    - Linear and non-linear multiple regression (with one dependent and one vector of independent variables)
    - Multivariate regression (with one vector of dependent and one vector of independent variables)
- Independent variable categorial, dependent variable metric:
    - Univariate and multivariate variance analyses (depending on whether a dependent variable or a vector of variables is used)
- Independent variable mixed categorial/metric, dependent variable metric: With one dependent variable: Covariance analysis
- Independent variable mixed categorial/metric, dependent variable categorial: Logistic regression

This list shows that biometrics is able to provide a number of methods for analyzing relationships. In our opinion the low level of correct application of statistical methods in biomechanical research to date is therefore not due to a lack of suitable methods, but to a frequently inadequate co-operation between the disciplines involved.

The chain of reasoning in these methods can be explained with a simple example as follows:

On N test objects (e.g. cadavers i = 1, N), p variables are measured as influencing factors ($x_1, \ldots, x_p$); a dependent variable y is also observed on N objects. The classic approach to univariate linear regression is then:

$y_i = \beta_0 + \beta_1 x_{i1} + \beta_2 x_{i2} + \ldots. + \beta_p x_{ip} + \varepsilon_i, i = 1, N$
(ε_i as a random error).

In the simple case of a discrete categorial regression, the dependent variable has only 2 outcomes identified by the code 0 or 1 /21/. ($y = 1$ e.g. injury severity AIS ≥ 4; $y = 0$ injury severity AIS < 4). In a linear probability model, the probability (p) that y assumes the value 1 can be estimated by determining the regression coefficients $\beta_0, \beta_1, \ldots \beta_p$, provided the influencing variables $x_1 \ldots x_p$ are known. Using statistical notation, the regression then reads:

$$p = p(x_1 \ldots x_p) = P(y = 1 \mid x_1 \ldots x_p) = \beta_0 + \beta_1 x_1 + \ldots + \beta_p x_p$$

If, instead of p, the regression of Φ^{-1} (p) is performed on the vector of the influencing parameters, whereby Φ^{-1} is the inverse of the standard normal distribution, then the following probit model is obtained:

$$p = P(y = 1 \mid x_1 \ldots x_p) = \Phi(\beta_0 + \beta_1 x_1 + \ldots + \beta_p x_p)$$

In the logit model, the logistic distribution function is used instead of the normal distribution:

$$p = \frac{e^z}{1 + e^z} \qquad \text{where } z = \beta_0 + \beta_1 x_1 + \ldots + \beta_p x_p$$

The "maximum likelihood" method is frequently used to estimate the parameter of a distribution function of a random variable. The value determined as the parameter is that which maximises likelihood L with

$$L(x_1, x_2 \ldots, x_n) = f(x_1) \cdot f(x_2) \cdot \ldots \cdot f(x_n)$$

for constant distributions, where

$x_1, x_2 \ldots, x_n$ = Realizations of n independent, identically distributed random variables $X_1, X_2 \ldots, X_n$
and $f(x_1), f(x_2) \ldots, f(x_n)$ = corresponding density functions/22/.

Ran et al. have applied the Weibull cumulative frequency distribution to define a risk function between exposure data and injuries /17/. This distribution with one variable and three parameters is defined as

$$p(X \leq x) = F(x_1 \alpha, \beta, \gamma) = 1 - e^{-\frac{(x-\gamma)^\beta}{\alpha}}$$

where:
x is a random variable
F is the cumulative frequency distribution
α is the scale parameter > 0
β is the shape parameter > 0 and
γ is the location parameter .

These three parameters permit a wide flexibility when modeling distributions. The parameter β is of special interest:

- β close to 1: The Weibull distribution is close to an exponential distribution with no relation between accumulated loading level and risk of injuries

- $\beta > 1$: The risk of injuries increases with increasing load

The authors /17/ discussed in their IRCOBI 1984 publication many important items, e.g. the treatment of unlikely low observations. If there are physical reasons for a possible "loading which can always be withstood" which must be exceeded before any significant damage is caused, this corresponds to a lower limit for γ equal to that "loading which can be withstood". Therefore for some of the lowest data, the damage probability is assumed to be zero. The authors describe an example of this discarding method. They chose data from Mertz and Weber who studied the maximum rate of chest compression in airbag tests with animals. The response was classified in a 6-interval threat to life scale, see Fig. 3 /17/.

The risk distribution is determined from the particular sample of specimens. Probability regression curves predict the likelihood of injury at any level of loading for the whole population from which the sample is taken. This implies calculation of confidence limits for the various parameters characterising the distribution.

Based on publication /17/, Morgan applied the Weibull distribution to side impact analysis /23/. 49 cadaver tests were re-analysed using the thoracic trauma index TTI as a descriptor for mechanical input and AIS classification for the injuries to and within the thoracic cage.

Figure 4 compares the functional relationships based on a probit analysis and the Weibull approach. For this example, both methods give roughly the same results, but differ for other AIS classes. When employing different fitting methods for determining an injury risk function, this gives rise to the statistical problem of testing the goodness of fit. In related literature /17,23/, the variable of the likelihood function is regarded as a suitable assessment criterion. Literature in the field of biomechanics to date includes no reports on statistical methods for adaptation tests based on the chi^2 distribution.

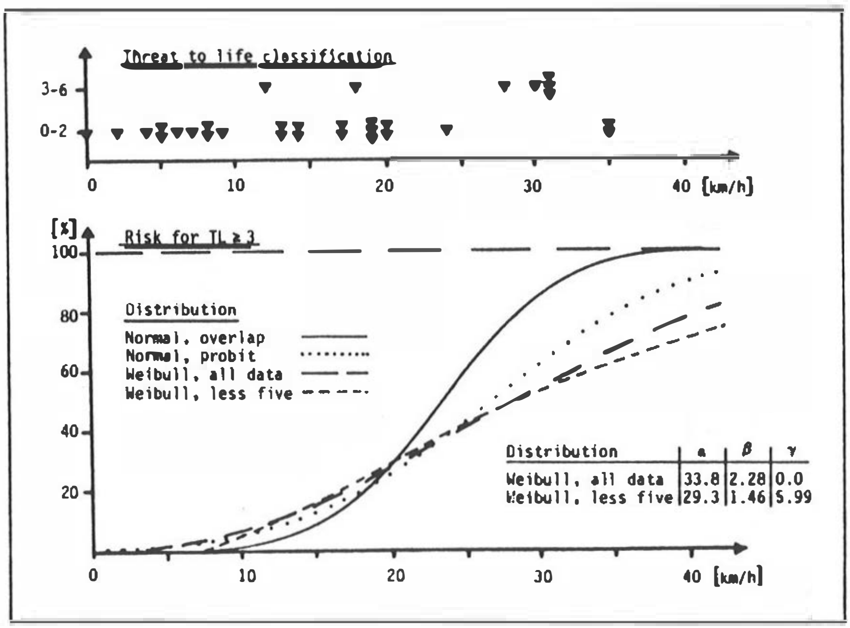

Fig. 3: Risk distributions for chest damage from /17/

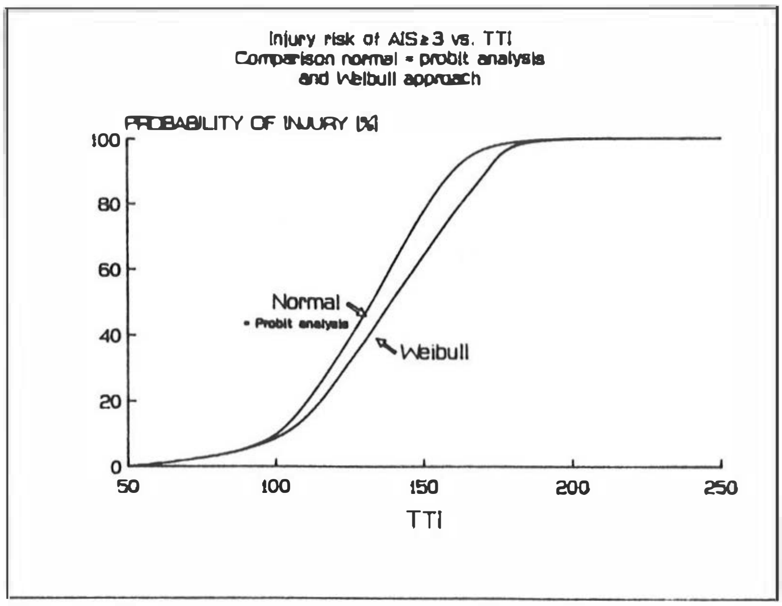

Fig.4: Injury risk of AIS ≥ 3 v. TTI; comparison normal = probit analysis and Weibull approach (from /23/)

Based on these results, the development of lateral injury criteria is described in NHTSA's "Preliminary Regulatory Impact Analysis, New Requirements for Passenger Cars to Meet a Dynamic Side Impact Test, FMVSS 214" /24/. The final TTI formulations is as follows:
$TTI = 1.4\,Age + 0.5\,(rib\,(max) + T12y) \cdot mass / 165$, where rib (max) is either the maximum upper or lower rib acceleration. Confidence levels have been calculated for each of the Weibull functions for 3 different AIS classes. These 95% confidence limits were calculated using the "statistical jackknife method" /25/, see Fig. 5.

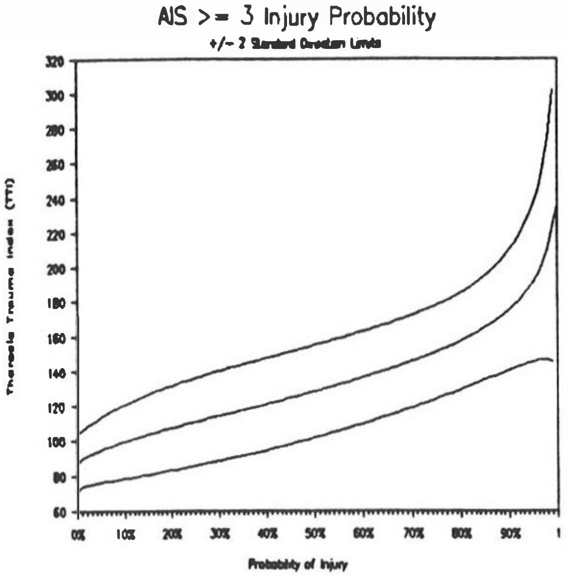

Fig. 5: Injury risk of AIS ≥ 3 v. TTI with 95% confidence limits (from /24/)

At this point it should be mentioned that, depending on the models to be used, certain conditions have to be satisfied which must be taken into consideration at the test planning stage. Statistical advice is therefore necessary at this early stage.

As already mentioned above, such relationships are tested in laboratory experiments using various types of surrogate for the human body. Transformations are therefore subsequently necessary to be able to apply the probability statements discovered to the living human. Very few statistical studies on this problem area have been published to date.

Tolerance limits are, as already mentioned, dependent on the injury severity and on the accident victims observed. Aldman /1/ has presented this situation schematically:

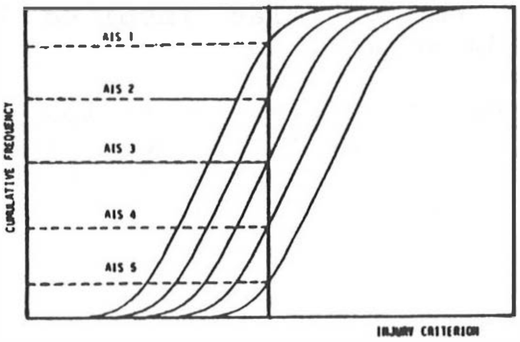

Fig. 6: Hypothetical distribution of tolerance levels in a population (from /1/)

The understanding of these distribution functions for the various organs of the body, differentiated according to types of injury, is patchy. Specification of limit values - for example, in regulations - generally requires this type of knowledge in order to be able to specify the probabilities of accepted injuries or of various classes of injury severity in a statistically satisfactory manner. Here again, statistical methods - such as discriminance analysis - can be applied. Nor has it been satisfactorily proven that the expected values of such random variables increase with the AIS classes from slightly to fatally injured. It is also conceivable that the type of injury criterion depends on the AIS class.

3. Protection Criteria, Dummies

According to the definition in /1/, protection criteria are those parameters recorded from dummies which correspond to injury criteria for living human bodies. Assignment of these variables also involves statistical methods of relationship analysis - as already described in section 2.

The transfer function of cadaver data to dummy data can be determined under the same test conditions. Within the framework of the Joint Biomechanical Research Project KOB, an attempt was made in this direction by reconstructing real accidents with cadavers and test dummies. In view of the (cost-related) small number of case figures for the reconstructed accidents, the results obtained were compared in the form of individual case presentations /8, 26/.

At the 8th ESV Conference, Overdiek et al. /27/ presented another possible method which is described briefly below:

- Starting from an analysis of the accident data, accident characteristics (UKG) for various types of collision are determined. These characteristics describe the severity of the accidents of special type in terms of velocities, masses and impact directions of the vehicles involved in the accident (e.g. Δv for frontal impacts)

- For various categories of the collision-typical accident characteristic (UKG), the empirical OAIS distribution of the injuries to the head, chest and pelvis is drawn up and a function OAIS = f(UKG) determined. In /27/, 3 different approaches are proposed for determination of this function: Non-weighted mean value of the OAIS values in each UKG class, cost-weighted means of the OAIS values and adaptation of a binomial distribution of the OAIS values. For all three approaches, a "representative" injury severity can be calculated

- In crash tests with the same input parameters (UKG), the dummy loading values for head, chest and pelvis (e.g. HIC, 3 ms values) are determined empirically and estimated for all the classes of the UKG observed using a computer simulation. These dummy values are combined to form a load index BI*:

$$BI^* = 1 - \frac{1}{BI} \quad \text{where } BI = \alpha\,\text{Head} \cdot \frac{HIC_0}{HIC_0 - HIC}$$

$$+ \alpha\,\text{chest} \cdot \frac{a_{chest_0}}{a_{chest_0} - a_{chest}} + \alpha\,\text{pelvis} \cdot \frac{a_{pel_0}}{a_{pel_0} - a_{pel}}$$

with HIC_0, a_{chest_0} and a_{pel_0} as "limit values" and the weight factors α head, α chest and α pelvis.

These six constants are determined for those accident characteristic data where the "representative" degree of OAIS shows fatal injuries, see Fig. 7. BI* is estimated as f(UKG)

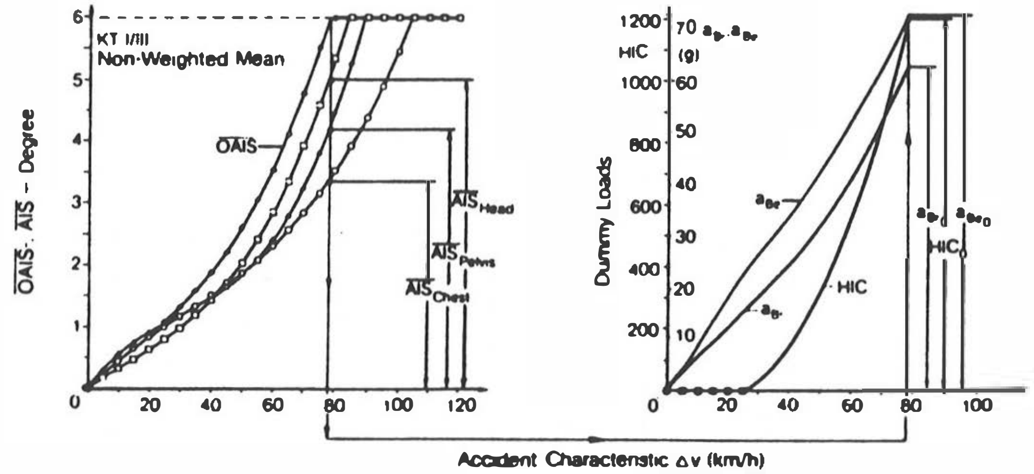

Fig. 7: OAIS, AIS degree and dummy loads as a function of the accidents characteristics Δv (from /27/)

- In the final step, the OAIS values are compared with load parameters of the BI* using the accident characteristic, see next figure

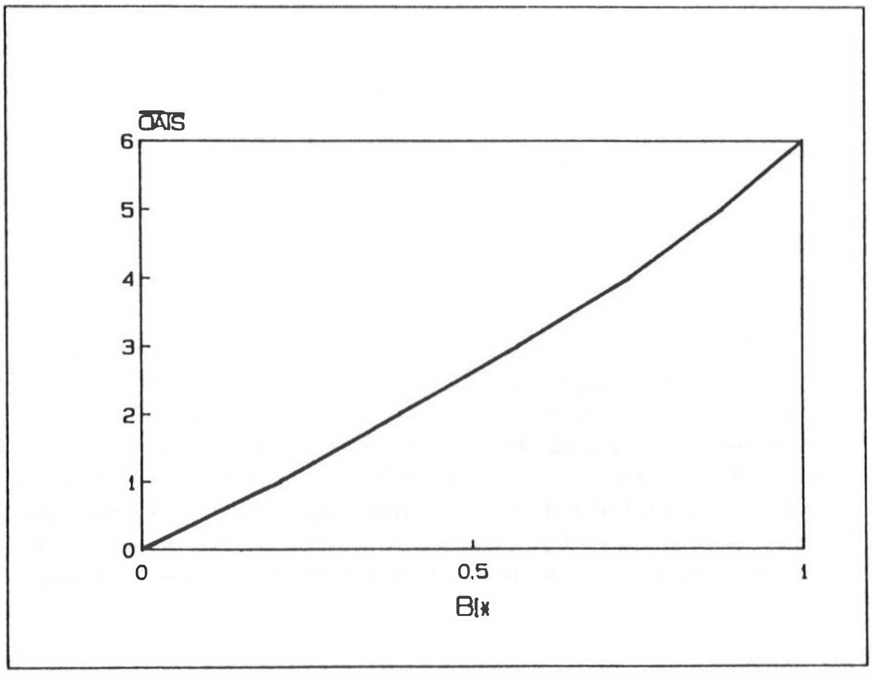

Fig. 8: Occupant injury OAIS as a function of the resulting dummy load BI* (from /27/)

Similarly, Langwieder et al. have determined a transfer function between injury severity and dummy loads /28/. How wide the spread is can be seen from the following illustration which is taken from the above-mentioned work. For the confidence interval 5% to 95%, HIC values between 200 and 1300 can be assumed for injury severity AIS 3.

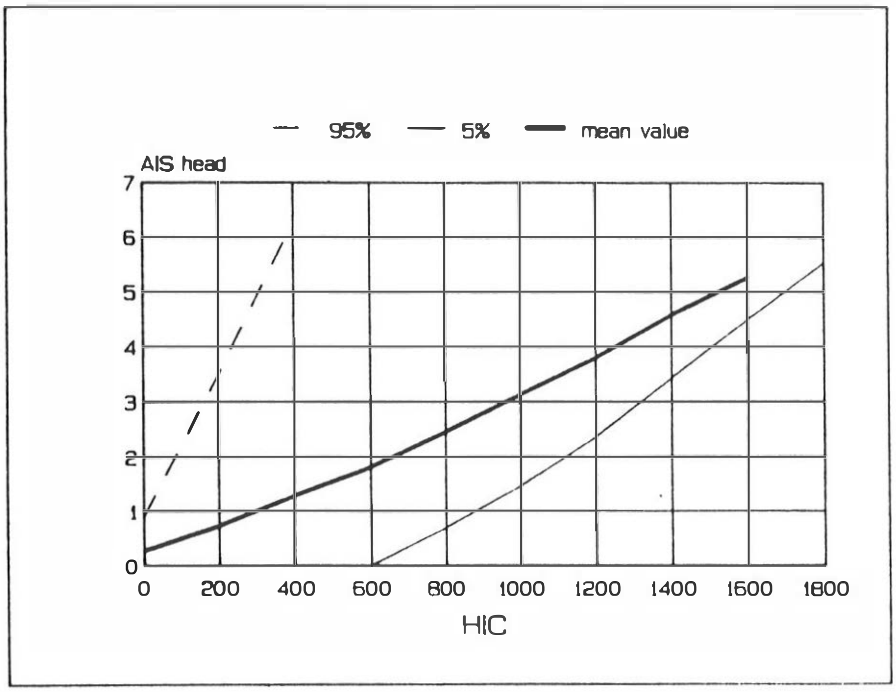

Fig. 9: Dummy loading and (head) injury severity relationship in frontal car collision (from /28/)

Statistical problems in the method described which in our opinion still require further analysis are primarily the determination of the function OAIS = f(UKG). Using categorial regression, suitable assignment methods must be determined which take into account the distribution of the random variables OAIS in each class of the UKG. A further problem which still has to be statistically solved is the development of a suitable index for summarizing the dummy loads of various parts of the body into a suitable coefficient. The determination of the relationship between this index and the accident characteristic also requires the use of statistical methods, whereby sufficient information on the distribution of the index values in each class of the accident characteristic must be available. Finally, both random variables (OAIS and load index) must be correlated with one another. When applying all these steps, sensitivity analyses must be used to determine the effects of various model assumptions for these different problem areas.

In order to describe the relationship between the injury severity of a car occupant and dummy load values, Meyers /29/ applied logit analysis based on discriminance analytical methods. An assignment rule d is estimated on the basis of selected characteristics of accidents (vector x) which assigns the vectors x to one of the two classes g_1 (AIS $\leq$ 2) and g_2 (AIS > 2). In a second step, the vectors of a standardized laboratory experiment are then inserted into the assignment rule, whereby the dummy load values can be assigned to a hypothetical injury severity. Using a logit analysis, the dummy load is then determined at which the number of the serious injuries does not exceed a given percentage. In his work, Meyers examined various mathematical aspects of the discriminance analytical methodology. An empirical application of the proposed method has not yet been implemented.

Reference points for the spread of the dummy test values can be obtained from calibration tests /30, 31/. A variance of 5% to 6% is considered optimal, values between 5% and 10% are regarded as usable and spreads of more than 10% are considered unsatisfactory. These values are based on repetitive tests on the same dummy. The same calibration tests with different dummies naturally result in larger variances, whereby values between 10% and 15% are regarded as acceptable and usable.

In full-scale vehicle tests, differing dummy test values can be obtained under the same test conditions. Between vehicles of the same type, production and measuring tolerances can result in differences - e.g. in the position of the H point - which have a major influence on the kinematics of and load on the test dummy. Färber will discuss this problem in a separate paper /32/ at this conference.

CONCLUSIONS

A number of problems are still unsolved in biomechanical research which require the use of statistical approaches and methods. Even the collection and analysis of accident data as the basis for purposeful research work in developing passive protection systems require careful test planning in order to ensure that the application of statistical methods can be based on clearly defined random variables. Greater consideration must also be given to a number of biometric approaches in the future in order to be able to draw scientifically proven conclusions in response to the question of human tolerance limits, despite the variability in the reaction of human tissue to physical loads and the generally unavoidable small number of tests. The need to employ statistical methods applies also to the use of test dummies for the assessment of efficient passive protection measures.

The aim of this introductory paper was to increase the awareness of the necessity for a more intensive contact between biomechanics and statistics.

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