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RIB CHARACTERIZATION OF HUMAN SUBJECTS*

by

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INTRODUCTION

Over the past years, a large number of tests with cadavers have been performed, including real-world accident reconstructions. Unfortunately, where injury levels are concerned, the differences observed between those occurring in cadaver tests and those sustained by the real world accident victims - as well as the differences in injury levels from one cadaver test to the next - make it difficult to interpret these tests and hence limit the conclusions that might be drawn-up from these experimental procedures: that is particularly true for thoracic resistance.

The purpose of this communication is to supply a more objective basis for the evaluation of inter-individual variations, and thereby to pinpoint those specific parameters to impact that can be correlated with human thoracic tolerance to impact.

Therefore, this paper is written as follows: firstly analysis of thoracic bone characteristics, secondly a factorial analysis of bone characterization data which allowed to define a bone resistance index and, thirdly, the control of the validity of this index from side impact results.

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I. ANALYSIS OF THORACIC BONE CHARACTERISTICS

I.1. Methods Available

The first experiments conducted with recently deceased, unembalmed cadavers did not yield quantitative evaluations of the skeletal resistance peculiar to the individual subjects tested. However, since age did not emerge as a sufficient criterion to account for these differences, the need was soon perceived for "characterizing" the individual resistances of the subjects. For this purpose, various techniques were available, the object of all of which was to evaluate the subjects' degree of osteoporosis on the basis of measurements of isolated bone fragments. Three major test groups, described below, were known, as follows:

- Geometrical (or radiological) analysis of a section either of the ribs or of a long bone (femur, radius, etc.) (1, 2). It is a known fact that the proportion of cortical bone decreased with age, and that the osteoporosic degree is defined by the loss of cortical bone matter.
- Measurement of mineral salts via the fragment calcination process; this provides evidence of loss of mineral matter responsible for bone resistance.
- Mechanical tests (3) which assimilate bone with a standard material and thereby enable calculation of resistance modules. What is mainly involved here was the Granik and Stein test, which is a simple bending test performed between supports.

Each of these tests individually yields some idea of the local resistance of the bone tested, but before describing the tests used by us, we shall "criticize" the methods available and, above all else, we shall consider the ways in which each measurement can satisfy our concern with classifying the subjects in terms of thoracic resistance.

1. Geometrical measurements

The detailed features of the methods employed are taken from the Walsh report (1).

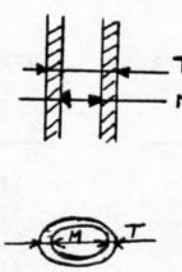
a. Radiology

Lumbar X-rays enable detection of possibly existing osteoporosis in a subject, but, in addition to the fact that it valid only for extremely osteoporotic subjects, this method has three disadvantages:

- It is difficult to "quantify" the degree of osteoporosis - which is not measurable in the physical sense - by such a technique.
- The findings do not reveal possible bone efficiency (osteopenia), even in the absence of osteoporosis.
- No constant correlation exists <u>a priori</u> between lumbar and thoracic osteoporosis.

This disadvantages emerge if we consider the X-rays of the metacarpus (2) and of the femur, the difference being that a geometrical measurement can be calculated: the percentage of cortical bone, or PCA, which is defined (see drawing below) as follows:

$$PCA = 100(T^2 - M^2)/T^2$$



The correlation considered makes it possible, on the basis of the X-ray image, to evaluate the loss of cortical bone in relation to a normal population. However, it should be noted that there is considerable inaccuracy involved in this measurement, and that it is not truly efficacious unless bone loss has been considerable. However, measurements of the femur can be valuable in so far as we know that the characteristics of the long bones (especially those of the lower limbs) are affected by the individuals' way of life; such a test might therefore constitute an acceptable indicator*.

b. Direct measurement

Since the tests were performed with cadavers, it was clearly simpler to take measurements of bone sections collected during autopsies.

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* It should be noted that currently ongoing investigations (4) have shown that the tomodensitometry (scanner) of long bones enables a much better definition of the degree of osteoporosis than does the standard X-ray process. However, this technique is unwieldy and is largely incompatible with the constraints of present day testing conditions.

Measurement of the characteristic dimensions of the section involved is then direct; <u>in cases involving</u> the occurrence of thoracic impact, rib sections are analyzed. Measurements of the radius are significant only in the case of an evaluation of the subject's condition prior to testing, since an evaluation performed on the basis of rib tests would rule out the testing of the rib cage that undergoes stress during impact.

Although analysis of rib sections does supply an evaluation of the degree of thoracic osteoporosis, by its very nature this test does not yield an evaluation of the osteopenia. In addition, the problem of geometrical measurements resides in their great variability linked to the localization of the material collected. The table below illustrates this fact. The PCA will be seen to vary abruptly, even for sections located quite close together.

Subject No.	Distance between sections (cm)*	Minimum $\frac{s}{S}$	Maximum $\frac{s}{S}$	Relative distance in %
169	1	.445	.471	5
170	1	.458	.523	14
136.1	3	.487	.613	26
135.1	3	.317	.516	30
178	1	.369	.503	36
157.1	4	.366	.514	40

*Distance between two sections spaced a maximum of 4 cm apart, such that the relative distance is maximum.

The measurements proposed by Epker and Frost (5), which are derived from rib section measurements, will vary to the same extent, whether we use the parabolic index:

$$PI = \frac{(AT-Am) \times Am}{AT^2}$$

or the normalized parabolic index K:

$$K = PI \times [4(\frac{265 + \gamma}{165})] \qquad \gamma = \text{(absolute value of age - 20) in years}$$

All the foregoing does not lead to excluding these tests: rather, it leads to the extremely rigorous fixing of their protocol, especially if they constitute the only evaluation that is used of the bone condition.

2. Mineralization

This report will not deal with the Laboratory techniques designed to accurately pinpoint the quantities of the various mineral salts contained in bone (phosphore, calcium, etc.). Rather, the problem involved the obtaining of an evaluation of the proportion of mineral constituents in the rib, said constituents being responsible for the bone's mechanical behaviour. Rib fragment calcination then supplies the data required, since the post-calcination content of the ash is mainly mineral salts. The methods were available, as follows:

- direct calcination of fresh rib fragments
- drying of ribs, followed by calcination of fragments

The first method takes into account all the bone constituents, and enables correlation between the ash mass with the fresh mass, which is additionally constituted by mineral salts, fats, water, etc. However, in the second method, preliminary drying eliminates the free water contained in the compact bone, or even that contained in the hydroxides. We believe that the second method does not enable a true evaluation of the proportion of mineral salts in relation to the fresh mass, and that the first method is preferable to it.

3. Mechanical Tests

By analogy with the methods of investigation of materials a large number of tests of principle were possible. The most common ones are the simple traction test, the torsion test, the bending test, etc. But since bone is a heterogeneous, anisotropic, visco-elastic, etc. substance, its characteristics cannot be summarized in a few simple coefficients; in particular, there is no <u>one</u> Young's module of bone, and the orientation problem must be considered. It is not easy to design holding jaws that would enable the fixing of a rig for the purpose of a traction - or torsion test. In addition, if we wish to ascertain a rib's overall mechanical characteristics, it is not desirable to analyze only a cortical bone fragment; these reasons account for the importance of the Granik and Stein test (3) which is a simple bending test performed between supports. In fact, by ascertaining the geometrical characteristics of the fractured section, this test makes it possible to calculate the normal fracture strength and Young's longitudinal module.

It will be seen below that we introduced an additional shearing test, or more specifically a crushing test, which provides data on the energy required for fracture.

Dynamic Tests

The purpose of the tests devoted to characterization is to evaluate the thoracic resistance of an individual undergoing impact, either direct impact or impact restricted by a seat belt; it is therefore tempting to perform dynamic testing of rib fragments, for example, by dropping an impactor onto a rib fragment. The impactor's deceleration values thus make it possible to calculate the fracture strain and the associated energy. A large number of tests were performed on subjects.

Two major disadvantages emerged, as follows:

- the complexity of the test,
- the low degree of accuracy of the results.

The fact is that these are not simple tests that can be performed on just any traction-compression machine; rather, they are tests that require magnetic recording of the acceleration curves, since a UV recorder is unsuitable for the briefness of the impacts. In addition, the processing of the data necessarily requires a considerable amount of time. The accuracy of the results is low because the impactor's propulsion speed is calculated, not measured; naturally, direct measurement of velocity is possible, but it further burdens the testing process. Last but not least, for the impactor drop, guiding is performed by means of friction, which reduces the repeatability of the tests. Moreover, the testing technique rules out analysis of fractured rib section, which splits under impact. In any event, the findings obtained with this test are compatible with those yielded by static tests, and they shed but scant additional light. We therefore believe that, barring the development of a highly sophisticated apparatus (instruments and measuring device), they can advantageously be replaced by static tests without incurring any significant loss of data.

Other Methods

For the record, let us note hardness measurements, density measurements, etc. Every test can yield a certain amount of information on bone characteristics, and a sizable number of research teams are concerned with this matter from the medical angle (orthopaedics, artificial limbs, etc.). It is not our purpose to find out these characteristics for themselves alone; rather, we aim to evaluate the extent of inter-individual differences.

1.2. Description of Characterization Tests Performed in the Scope of this Investigation

During the autopsy process, the 4th, 5th, and 6th ribs are collected; the left- and right 4th ribs are used for a mineralization test, while the 5th and 6th are used for bending and shearing tests.

a. Mineralization

Four fragments from the 4th ribs are sectioned into left and right anterior and posterior parts. The fresh rib fragment is measured - length, width and thickness - and weighed. The fragments are then calcinated in a crucible for 15' under a Bunson-burner flame. The ashes thus produced are weighed. For each fragment, the following ratios are calculated:

C/M: ash mass/fresh mass (CM)*

C/L: ash mass/unit of length (CL)

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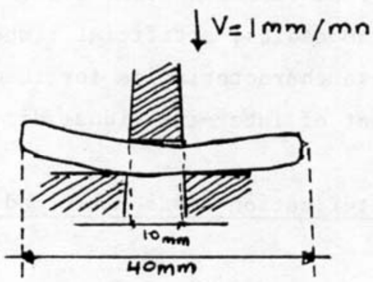
* For each measurement (C/M in the present instance), we define a symbol (CM in the present instance) which will thereafter be used in the analysis.

We will subsequently investigate the existing correlations between age and the various bone-resistance parameters. At present writing, it should be noted that the values of all these parameters decrease with age, although with extremely high scatter.

b. Shearing Test

The sample-collection technique is the same as above. A 4-centimeter rib fragment is placed between two supports spaced 1.2 cm apart, and is crushed by means of a flat-surfaced die with cutting edges, one cm wide (see drawing below). This test achieves double shearing of the rib along two sections. This shearing process also entails actual crushing of the rib fragment.



The strain/deformation curve is recorded; the figure shows an example of a recording; linear strain (elastic part of the rib) increases, followed by a deformation accompanied by quasi-constant strain.

The increased strain at the end of the test corresponds to the crushing of the supported fragment. The parameters used for this investigation are as follows:

FK: maximum strain recorded before fracture,

UK: absorbed energy, i.e., area under the strain-deformation curve.

Departing from frequently-used procedure, we did not consider voluminous energy (i.e., UK/rib surface area x one cm). This was because of our desire to preclude all a-dimensioning of measurements prior to analysis.

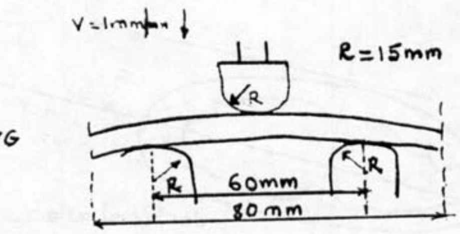
c. Bending Test

The bending test is the same type as the shearing test, but the fragment-support conditions are different (see drawing below). As in the shearing test, the strain/deformation curve is recorded. The following parameters are noted:

FF: maximum strain before fracture

LA: initial slope of the strain/deformation curve (elastic area).

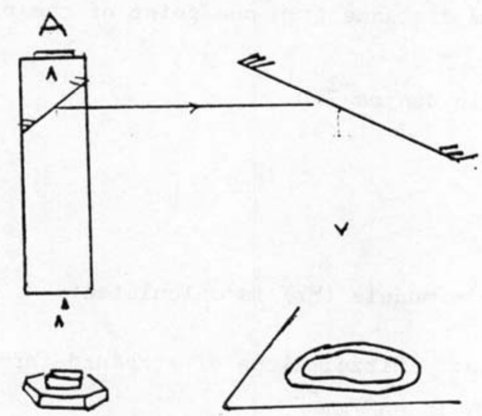
BENDING TEST



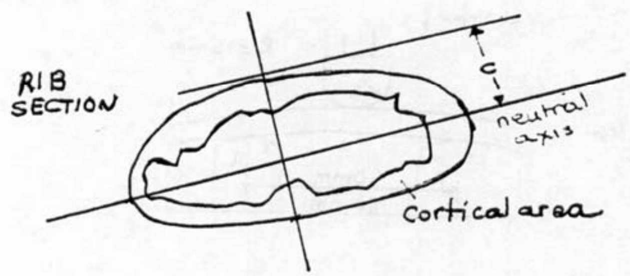
In addition, at a distance of 1 cm on either side of the fractured section, two rib sections are analyzed for the purpose of calculating the normal fracture strain and Young's module.

The section analyzed is cleaned and its image is then enlarged 15 times by means of a special optic device (see sketch below).

OPTICAL DEVICE



On the enlarged sketch, all that is seen is the approximate representation of the cortical bone section. This section is pointed on a digitalizing table (the hereafter figure shows an example of a section after digitalization). Next, a computer program enables calculation of the cortical bonesurface area of the moments of inertia in relation to various axes. The one considered by us is the moment of inertia in relation to the axis of minimum inertia which corresponds approximately to the moment of inertia in relation to the neutral fiber.



It is then possible to calculate the normal maximum strain on breaking point SG (σ).

$= \frac{Mc}{I/c}$ with MC: moment of bending in a straight line from the load

$Mc = FF \times \frac{L}{4}$ (L = 60 mm)

I = moment of inertia of fractured section

C = maximum distance from one point of the rib secton to the neutral fiber

$SG = \frac{60}{4} \times \frac{FFxC}{I}$ in daN mm^{-2}

FF in daN

C in mm

I in mm^4

Similarly, Young's module (MY) is calculated:

$MY = \frac{LAxL^3}{48xI}$ LA: initial slope of strain/deformation curve in daN/mm^{-1}

MY in daN/mm^{-2}

For both the bending test and the shearing test, as well as for the mineralization test, intermediate results are available but only 8 of the most significant parameters will be analyzed. These are as follows:

CM: rate of mineralization (average for four fragments)

CL: ash mass/unit of length (average for four fragments)

FK: maximum shearing strain

WK: shearing energy

SG: maximum bending stress

MY: Young's module

CL, FK, UK, FF and LA are what we call "raw" data, i.e., they are not related to a percentage, nor are they a-dimensioned. The greater the rib volume, the higher these values will be.

CM, SG and MY are values of "a-dimensioned" variables, with SG and MY being indicator's of the quality of the cortical bone's constituent matter.

1.3 Influence of Age on Bone Characteristics

In characteristics with increasing age, and, on the other hand, an extremely broad scatter of results; for a given age, the values of a given parameter can vary from single to double. These two facts emerge if we consider the correlation coefficient between age and the various bone-stress parameters (for 100 individuals):

	CM	CL	FF	MY	SG	FF	UK	LA
AG	-.60	-.44	-.52	-.28	-.52	-.48	-.52	-.41

(The number of subjects is shown between parentheses).

As noted earlier, all the characteristics decreased as age increased ($\rho < 0$), with Young's module MY revealing itself to be the least related to age, while, on the contrary, CM - the percentage of mineral salts - proved to be the most closely "linked" to age. Two known facts do emerge:

- the percentage of cortical bone (which is in fact measured by CM) clearly decreases with age, corresponding to physiological osteoporosis.

- Cortical bone quality (of which MY is a good indicator) does not actually depend on age; this is tantamount to stating, with a certain amount of subtle distinction involved, that bone becomes osteoporotic with age, but without this necessarily involving the occurrence of osteomalacia (6).

The low values of the correlation coefficients illustrate the well-known fact of the scatter of biological measurements. For one thing, costal characteristics vary with the subjects' ages, and, for another thing, a large number of parameters influence these characteristics. Among others, let us note the following:

- anthropometry: a large-sized individual can be expected to possess thick ribs. This point will be investigated in more thorough details in the next section.

- way of life: it is a known fact that bone is not an inert substance and that it is influenced by the mechanical stresses to which it is exposed. A largely sedentary way of life predisposes individuals to a light bone structure; on the other hand, a highly active pattern of living, involving the practice of sports, can connote thicker bones.

Correlations between the various parameters

The correlation between matrix below (table) highlights two facts:

- all the parameters are correlated positively; as a whole, they express the same tendency; this should be correlated with the decrease in these values as age increases.

- If, for certain pairs fo variables, the correlation coefficient is higher than 0.7 (CL/FF or UK/FK), in certain cases, it can be quite low or even be close to zero (CL/MY). These parameters cannot be said to express exactly the same effect; in other words, it is unjustified to summarize these eight parameters in a single one selected from among the eight.

Table

	CM	CL	FF	MY	SG	FK	UK	LA
CM	1.							
CL	.54	1.						
FF	.49	.70	1.					
MY	.44	.02	.29	1.				
SG	.51	.30	.62	.66	1.			
FK	.50	.50	.51	.12	.19	1.		
UK	.43	.61	.62	.15	.36	.72	1.	
LA	.39	.58	.73	.39	.44	.29	.40	1.

In the following section, the use of a factorial analysis will enable simultaneous visual inspection of the principal correlations between the various parameters.

II. FACTORIAL ANALYSIS OF BONE CHARACTERIZATION DATA

In the preceding part, it was seen that although they express an identical tendency, the test findings for the various ribs are relatively uncorrelated with one another and are poorly correlated with age.

By analogy with other disciplines (biology, economic science, etc.) in which this same type of phenomenon has occurred, we employed factorial analysis. The use of this method enables us to summarize the principal tendencies contained in a data table and to thus define the indicators that best adjust these tendencies.

The processing programs used were published in "Techniques de la description statistique", by Lebart, Morineau and Tabard (7) and were taken from the computer tape of the CESIA*.

II.1. General Remarks Concerning Factorial Analysis

The purpose of this section is not to provide an exhaustive description of the method; rather, it is to review the principles of its functioning and the results that can be anticipated therefrom. For more complete details, the reader is referred to the books listed in the references (7, 9 and 9), which further contain very detailed bibliographies. (Note: the text below concerns analysis in normed principal components).

The data are in the form of a measurement table whose columns represent the variables (CL, CM, etc.), while the lines represent the individuals the values of whose variables are known. In the present instance, we have 8 bone-condition variables and 121 subjects. This 8 x 121 table is difficult

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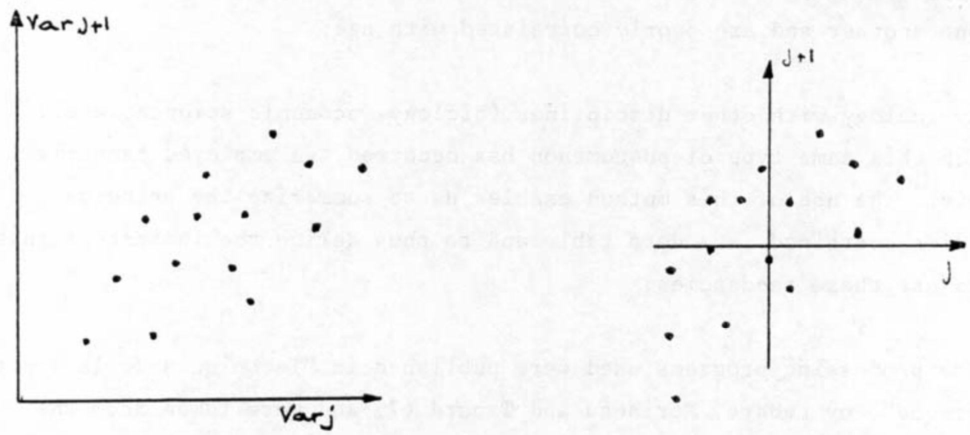
to synthesized factorial analysis makes it possible to extract the essentials from it. Geometrically, the 121 points can be represented in an 8-dimensional space. The group of points thus defined forms a "cluster" of points that we are going to try to determine. To this end, we will perform a data transformation designed to consider not the raw data but the centered data (figure below), i.e, data for which the origin of the space axes is located in the center of gravity of the cluster of points.



If r_{ij} is the coordinate of the individual "i" in accordance with the variable "j", this transformation allows us to analyze the table of general terms $x_{ij} = r_{ij} - \bar{r}_j$, $\bar{r}_j$ being the mean of the variable "j" for all the individuals. The quadratic distance between two individuals k and k' is written as follows:

$$d^2(k,k') = \sum_{j=1}^{8} (r_{kj} - r_{k'j})^2$$

Not all the variables considered are variations of identical amplitude. CL varies from 0.12 to 0.49, while FF varies from 42 N to 570 N. So that each variable will play an identical role, we use the analysis of normed principal components, correcting the scales by adoption of the distance:

$$d^2(k,k') = \sum_{j=1}^{8} \cdot \frac{r_{kj}-r_{k'j}}{s_j \cdot \sqrt{n}}$$

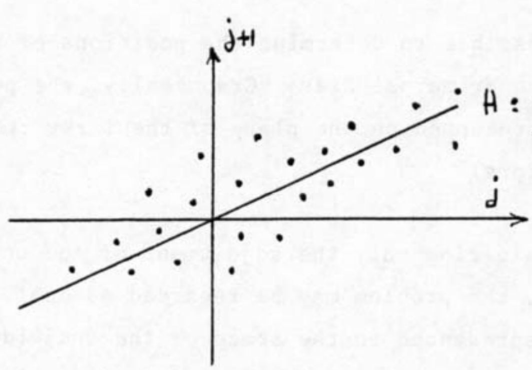
with sj: standard deviation of the variable j

and n: sample size (121 in this case).

This is tantamount to performing the analysis of a 8 x 121 table of general terms:

$$x_{ij} = \frac{r_{ij}-r_j}{s_j \cdot \sqrt{n}}$$

The analysis will then consist in calculating the principal axes of the point-cluster; this involves adjusting the point-cluster via a sub-space to one dimension, then to two dimensions, etc. This operation reduces to a minimum the sum of the distances of the squares of the distances between all the pairs of individuals (see below).



The principal axes will constitute a new system of description of the data, the latter being classified in decreasing order, the first representing the direction of the largest extension of the cluster, and continuing in the same way for the following ones.

In order to calculate the coordinates of the individuals along these axes, we diagonalize the matrix C = X'X (product of the matrix of the data of the general term x_{ij} (see above) by its transpose. The general term of C is written:

$C_{jj'} = x_{ij}x_{ij'}$ or rather

$$C_{jj'} = \frac{1}{n} \sum_{i=1}^{121} (r_{ij}-\bar{r}_j)(r_{ij'}-\bar{r}_j)/s_j s_{j'}$$

In other words, it is the coefficient of empiric correlation between the two variables "j" and "j'". Matrix C is hence the matrix of correlation of the initial data. The principal axes will be defined by eigen vectors associated with the eigen values of matrix C, calculated after diagonalization.

The abscissa of an individual-point "i" on a principal axis (or a factorial axis) is then written as follows:

$$v_i = \sum_{j=1}^{8} u_{\alpha j} x_{ij} = \sum_{j=1}^{8} u_{\alpha j} \frac{r_{ij}-\bar{r}_j}{s_j \sqrt{n}}$$

with $u_{\alpha j}$ as the component of the eigen vector α on the variable "j".

The foregoing makes it possible to determine the positions of the individuals in the space of the principal axes. Graphically, the positions of the 121 subjects can be represented on the plane of the first two factors (the two most explanatory factors).

So far, we have been considering only the adjustment of the point-cluster in the space of the variables, the problem may be regarded as dual, by considering variable-points represented in the space of the individuals. This leads us to diagonalize not the matrix of correlation C* = X'X but XX'. We can show that the eigen values of C and C* are equal and that the eigen vectors associated with an eigen value are proportional.

We then represent the variable-points in a sub-space constituted by the first eigen values, for example axes 1 and 2. We show that all the variable-points are on a sphere of radius 1 centered at the origin of the axes.

Two strongly-correlated variables are quite close together in space (conversely, quite far distant from each other if they are connected by an inverse relationship [$\rho \neq -1$]).

Two orthogonal (decorrelated) variables are at mean distances and the directions of their guide vectors form a right angle in space.

Examination of the positions of the variables on the factorial planes will therefore show-up the correlations between variables and will thus assign a meaning <u>a posteriori</u> to the factorial axes. The respective positions of the variables allow us to assign names to the axes (e.g., axis of increasing bone resistance, etc.). In this space, the abscissa of the variable points is the components of the vector $u_\alpha \cdot \sqrt{\lambda_\alpha}$ with the eigen vector "u_α" defined above, λ_α an associated eigen value. This abscissa is none other than the coefficient of empiric correlation between the variable considered and the artificial variable constituted by the axis, which is a linear combination of the initial variables. This artificial variable will then constitute a representative indicator not of one variable but of all the initial variables (8 in the present case).

In addition, it is possible to calculate the position on the factorial axes of variables or of individuals that are not taken into account in the analysis and that do not participate in the definition of the axes. In the present case, all the individuals available have participated in the analysis, but an additional, sheerly illustrative variable has been projected on the axes: this is age.

II.2. Findings Obtained Through Factorial Analysis

An analysis involving normed principal components was performed of a sample of 121 subjects concerning whom the following 8 bone-condition parameters, described in teh first part of this report, were known: CM, CL, FF, MY, SG, FK, UK and LA.

These 121 subjects included the following:

a. 98 subjects who had been exposed to test impacts of all kinds (frontal, lateral, etc.)

b. 15 subjects taken from a population of individuals analogous with Group A, but who had not been exposed to impacts.

c. 8 individuals who had not been exposed to impacts but who had met sudden death without having undergone protracted hospital stays.

In addition to the correlation matrix described above, the program supplies the following:

- an elementary description of the data (mean standard deviation).
- list of eigen values and their percentage of inertia
- the projection on planar graphs of the variable-points and individual-points in the plane of the first two factorial axes (and, if necessary, in the planes of axes 3 and 4 or 5 and 6).
- The coordinates of the individual-points and variable-points on the factorial axes.

Elementary Description of the Data

Variable	Mean	Standard deviation	Unit
CM	30.6	6.7	%
CL	.24	.07	$g.cm^{-1}$
FF	195	111	N
MY	605	270	$daN.mm^{-2}$
SG	9.2	6.0	$daN.mm^{-2}$
FK	780	457	N
UK	2.24	1.36	J
LA	165	95	$N.mm^{-1}$

Eigen values

The sum of eigen values is equal to 8

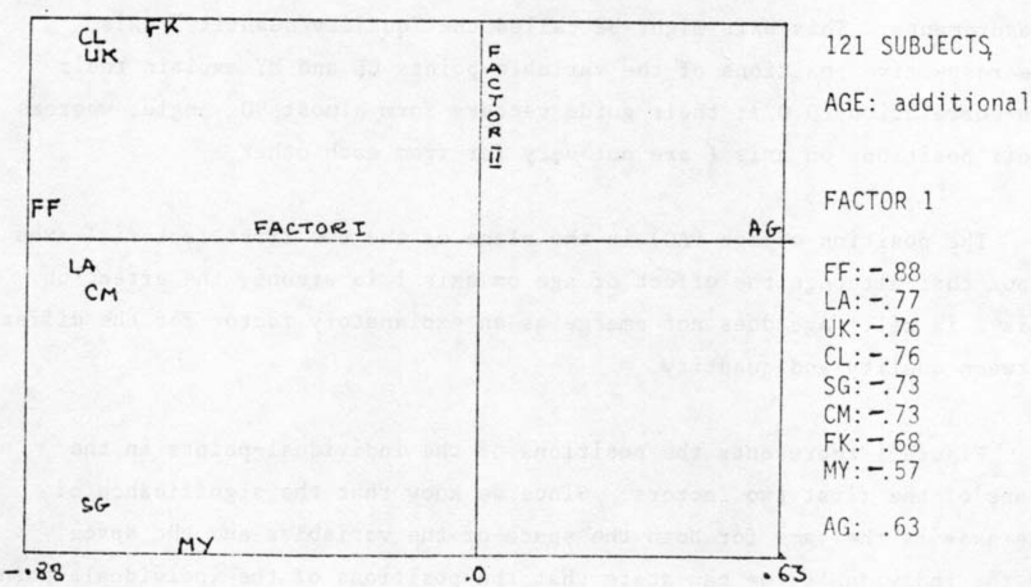
Axis	Eigen value	%	Cumulated %
1	1 = 4.37	54.6	54.6
2	2 = 1.36	16.9	71.5
3	3 = .84	10.5	82.0
4	4 = .54	6.8	88.8
5	5 = .37	4.7	93.5
6	6 = .24	3.0	96.5
7	7 = .17	2.2	98.7
8	8 = .10	1.3	100.0

An initial remark is necessary, i.e., the percentages of inertia (of variance (are exaggeratedly pessimistic (7). The "explanatory" power of the first axis data is much greater than the percentage indicated. This remark allows us to state that, by itself, the first axis sums up the principal tendency that emerges from the data.

The second axis will enable the providing of useful additional data, but the following axes will probably be only evidence of phenomena of the second order, containing no noteworthy physical significance.

Planar Diagrams

The figure below represents the position of the variable-points in the factorial plane constituted by the first and second factorial axes (this plane contains 71.5% of the inertia). As noted in paragraph II.1, age has been added, and the variable-point "AG" appears on the diagram.



FACTOR ANALYSIS FROM 8 BONE CARACTERISTICS

Positions Along Axis 1: All the bone-characterization variables are situated on the far left of the diagram, on the negative side of the axis; they are located opposite the position of point AG (age) situated on the positive side. We find in another form what had been shown previously, i.e., an inverse relationship between age and bone characteristics, as well as an identical tendency expressed by the various parameters. The new point is that axis 1 constitutes a new artificial variable, a linear combination of the 8 initial variables, and thereby synthesizes the principal tendency contained in the data. Axis 1 can be called the "bone-characteristic" axis.

Positions Along Axis 2: On either side of the origin along the direction of axis 2, we find opposition between FK, UK, CL (the positive side of axis 2) and SG, and MY. In other words, the variables that are highly sensitive to the quantity of compact bone contained in the rib (CL, FK, UK) are in opposition to the variables that characterize the compact bone matter (SG, MY). Caricaturally, we can say that axis 2 places into opposition two types of measurements: bone quality measurements and bone quantity measurements. This axis might be called the "quality/quantity" axis. The respective positions of the variable-points CL and MY explain their non-correlation (0.02); their guide vectors form almost 90^o angle, whereas their positions on axis 1 are not very far from each other.

The position of age (AG) in the plane of the two first factorial axes shows that although the effect of age on axis 1 is strong, the effect on axis 2 is nil. Age does not emerge as an explanatory factor for the differences between quality and quantity.

Figure 1 represents the positions of the individual-points in the plane of the first two factors. Since we know that the significance of the axes is the same for both the space of the variables and the space of the individuals, we can state that the positions of the individuals-points along axis 1 constitutes a classification of the individuals in terms of skeletal resistance. The subjects with the strongest characteristics are

LOCATION OF THE SUBJECTS
ONTO THE TWO FIRST FACTORS PLANE

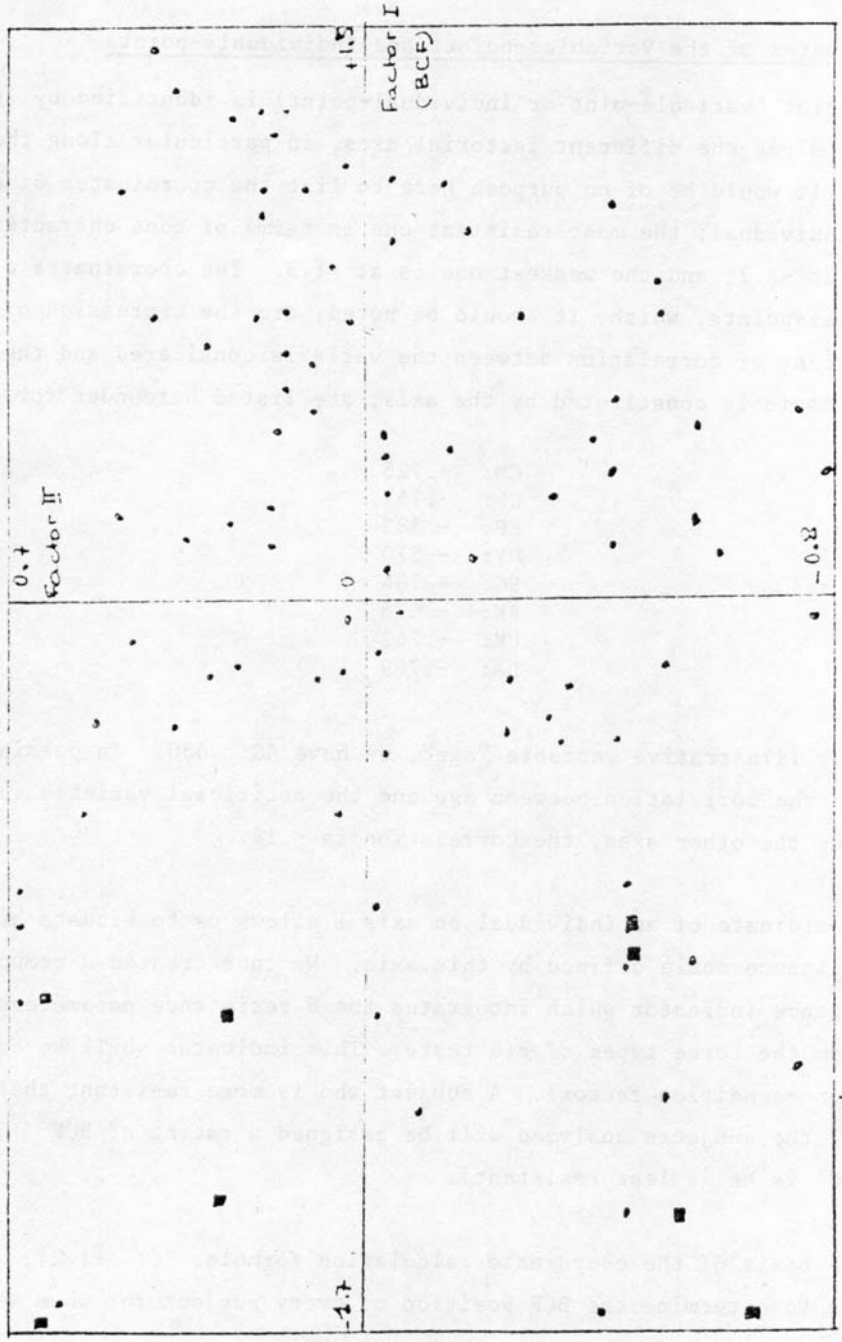


Figure 1

• Subjects

■ Young persons who met suddenly death

on the negative side (on the left part of the diagram), and are in opposition to the most fragile subjects, located on the positive side of the axis (on the right part of the diagram).

Coordinates of the Variables-points and Individuals-points

Each point (variable-oint or individual-point) is identified by its coordinates along the different factorial axes, in particular along the first one. It would be of no purpose here to list the coordinates of each and every individual; the most resistant one in terms of bone characteristics is located at -2.2, and the weakest one is at +1.3. The coordinates of the variables-points, which, it should be noted, are the expression of the coefficient of correlation between the variable considered and the artificial variable constituted by the axis, are listed hereunder for axis 1:

CM:	-.725
CL:	-.757
FF:	-.882
MY:	-.570
SG:	-.734
FK:	-.676
UK:	-.762
LA:	-.769

For the illustrative variable "age", we have AG: .630. In passing, let us note the correlation between age and the artificial variable, equal to .63. For the other axes, the correlation is <.18.

The coordinate of an individual on axis 1 allows us to situate him on the resistance scale defined by this axis. We thus created a compound bone-resistance indicator which integrates the 8 resistance parameters deduced from the three types of rib tests. This indicator shall be called the BCF (bone-condition factor). A subject who is more resistant that the mean of the subjects analyzed will be assigned a rating of BCF 0 (or BCF 0) is he is less resistant).

On the basis of the coordinate calculation formulas (Cf. II.2), it is possible to determine the BCF position of every subject for whom we have the findings pertaining to the 8 bone-characterization parameters. Let us restate here the formula for computing the coordinates of an individual point "i" along a factorial axis ($V_{\alpha i}$):

$$V_{\alpha i} = \sum_{j=1}^{8} u_{\alpha j} \frac{r_{ij} - \bar{r}_j}{sj \cdot \sqrt{n}}$$

with the components of "u" being equal to the coordinates of the variable-points on the axis divided by λ_α.

The calculation formula becomes as follows:

$$\text{BCF } i = \sum_{j=1}^{8} \frac{j_{ij}}{\sqrt{\lambda_1}} \frac{r_{ij} - \bar{r}_j}{s_j \cdot \sqrt{n}}$$

$\sqrt{\lambda_1} = 2.09$

$n = 8$

$\sqrt{1i}$: components of variables on axis 1

$\bar{r}_j, s_j$: mean, standard deviation of variables

It is then possible to position all the subjects along the BCF axis.

Age/BCF Relation in Terms of Sex of Subjects

As noted earlier, the coefficient of correlation between age and the bone condition factor is 0.63. Figure 2 shows this correlation. The squares represent hte 8 subjects who had died sudden deaths; their ages range from 16 to 24 years, and all of them have a BCF of 0.7, i.e., with a very good bone condition. These subjects do not differ from the population of the other subjects of the same age range. Their bone condition does not appear different in the case of the two youthful populations considered. This fact is due to the nature of the selection of the experimental subjects. In the case of the young individuals, death had most often been sudden (suicides, for example). There was therefore no influence of a hospital stay. In order to collect more ample data on the bone conditions of the risk-exposed live population, the following are necessary.

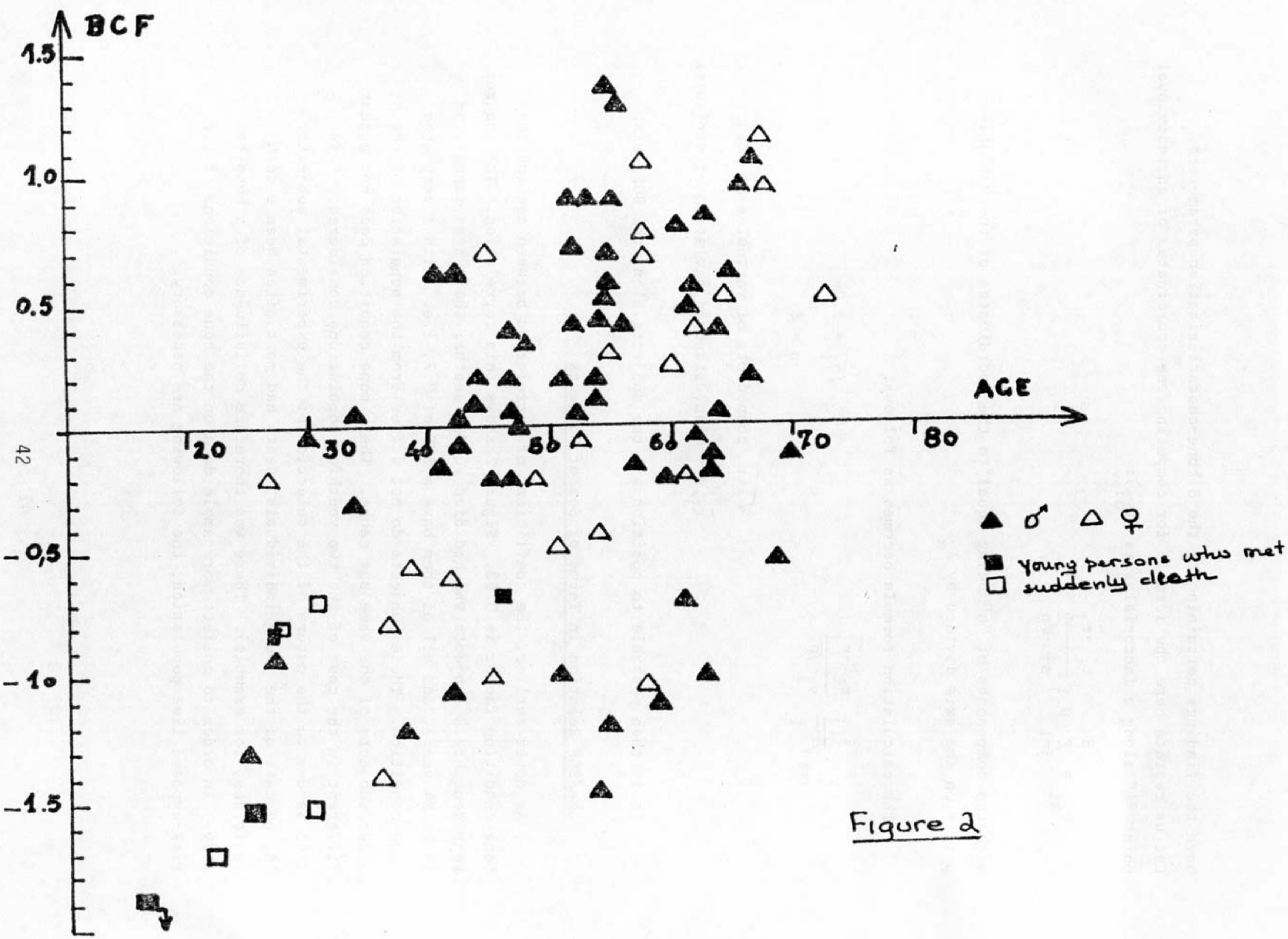

BCF
1.5
1.0
0.5
- 0,5
- 1o
-1.5
AGE
20
30
40
50
60
70
80
▲ ♂ △ ♀
■ young persons who met
□ suddenly death

Figure 2

- increased number of tests on rib fragments of subjects who have died sudden deaths,
- extension of the selection process to include subjects in all the age ranges, including the over-50 range.

Work devoted to achieving these two additional objectives is currently under way.

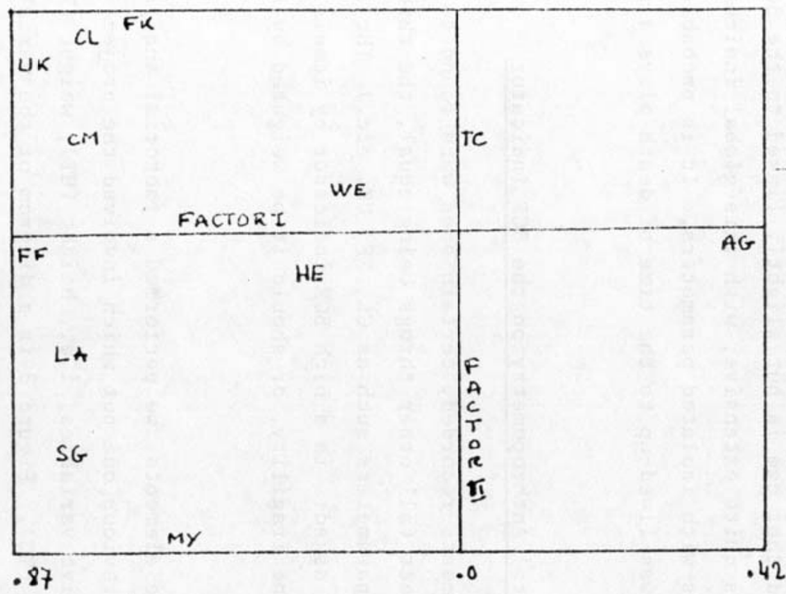
Examination of the figure shows that the female subjects are quasi-randomly divided in the point cluster. In any event, they do not emerge as less resistant than the male subjects in terms of BCF and for equal ages.

It should be noted that age is but slightly linked to the BCF indicator (= 0.63). Scatter is quite extensive; with this global indicator, we find similar results as with isolated parameters. It is probable that the kind of life that was lived-up to the time of death plays a preponderant role.

Effects of Subjects' Anthropometry on the BCF Indicator

Among the measurements recorded, certain ones were found to be influenced by the dimensional effect (all other things being equal, the thicker the ribs, the greater the parameters such as CL, FF, UK, etc.) The following question could then be asked: is a high BCF indicator by itself a representative indicator of bone fragility, or should it be weighted by a dimensional factor?

To obtain response elements, we performed a factorial analysis which was identical to the previous one but which involved the projection of new, sheerly illustrative variables, i.e., height (HT), weight (WT) and thoracic circumference (TC). Figure 3 is a diagram of the variables in the plane of the first two factors. (For reasons having to do with simultaneity of data, only 87 subjects were taken into consideration; the



87 SUBJECTS

AGE, DIMENSIONS: additional

FACTOR I

Rib Char. :(-.87,-.50)

Thor. Circ. : .04 (TC)

Heigth :-.27 (HE)

Weigth :-.15 (WE)

Age : .42 (AG)

Figure 3

FACTOR ANALYSIS : INFLUENCE OF BODY DIMENSIONS respective positions of teh variables and the individuals were not greatly disturbed; this fact is an indicator of the stability of the method).

The three additional variables (HT, WT and TC) are located toward the center of the diagram, their extent can be only of a secondary order. The coordinates of the variables along axis 1 (BCF) illustrate this fact:

HT: -.27, WT: -.016, TC: 0.04

It should be borne in mind that these coordinates express the coefficient of correlation between the variable considered and the artificial variable constituted by the axis, i.e., the BCF. We therefore find that the correlations for TC are low or even nil. Only HT emerges as being slightly related to the BCF ($\rho = -0.27$). It is possible to consider weighting by the height however, two facts should be noted, as follows:

- the younger subjects on the average are taller than the older individuals. The age/height correlation is not nil.
- the most characteristic thorax size considered here is the thoracic perimeter; $\rho(AG/BCF) = 0.04 \simeq 0$.

Actually, the BCF seems not to be related to a size factor; the BCF/height relationship appears to be due more to the fact that age and the BCF are related and that age and height are related. The existance of a height/BCF causal relationship seems unlikely, at least on the basis of the sample analyzed here.

In conclusion, direct utilization of the BCF indicator is possible without size weighting, as an indicator of rib bone resistance.

III. INVESTIGATION OF INFLUENCE OF BONE CONDITION ON THORACIC INJURY LEVEL

The foregoing material enabled us to define an indicator of skeletal resistance, i.e., the BCF indicator, computed on the basis of rib-test parameters. This indicator is related to the local rib resistance; it characterizes the ribs, and not, a priori, the thorax. We shall see below that, on the basis of this local indicator, it is possible to characterize the total resistance of the thorax to impact.

III.1. Side Impact

Two types of experiments were performed for side impact, i.e., car-to-car impacts, in which the subject on the impact side is struck by the side panel, and free-fall drops against rigid or padded surfaces.

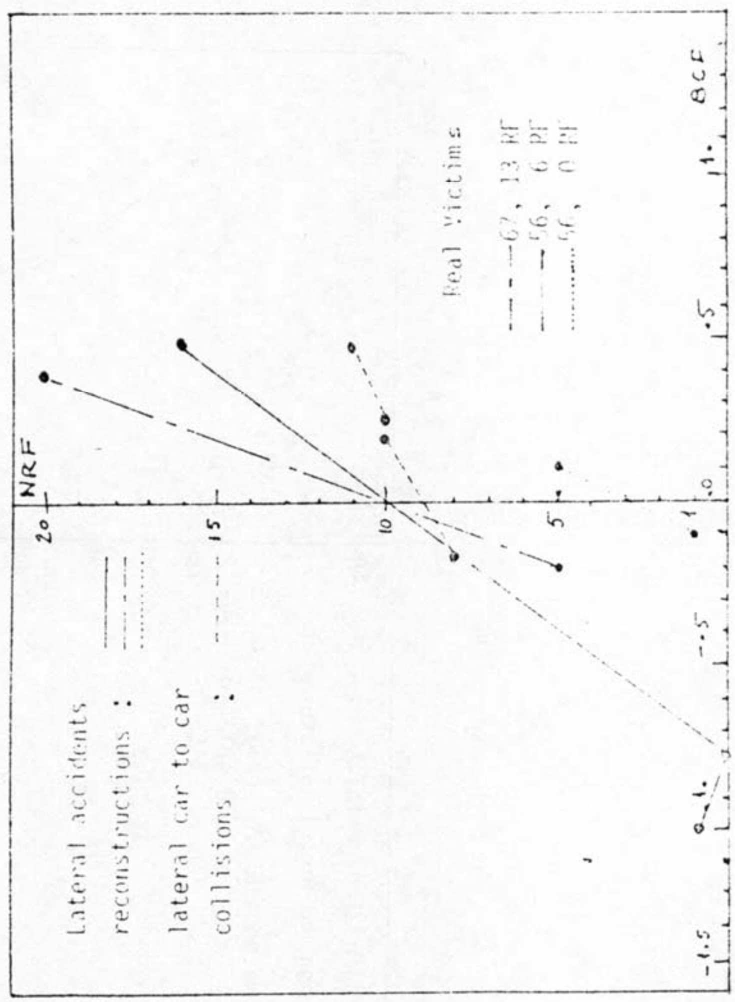
Independently from physical measurements, it is possible to compare the number of rib fractures sustained by subjects who incurred identical impacts. Figures 4, 5a, and 5b represent, on a plane (BCF-number of fractures), the positions of the individuals subjected to car-to-car side impacts Figure 4) as projected in free-falls (Figure 5). The individuals exposed to identical impacts are interconnected by lines. We see that regardless of the impact violence conditions, the number of rib fractures increases when the BCF increases, i.e., when the bone condition, described by this indicator, decreases. Only one individual shows a sharp deviation from this classification (Figure 5b). This is an individual who sustained 7 fractures, for an extremely low BCF indicator. Detailed investigation of the rib-test findings showed a fair-above-average stiffness of the ribs in subjects having a very low BCF. It is possible that this characteristic may have played a role.

If we exclude this case, it can be stated that the BCF indicator does indeed constitute an indicator of overall resistance of the rib cage in in side impacts, in both free falls and car-to-car collisions.

Consequences for the Evaluation of Protection Systems

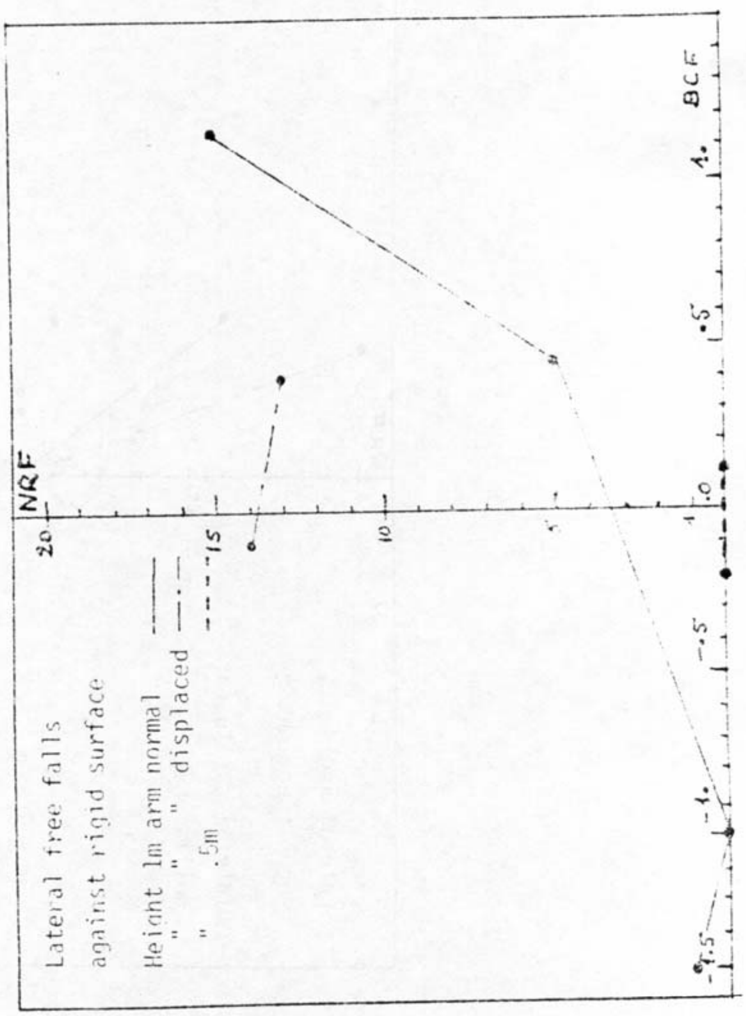
One of the principal consequences of the determination of such an indicator is that it allows us to judge the relative effectiveness of the various protection systems on the basis of a small number of tests. If

Figure 4



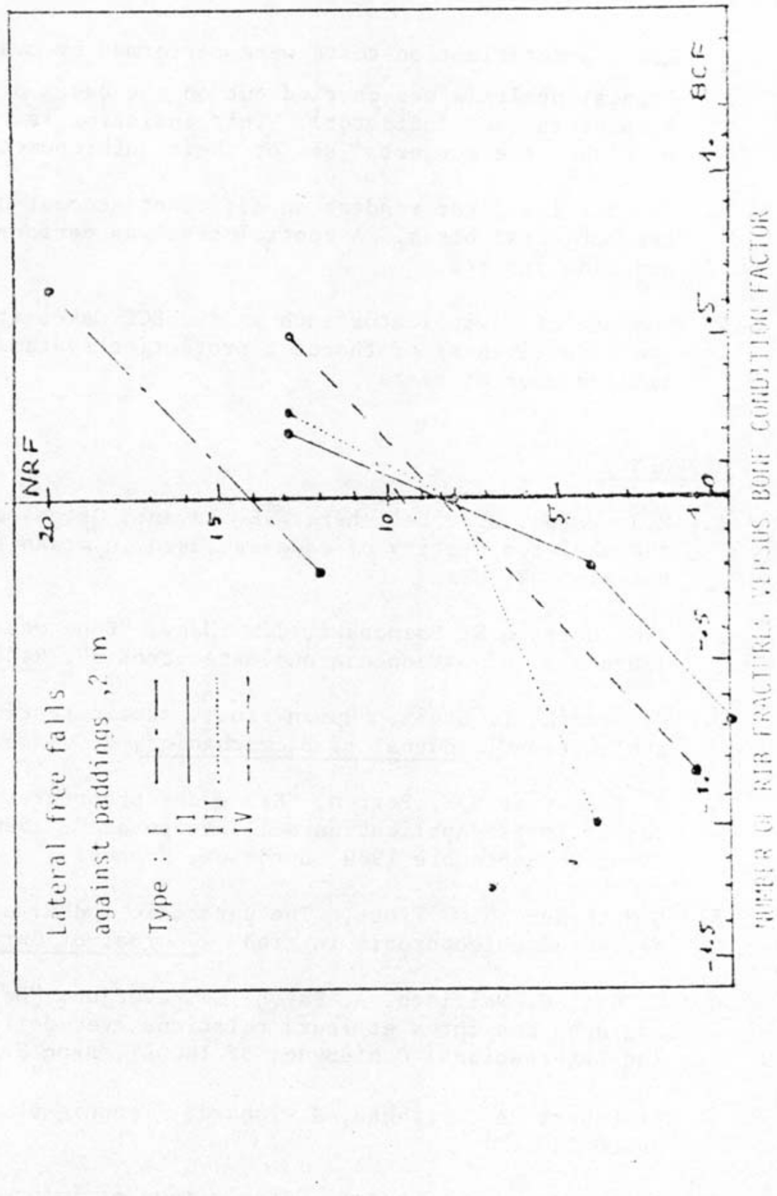
NUMBER OF RIB FRACTURES VERSUS BONE CONDITION FACTOR

Figure 5a



NUMBER OF RIB FRACTURES VERSUS BONE CONDITION FACTOR

Figure 5b


Lateral free falls
against paddings ,2 m
Type : I
II
III
IV
NRF
20
15
10
5
BCF
-1.5
-1.
-.5
0
.5
1.
NUMBER OF RIB FRACTURES VERSUS BONE CONDITION FACTOR

we consider Figure 5, which concerns falls from a two-meter height onto five paddings, we see that the type I padding emerges as the worst padding while by contrast, type II and IV seem to be better ones. These identical considerations can be put forward with respect to frontal impact.

Summary and Conclusions

1. Rib characterization tests were performed by over one hundred subjects.
2. Frontal analysis was carried out on the basis of eight bone-condition parameters (BCG indicator). This indicator is not significantly influenced by either the subjects' sex or their anthropometry.
3. The BCF indicator renders an efficient account of the fragility of the subjects' bones. A control test was performed for both frontal and side impacts.
4. The use of an indicator such as the BCF makes it possible to judge the effectiveness of thoracic protection systems on the basis of a small number of tests.

REFERENCE

1. M.J. Walsh, B.J. Kelleher, W.E. Levan, "Osteologic studies for determining the skeleton quality of cadavers used in crash testing", CALSPAN, Buffalo, NY, USA.

2. S.M. Garn, A.K. Poznanski, J.M. Nagy, "Bone measurement in the differential diagnosis of osteopenia and osteoporosis", Radiology Sept. 1971.

3. C. Granik, I. Stein, "Human ribs: static testing as a promising medical application", Journal of Biomechanics, V. 6, no. 3, p. 237, 1973.

4. J. Cordey et S.M. Perren, "Etude des proprietes radiologiques et geometriques des os longs. Application a l'osteoporose". 5eme Congres de Biomechanique, 25 et 26 Septembre 1980, Bordeaux, France.

5. B.N. Epker, H.M. Frost, "The parabolic index: a proposed index of the degree of osteoporosis in ribs", Journal of Gerontology, V. 19, Oct. 1964.

6. C. Got, G. Walfisch, A. Fayon, G. Faverjon, "Les caracteristiques morphologiques des cotes et leurs relations avec deflexion provoquee du thorax", 2nd International Conference of IRCOBI, Bron France.

7. L. Lebart, A. Morineau, N. Tabard, "Techniques de la description statistique", DUNOD Edit.

8. L. Lebart, J.P. Fenelon, "Statistique et informatique appliquee, DUNOD, 1975.

9. J.P. Benzecri et col., "L'analyse de donnees. Tome 1: la taxinomie, Tome 2: l'analyse factorielle des correspondances", DONOD Edit.