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ERGONOMIC ANALYSIS OF HELICOPTER COCKPIT GEOMETRY

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In the paper written by A.C. Mandal, a human engineering expert [1], the man living in the modern industrial world is called the "homo sedens" (the seated man) because he spends most of his life in a sitting position. It is stated there that almost half the population suffers from some form of back complaint which is directly related to the above mentioned position. Numerous investigations carried out during the last 25 years have shown that back pain is quite a widely spread complaint among helicopter pilots. Different authors estimate that the number of those complaining of this pain is from 50% to 70%; this wide scatter can be evidently attributed to the sample size. The above mentioned figures exceeding those found out for the general population cannot help drawing close attention of those who design and operate helicopters.

In 1984 the data obtained during research into causes leading to occurrence of back pain among the US Army helicopter pilots in the US Army Aeromedical Research Laboratory, Fort Rucker, [2,3] were published. The survey of 802 US Army helicopter pilots has revealed that 72.8% of them experience back discomfort. Although the average intensity of pain has been estimated quite low, the authors think it is quite of importance that 28.4% of the pilots rushed through their missions due to the back discomfort, and another 7.5% reported of their refusal to perform a mission because of the back pain. It is quite evident that there are certain factors inherent in helicopters that lead to the occurrence of the phenomenon. Two factors are singled out as such: exposure to vibration and an unsatisfactory sitting position. But now data indicating that a bad working posture is typical of helicopter pilots are available. This posture essentially differs from that assumed by the operator of any other transport means, fixeg–wing aircraft included. Full helicopter control often requires simultaneous inputs from all four extremities, and the missions performed rarely allow the pilot to be free of controlling the aircraft. It should be noted that the arrangement of the seat and controls relative each other makes the pilot assume an asymmetrical posture– to flex forward and slighly tilt to the left [2].

To make comprehensive investigations into causes inflicting back pain, it is necessary, within the framework of a strictly controlled experiment, to reproduce conditions completely simulating the effect of harmful factors typical of any helicopter flight. Such an experiment is described in [2,3]. A vibration table with the UH–1 helicopter pilot's station installed on it was used in this experiment. The vibration table software provided simulation of flight vibration occurring in the floor in the vicinity of the seat. For the investigations, 11 pilots complaining of pain in the lower back after less than 2 hours of flight in the helicopter have been sampled. Each of them took part in two investigations of 120 minutes each; one investigation was conducted with vibration application, and the other, without it.

Twenty four hours later another investigation was conducted. The subjects wore the USAF standard flight suits. The following parameteres were registered: the time when the pain occurred, the intensity of pain; the latter was evaluated subjectively by using the visual analog scale (VAS).

Back pain occurred both in the presense and absense of vibration. The statistical analysis did not reveal any reliable difference in intensity and time of pain occurrence depending on this condition of the experiment. These results allowed to make a conclusion that the main factor inflicting back pain is an unfavourable working posture.

This conclusion is in good agreement with the results of the investigations into working postures assumed by pilots flying the following French helicopters: Puma, Gazelle and Alouette. The investigations were performed by using a dedicated X–ray installation. The conclusion made is: the working posture is unsatisfactory.

From our point of view, the most probable mechanism inflicting this discomfort is as follows. When changing the standing position to a sitting upright one, for instance, the hip joint rotates only by 60 degrees, and the remaining 30 degrees are added by flattening the S–shaped lumbar curve (lordosis). This flattening occurs in the fourth and fifth lumbar intervertebral disks additionally loaded by deformation [1,5] (Fig. 1). The aim of many studies involved in optimization of the seat back support surface is to retain this S–shaped lumbar curve in the sitting position. The problem is that some pilots operate the helicopter controls without using this ergonomically optimized seat back, as the cockpit geometry makes them bend forward. In this case the load is such that it can make these intervertebral disks displace when the person is exposed to this loading for a long time.

These investigations allow to make a general "diagnosis", i.e. the helicopter pilot station is unfavourable from the point of view of a certain number of pilots. But this is not enough for the designer. He would like to know how many pilots are not satisfied with this working position on this or that helicopter. And if the number of the pilots is less for one type of the helicopter why is it so?

There are at least two approaches used to find the answers to these questions. One approach is to use a "live dummy". The actual stations or full–scale mockups are studied by a team of subjects (experts) who have been selected according to certain anthropometric characteristics; each person uses his body as an experimental tool. This method, undeniably an advantageous one, has some essential constraints:

– no matter how thoroughly the "live dummies" could be sampled in height groups, they, in compliance with the laws of mathematical statistics, cannot be quite a representative sample covering the whole flight personnel due to a limiting number of the expert team;

– to conduct an investigation it is necessary to have an actual helicopter cockpit or a very accurate station mockup.

The second approach is to use a mathematical model of the pilot's body, to accumulate a database of anthropometric properties and to use computer technogies. We believe that the latter offers a means to obtain the most comprehensive information required for evaluation and designing purposes, although it does not completely rule out the possibility to use the first approach, the approach of expert procedures, because each approach helps to obtain some specific information about the problem under study.

At present, the publications describe numerous computer models of the man–operator body used for designing purposes [5,6,7]. These quite effective ergonomic computer technologies allow to avoid bad mistakes prior to building a full–scale mockup. The station version is shown on the computer display; further improvement of the version is accomplished through a dialogue with the computer. The operator's body is presented on the display either in a 3–D shape comprised of straight lines or in the contour one. As a rule, three versions of these computer dummies are used of minimum, medium and maximum sizes corresponding to the 5th, 50th and 95th percentiles respectively. One cannot but notice that this approach reproduces the old "drawing" technology existed prior to the advent of the computers, and in this case the estimation of the fact whether the geometric parameters have been properly chosen is carried out by using drawing dummies incorporating articulated "joints".

But even this does not give a full answer. At the same time anthropometry has accumulated an enormous wealth of data about human body sizes, and about pilots' ones in particular. These data can be only partially used in conventional design practice; and only computers will allow their effective utilization. Instead of a few determined models, it would be more properly to use such a model in which the link dimension could represent a parameter. The designer could deal with the whole complex of anthropometric dimension combinations within the given limits. In aviation these limits are $\pm 3\sigma$ of m where σ is a standard deviation, and m is an average value of the parameter. But to make this parametric model "alive", to fill it with an actual content, it is necessary to create a dedicated computer base of anthropometric data.

Our computer anthropometric database is derived from statistical data which has been used earlier for elaboration of a number of standards and manuals for designing aircraft cockpits and components of aircrew stations. These data have been obtained by anthropometric experts during a survey of 2,000 pilots with the help of the coordinate measurement method [8]. In contrast to all other well-known methods, all measurements of the human body or its separate elements in this case were made either in the rectangular or spherical coordinates. The anthropometric data obtained in this way are, for the most part, ready to be used for design purposes whereas the majority of data obtained by conventional measurement techniques (point by point) require recalculation to tie them up with the coordinate system. However, it is by no means so easy to recalculate all the anthropometric parameters in this way. And in similar cases the designer has to make use of approximations which, as a rule, results in errors. Special measuring devices and appliances have been developed to make these measurements.

Some of these data have become a part of our computer database. The measurements of 560 pilots covering 67 anthropometric properties were fed into the computer storage. These data are statistically processed by using the dedicated sofware developed specifically for this particular system. The computer groups the data, calculates histograms, all numerical distribution characteristics (statistical average, standard deviation, asymmetry and excess coefficients), plots a theoretical distribution curve. The Gaussian distribution hypothesis is specially checked by using the chi-square criterion, as well as the asymmetry and excess coefficients.

One of the most essential features of the computer database is calculation of a full correlation matrix of the anthropometric data. The statistical processing system operates in the dialogue mode, thus providing its versatility.

Sometimes sophisticated, comprehensive models of the human body used for design purposes, for example a Boeing model, are described in publications. In these models, account is taken of the length of the links, constraints imposed on the movement of the links in joints, link location and weights, characteristics of physical efforts made. The joint movement range is determined by the limitations imposed by the elasticity of the muscles, tendons and ligaments, as well as by the resistance of the upper skin tissues [9].

These quite sophisticated models are expensive to develop and they are often critisized. The main critical argument is that they are irrational since these supermodels, despite being comprehensive, cannot replace an expert mockup assessment.

But the objective of making a model is not to give up the mockup stage to save time and money, but to provide a reduced number of the iterative cycles in designing a cockpit station and a possibility to study a greater number of its versions. The extreme model sophistication can be avoided if a special model (submodel) is taken to solve a particular design problem. In this case, the model can be built by using only the data relevant to that particular problem and not a whole set of information. For instance, to find out the adjustment of the helicopter yaw control pedals, a special model made only of one set of elements is used, and to solve the problem of choosing the proper cockpit width, another set of elements is required to build a model. This approach allows to greatly simplify the mathematical description, to minimize the errors typical of multilink models, and to actually realize the great potential of the anthropometric database.

This concept will allow us to obtain the required information on the laws governing the pilot working posture in the helicopter cockpits.

To ensure the pilot's efficiency in doing his duties, the following conditions should be fulfilled simultaneously:

– the pilot's eye line should be aligned with the helicopter horizontal line of vision;

– the pilot should have a possibility to operate the cyclic control stick within the entire range of its travel;

– the pilot's back should lean against the back cushion.

The fixed horizontal vision line is used due to the fact that the military helicopter cockpit contains a sight as a part of the integrated sight and navigation system or a head-up display; in commercial helicopters, it is dictated by the necessity to provide the same (optimal) conditions to have the internal and external vision. The vertical adjustment of the seat ensures the alignment of the pilot's eye line with the horizontal vision line. It is evident that the vertical seat adjustment affects both the pilot working posture characterized by the relation of different body components towards each other, and the ability to reach different controls.

The second condition needs no comments; the third one, as it has been already stated above, is related to the necessity to maintain the lumbar curve (lordosis) with the help of a specially shaped pilot seat back required to optimize the working posture.

It is necessary to design a pilot's station meeting the above three requirements for all flight personnel, as well as to assess the extent to which the existing cockpits satisfy them.

Simultaneous fulfilment of the above requirements depends on the extent to which the station's geometry matches the appropriate anthropometric characteristics of pilots. For each group of people having the same "eyes–above–seat" height parameter , there is a certain range of the "hand reach" values. If the cockpit geomentry ensures the cyclic control stick travel within its entire range for pilots having the minimum hand reach in each group with the same "eyes–above–seat" height, this will guarantee the fulfilment of the three requirements for the whole flight personnel.

Fig. 2 (a, b) shows the principle used for building a special model of the pilot body for this particular task. The pilot body is presented as a system of straight lines ABCDS(i) incorporating hinge B simulating the shoulder joint (Fig.1a). The horizontal vision line and the adjustment axis S1S2 are the elements matching the link model with the helicopter cokpit and controls. The selected anthropometric characteristics defining the location of the body points in the model relative each other are dictated by the following considerations:

– to maximize the use of anthropometric data which are ready for design application (the information from the database about the "eyes–above–seat" height h36 and horizontal hand reach l4; all anthropometric dimensions are in compliance with those used in the Russian standards);

– to use a number of dimensions updating the location of the points of the body relative each other which are of significance for this task, i.e. the horizontal and vertical dimensions determining the centre of the shoulder joint and the projected hand length; they include:

h23, the height of the eyes above the seat at the zero seat angle;
h26, the height of the shoulder joint centre above the seat at the zero seat angle;
l2, the distance from the seat back to the shoulder joint centre;
l18, the length of the hand third finger.

Since the h36 and l4 dimensions play the key role in solving the particular problem they are selected as the model parameters.

h36, the height of the eyes above the seat with the seat tilted back by 17 deg. from the vertical line ($m = 767$ mm, $\sigma = 28$ mm);
l4, the horizontal hand reach measured from the seat back ($m = 853$ mm, $\sigma = 36$ mm),
where m is the average value of the parameter,
σ is a standard deviation.

As with the majority of anthropomentric lengthwise dimesions, the hypothesis about their normal distribution should be valid. There is a positive correlation between them and the coefficient r equal to 0.42. These data allow us to consider the combined distribution of the anthropometric properties of interest. As it follows from the theory of probability, the surface of a two–dimensional Gaussian distribution has the shape of a "hill" or a "bell" whose top is located above the point with coordinates of appropriate expectations of one and the other values respectively. If this surface is divided by vertical planes, then curves similar to those of one–dimensional Gaussian distribution can be obtained. If this surface is divided by horizontal planes, ellipses are obtained, and they are called ellipses of equal probability density. Fig. 3 shows a Gaussian distribution of two anthropometric properties, i.e. l4 (horizontal reach) and h36 ("eyes–above–seat" height). The axes conditionally show theoretical curves of one–dimensional Gaussian distributions for each of the property. The family of the ellipses and regression lines are built by the computer from the results obtained from the statistical procession of information from the computer anthropometric database. The big ellipse limits the area of combined distribution of the dimensions that vary within 3σ, and the small one, within 2σ. The part of the general population falling into the K–sigma ellipse (here K *is a coefficient determining the normalized limits within which anthropometric properties* can vary in sigma fractions) is found from the following well–known formula:

$$P = (1 - e^{-\frac{k^2}{2}}) \times 100\%$$

It can be computed that, for K=3, 98.9% of the total distribution fall into the area limited by the ellipse, whereas for k=2, this value will be equal to 86.5%. In mathematical statistics the ellipse corresponding to K=3 is called a complete ellipse of dispersion. And we shall use it for solving our problem.

The diagram shows points presenting the measurement data of the above mentioned properties obtained from 560 pilots. This comparison clearly confirms the validity of replacing a combination of statistical data by a probability–theoretical notion.

A complete ellipse of dispersion is inscribed into a rectangular each side of the latter being a range *within which the anthropometric properties* $6\sigma_{h36}$ *and* $6\sigma_{L4}$ *vary. The centre of the ellipse is the point* whose coordinates are m_{h36} and m_{L4}.

It has already been mentioned above that, for each group of people having the same value of one dimension, there is a certain range of values of another dimension. Within any of these ranges, random values are also governed by the Gaussian law. In this case the conditional expectation will lie on the regression line.

It is necessary to pay attention to the following: the two–dimensional Gaussian distribution is characterized by two regression lines. The four points where the regression lines and the complete ellipse intersect have the following "anthropometric" meaning:

point A corresponds to a pilot having a minimum "eyes–above–seat" height and a certain (but not minimal) reach;

point B corresponds to a pilot having a maximum "eyes–above–seat" height and a certain (but not maximum) reach;

point C corresponds to a pilot having a minimum reach and a certain (but not minimal) "eyes–above–seat" height;

point D corresponds to a pilot having a maximum reach and a certain (but not maximum) "eyes–above–seat" height.

This means that, to solve our problem, traditionally "big" and "small" pilots, i.e. the models synthesized from all minimum or all maximum elements respectively, are not acceptable as these people do not exist in reality. The specific character in which multidimensional statistical distributions are used makes the application of the traditional percentiles quite useless. Sometimes use is made of another, more appropriate method to build models for maximum and minimum dimensions: all links are calculated by using regression equations for defining anthropometric dimensions by applying some leading dimension, e.g. the standing height. But even in this case we can deal only with one combination of possible anthropometric dimensions and we cannot be assured that this particular combination is the least favorable one out of all possible combinations (or, as engineers would say, "the worst design case").

Thus, another problem is brought up: looking for the most unfavourable combination out of all possible ones of anthropometric properties corresponding to the given design problem. Here the desired design case should be sought for along the boundary of the ellipse of dispersion, i.e. within the entire group of the pilots having the minimum reach within the range of the "eyes–above–seat" height variation. This applies to other design tasks, e.g. for assessment of the cross–sectional dimension of the one–seat cockpit. Taking into account the requirement for the vertical seat adjustment, it is necessary to consider a combined distribution of the "eyes–above–seat" height and "shoulder width" anthropometric properties. The required design case will belong to the ellipse–of–dispersion boundary, i.e. to the group of pilots having a maximum shoulder width within the entire range of the "eyes–above–seat" height variation.

A variety of other examples can be given, but even this one is quite enough to make a conclusion that the next logical step will be a change–over from the stochastic relation, existing between the anthropometric parameters under consideration, to the functional one, in the form of the appropriate part of the ellipse–of–dispersion boundary. Then, in our model the h36i parameter can uniquely define the l4i value and vice versa.

Additional anthropometric dimensions used in the model (Fig. 1b) are also unambiguously defined by the conditions of the design case. The fact is that from consideration of a system of three random values obtained from the Gaussian distribution follows that, if two of them are located on the boundary of the 3–sigma dispersion, the next random value is located on the line of the multiple regression. Therefore the h23,h26, l2, l18 k dimensions are determined from regression equations for the h36 and l4 parameters.

The algorithm for assessing the fulfilment of the three conditions is as follows. Let us vary the value of the "eyes–above–seat" height (h36) from the minimum value to the maximum one. Each h36i value corresponds to an appropriate position of the vertically adjusted seat required to align the pilot eye line with the horizontal vision line. Then, for each position of the seat, the arm length necessary for the pilot to easily reach the cyclic control stick in the extreme forward position (100% travel) without changing his posture is determined. Taking the entire range of the h36 parameter variation, we shall find a number of points with the (l4, h36) coordinates which, if connected, will form a curve of required reach (Fig. 4). This curve divides the ellipse of dispersion into two areas. The upper area contains that part of the pilot population for whom the following expression is valid:

$$l4 \geqslant l4 \text{ required},$$

i.e. their anthropometric parameters are such that they ensure a good working posture at that particular station with the cyclic control stick in the extreme forward position. The lower area will contain those pilots who have to bend their back (to a greater or lesser extent) to reach the cyclic control stick in this position.

The part of the distribution covered by each of the areas is quantitatively defined. Calculations are done with the help of the dispersion grid, an approximation computation technique based on the expression covering the probability of falling into the rectangular whose sides are parallel with the main axes of dispersion.

This sequence is repeated for intermediate values of the control travel. Finally, we shall obtain a number of points in the L–N coordinate system where L is the control travel in per cent, and N is the number of pilots in per cent. The connection of the points will give us a curve called an integral reach curve. The curve shows the number of pilots whose good working posture is ensured for control stick travelling by a certain value. For instance, for the transport helicopter, the cyclic control stick will mostly be in the position corresponding to cruise flight. The number of pilots who are guaranteed to get an optimal working posture for this most prolonged flight condition can be obtained by using the integral reach curve (Fig. 5).

It turns out that these diagrams give plenty of useful information. They are convenient for comparing ergonomic characteristics of typical components of different stations in helicopter cockpits. Softwares have been developed to assess cyclic control (easy functional reach and maximum functional reach), collective control and yaw control pedals; they take account of the seat back angle tilt, vertical and horizontal seat adjustment, yaw control pedal adjustment, availability of special–purpose equipment, as well as constraints imposed by the restraint system. Fig. 5 shows how these softwares are used for different types of helicopters.

These quantitative assessments have a good agreement with the qualitative "diagnosis" based on the observations and experiments mentioned at the beginning of the paper. Our investigations allow us to conclude that the extent to which the helicopter cockpit geometry matches the anthropometric characteristics of the pilots depends upon a variety of design factors such as controls radii, their travel, coordinates of the controls centres of rotation relative to the station, seat parameters, adjustment range, etc. Work involving a computer model allows to find out laws important for station optimization by changing numerical values of these factors.

The investigations have shown that, unfortunately, it is impossible to guarantee a simultaneous fulfilment of all three conditions and maintenance of the optimal back position for 100% pilots in helicopters equipped with traditional mechanical control systems. Here human engineering factors of different nature come into force. The bench test results and the service experience have allowed to define the value of the optimal control sensitivity, for instance, the characteristic that determines the cyclic control stick travel. The problem of the working posture in terms of controls reach is completely solved when a fly–by–wire control system incorporating side controllers is used. It is of interest to note, that the same conclusion was made after conducting studies on back pain suffered by helicopter pilots [2].

Besides, the technology described above and involving the ellipse of dispersion allows to establish the boundaries of functional reach zones (easy, maximum and exreme reach with due account of the constraints imposed by the restraint system) for different types of controls located on the control panels and instrument board: toggle switches, buttons, knobs, etc. The type of controls dictates the configuration of the hand and fingers and, thus, different reach capability.

Certainly, the problem of an optimized station cannot beconfined to the subject of the reach capability only. The controls can be easily reached but the posture when manipulating them may not be convenient. Detailed description of computerized methods of assessing and designing the pilot station developed for this purpose and based on three–dimensional distributions of anthropometric parameters (dispersion ellipsoids) is beyond the scope of the paper. They allow to assess the working posture in terms of comfortableness by the joint angles of the pilot body. One of the specific cases is the pilot station design with side controllers for the fly–by–wire control system.

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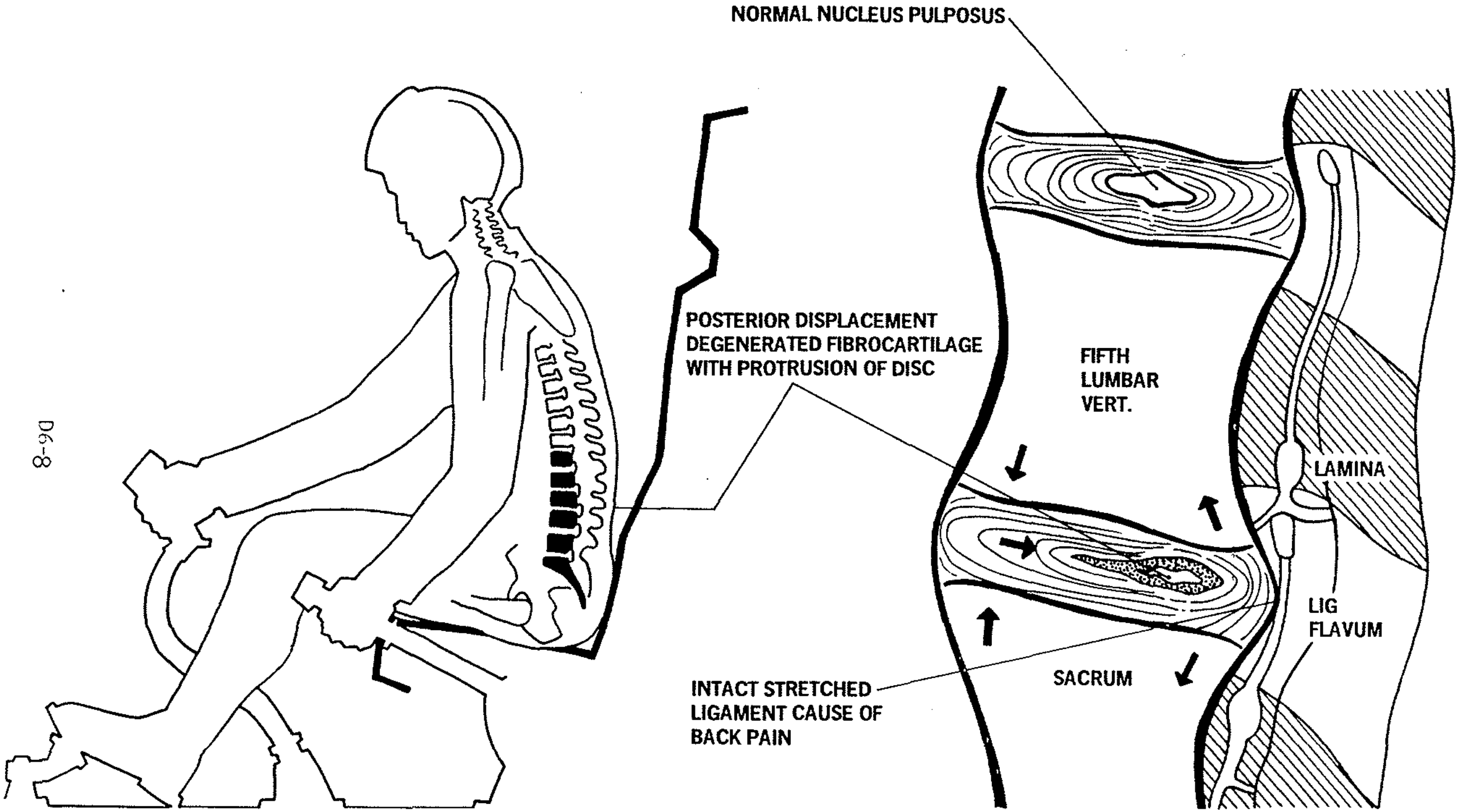
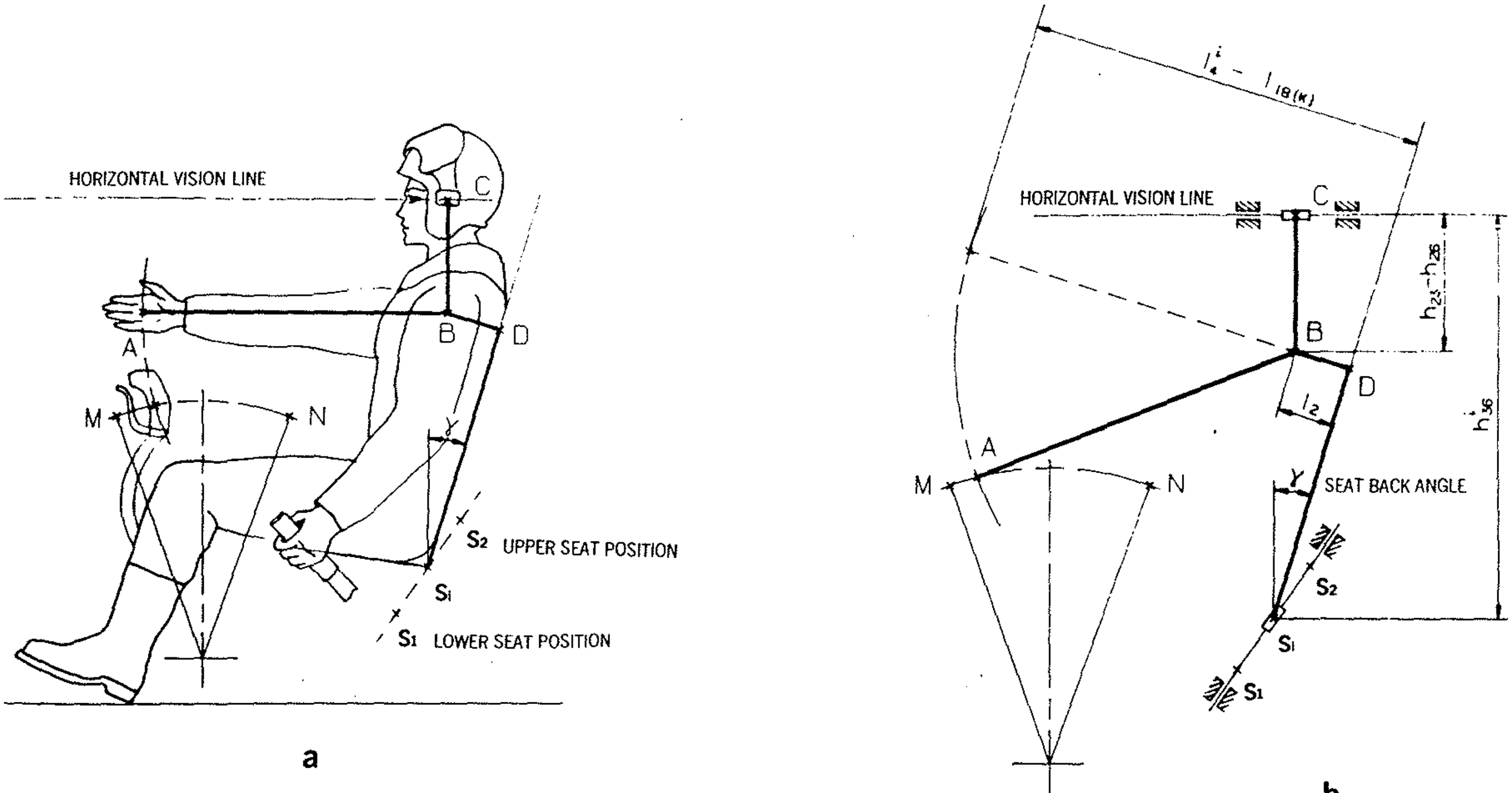
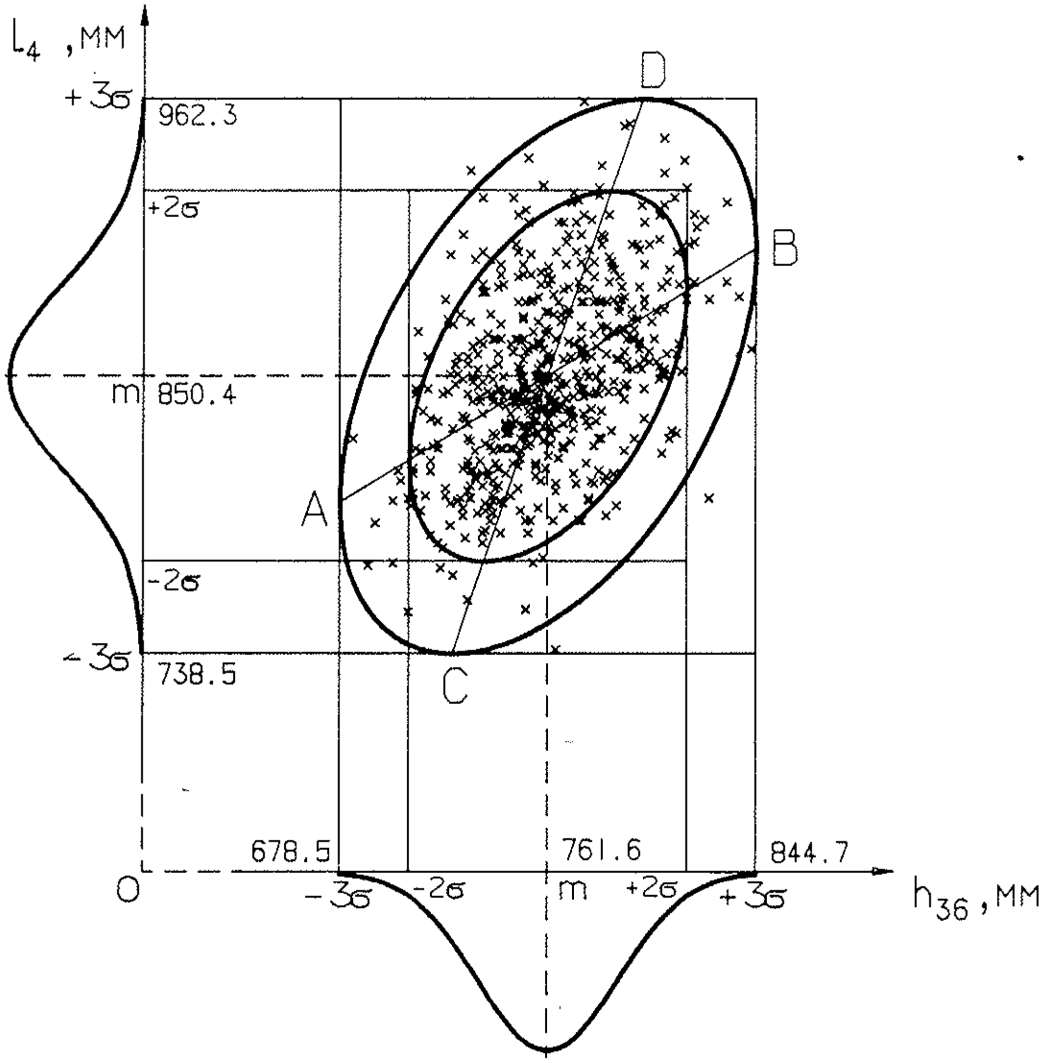

NORMAL NUCLEUS PULPOSUS
POSTERIOR DISPLACEMENT
DEGENERATED FIBROCARTILAGE
WITH PROTRUSION OF DISC
FIFTH
LUMBAR
VERT.
LAMINA
LIG
FLAVUM
SACRUM
INTACT STRETCHED
LIGAMENT CAUSE OF
BACK PAIN

Figure 1


HORIZONTAL VISION LINE
C
A
B
D
M
N
γ
S2 UPPER SEAT POSITION
Si
S1 LOWER SEAT POSITION
HORIZONTAL VISION LINE
C
$l_4 - l_{18(K)}$
$h_{23} - h_{26}$
h_{36}
B
D
l_2
A
M
N
γ SEAT BACK ANGLE
S2
Si
S1

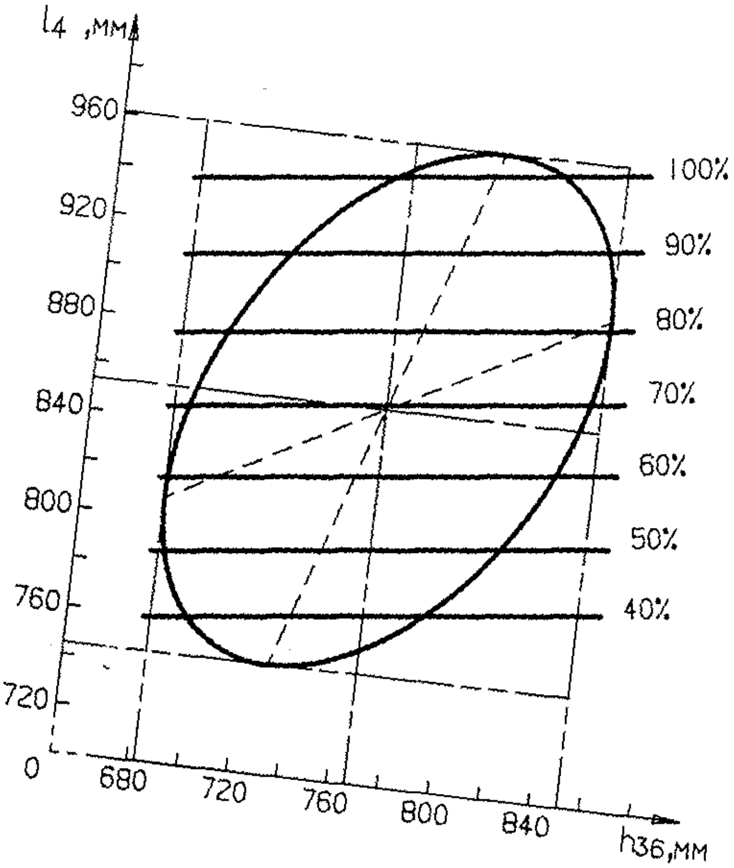
a b

Figure 2



L4 ,MM
+3σ
962.3
+2σ
m
850.4
-2σ
-3σ
738.5
D
B
A
C
678.5
761.6
844.7
O
-3σ
-2σ
m
+2σ
+3σ
h36 ,MM

Figure 3



l4 ,мм
960
920
880
840
800
760
720
0
680
720
760
800
840
h36,мм
100%
90%
80%
70%
60%
50%
40%

Figure 4

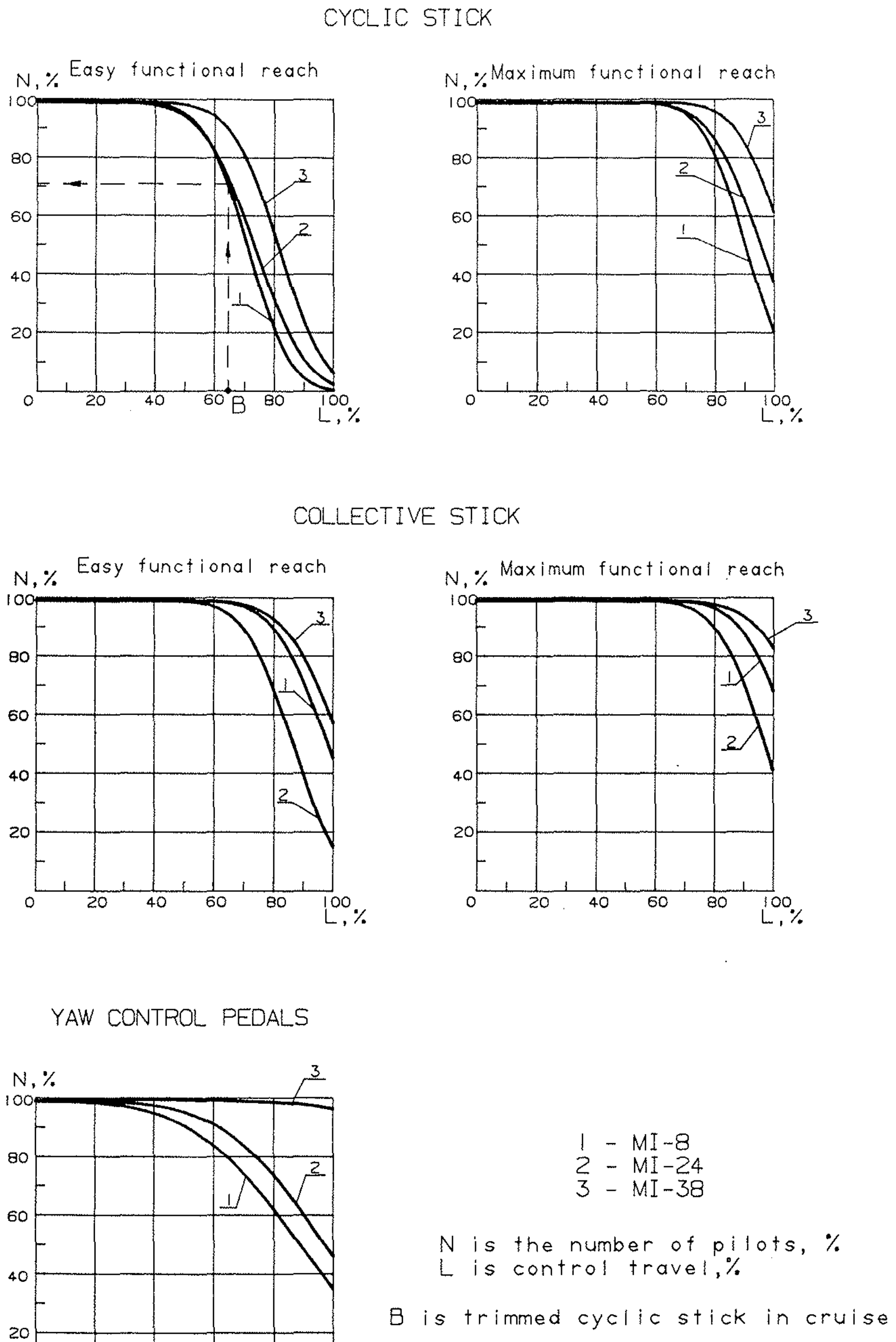

CYCLIC STICK
Easy functional reach
Maximum functional reach
N, %
L, %
B
COLLECTIVE STICK
Easy functional reach
Maximum functional reach
N, %
L, %
YAW CONTROL PEDALS
N, %
L, %
1 - MI-8
2 - MI-24
3 - MI-38
N is the number of pilots, %
L is control travel, %
B is trimmed cyclic stick in cruise

FIGURE 5