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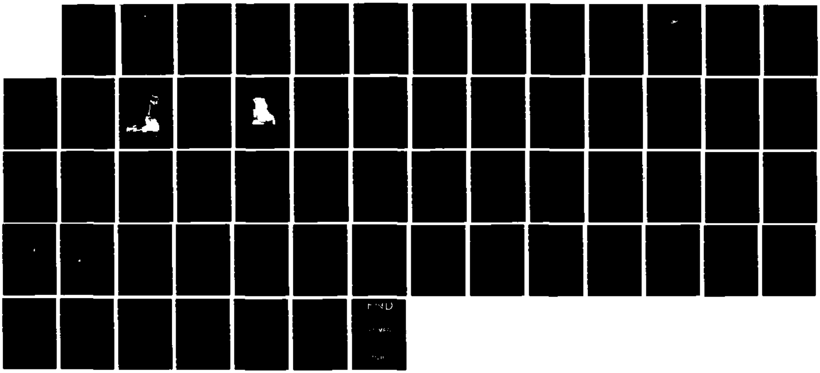

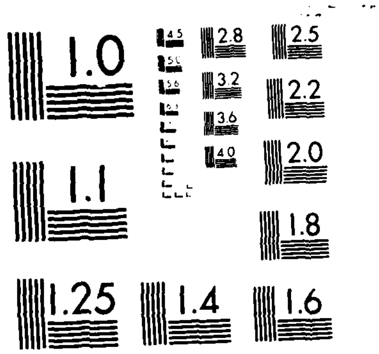

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MELBOURNE, VICTORIA

SYSTEMS REPORT 29

A GRAPHIC ANTHROPOMETRIC AID FOR SEATING AND WORKPLACE DESIGN

by

K. C. HENDY, K. W. ANDERSON and D. M. DRUMM

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SUMMARY

In recent workplace design projects at ARL, a procedure for the use of anthropometric information has been developed which relies on the use of sets of anthropometric data from individuals rather than the conventionally used pooled data. This Report describes a graphic anthropometric design aid which has been devised to assist in the implementation of this procedure. The aid predicts the positions, in side elevation, of certain cardinal points which are considered to be important to the design process, viz. the eye, thumb tip reach, knee point, seat reference point and heel point. This Report also contains details of the design aid's validation, the concept of the aid's use and the fidelity of the aid within the design process.

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Letter on file

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1. INTRODUCTION

Anthropometry is the science of human body measurement and therefore it should be the cornerstone for the design of all workplaces in which man is to function. Anthropometric data encompasses the measurement of people in dynamic work-related movement as well as in static stereotyped postures. The use of anthropometric data in the design process will not necessarily ensure an ideal layout, but the disregard of these data will probably mean that a significant proportion of the user population will be disadvantaged in their performance of the tasks expected of them. Further, it is not sufficient to rely on the designer's commonsense for a solution. The cockpits of many aircraft (Cressman 1972, Anderson, Clark, Hendy and Ross 1975, Hendy 1979*a* for example) demonstrate that such reliance would often be misplaced. Perhaps this sense is not as common as is often supposed.

Access to anthropometric data alone is not necessarily the designer's panacea. In order to make constructive use of these data a knowledge of the terms and concepts underlying the measurements is required. Even when the designer is armed with this knowledge, the success of the final outcome depends on a thorough understanding of the iterative nature of workplace design. This situation is rarely better demonstrated than in the design of an aircraft cockpit where a combination of rigidly specified requirements (e.g. various internationally agreed specifications), limited space and operational goals are sometimes mutually incompatible. In cockpit design the often tenuous correlation between various anthropometric variables adds a further difficulty to the problem. Compromises are required, and it is the role of the human factors specialist to assist in the manipulation of the set of design parameters in a manner which is intended to optimize man–machine system performance.

Anthropometric data exist in several forms. The most basic way in which these data have been made available to designers is in tabular form, usually as percentile values. In all but the simplest design exercises tabular data are of limited use. Two-dimensional articulated manikins, in various scales up to full-size, provide a means of presenting anthropometric data in a readily interpretable and usable format. These manikins have the advantage of providing some insight into dynamic anthropometry, although the accuracy of the conclusions that might be drawn depends on the fidelity with which the articulation of the manikin represents the range of movement of the human body.

It is generally supposed that a design which accommodates both the small person and the large person will be satisfactory for those who lie between these extremes. Accordingly, designers often use a *5th percentile person* and a *95th percentile person* to represent the extent of the design range. It is this philosophy which is embodied in many manikin designs (e.g. McConville and Laubach 1978) and their computer-graphic counterparts (e.g. Ryan 1970, Evans, Himes and Kikta 1976). However, in the cockpit a pilot must have adequate field of view and clearance from aircraft structures, be able to reach critical hand and foot controls and have access to arrays of knobs, switches and controls. These requirements are to be met with design constraints that usually imply minimum dimensions, minimum mass and minimum adjustability. Under these circumstances the imperfect correlation between different anthropometric variables (Moroney and Smith 1972) means that the concept of an *Nth percentile person* is, to a large extent, fallacious.

It may not be the large or small pilots who limit certain cockpit dimensions but rather those of, say, average stature but with long trunks and relatively short legs. This situation was demonstrated in recent ergonomic studies of the RAAF Airtrainer CT-4A cockpit (Anderson and Hendy 1983). For the CT-4A study, cockpit redesign was based on the concept of fitting a given percentage of individuals for which adequate anthropometric data existed, rather than use the conventional approach based on pooled anthropometric data. To assist the implementation of this approach, a simple graphic anthropometric design aid was developed for use in the CT-4A studies. This aid predicts, in side elevation, the positions of certain cardinal points for individuals given their basic anthropometric data. These cardinal points are: eye point, shoulder point, thumb tip reach, seat reference point, knee point and heel point of individual seated operators. The aid is intended for the specific purposes of defining the range and method of seat adjustment, the location of foot and hand controls, dash panel location and angles of view. The simple two-dimensional model, on which the aid is based, is not intended to be an articulated stick-man and hence it should not be used to define dynamic reach envelopes or volumetric relationships. These capabilities *inter alia* would require a model that duplicated, more accurately, the human skeletal link structure.

The structure of the graphic anthropometric design aid, its manner of use and its experimental validation are described in this Report. Confidence limits are developed from experimental data and presented in a way which directly relates to the use of the aid in workplace design. Although the aid was originally developed and validated for the specific geometrical arrangement of a particular workplace, a method is presented to extend the procedure to other comparable geometries.

2. A TWO-DIMENSIONAL MODEL BASE

The aid is based on a simple two-dimensional link model. This link model is shown in Figure 1 against an outline human form. The anthropometric parameters available and the specific use for which the aid was intended both influenced the form taken by the model. However, the fact that the aid is based on the type of variable that is routinely gathered as part of most anthropometric surveys extends, in some respects, the potential usefulness of the device.

The 1977 Australian tri-service anthropometric survey (Hendy 1979*b*, *c*) provides a data base of 32 anthropometric variables for members of various specialist trade groups within the three military branches of the Australian Defence Forces. One such specialist group consists of a combined services AIRCREW group. It is this group which has provided input data for the aid in all applications to date. Data from other groups can be used as appropriate.

The model shown in Figure 1 predicts the projected positions, in the midsagittal plane, of the points E, A, T, S, P, K and H. These cardinal points equate to anatomical landmarks as follows:

(i) *eye point* E, the corneal pole;

(ii) *shoulder point* A, a point on the extended (assumed to be rigid) backrest at its intersection with a horizontal plane containing the acromion;

(iii) *thumb point* T, a point, in the horizontal plane containing the acromion, defining the thumb tip reach with an allowance for shoulder extension;

(iv) *seat reference point* S, the intersection of the seat plane and the backrest;

(v) *popliteal point* P, the position of the popliteal with a correction made for leg extension;

(vi) *knee point* K, a point on the upper surface of the thigh directly above the popliteal; and

(vii) *heel point* H, a point at the intersection of the heel with the ground plane, with the foot flexed at 90° to the leg and with an allowance made for footwear.

The link lengths were derived from conventional anthropometric measures corrected where necessary for stretch, slump, leg extension etc. Where possible, the link lengths were computed using appropriate data from various source documents. In those cases not adequately covered by the literature the links were chosen empirically with the intention to correct them, during the

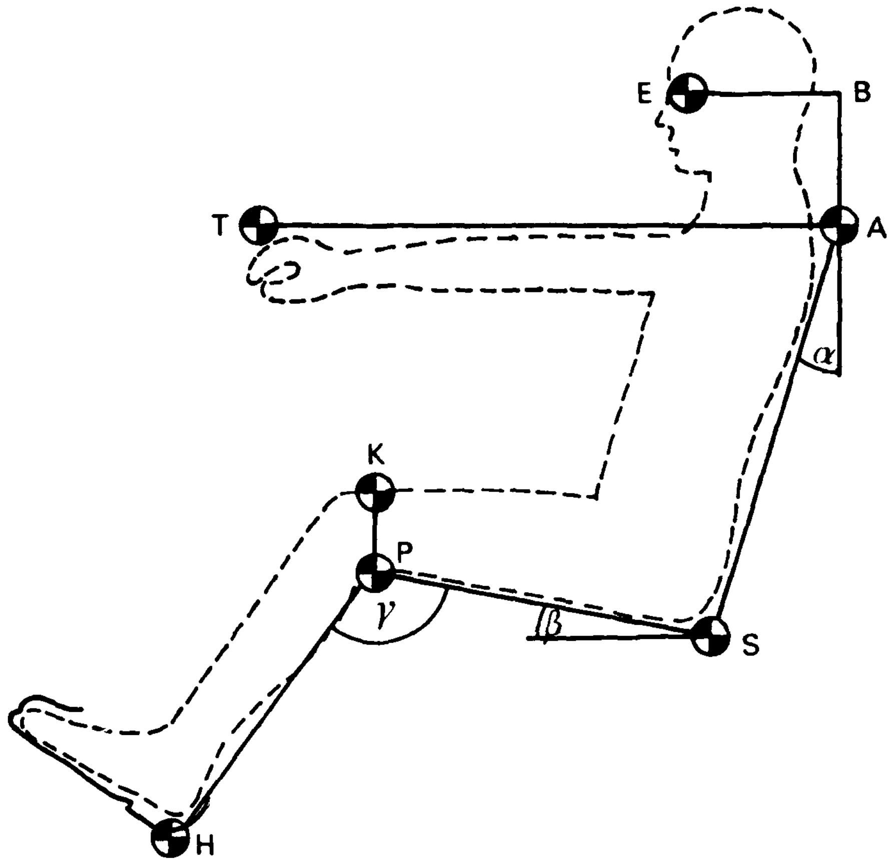


FIG. 1 A TWO-DIMENSIONAL MODEL BASE

validation experiment, on a trial and error basis. As it was planned to validate the parameter set, the form of the computations used to derive the initial estimates of the link lengths is of minor importance. However the basis for these computations is listed below for completeness:

(a) link EB was computed from the design eye position given in US MIL STD 1333A (see References) for 15° backrest angle together with the 50th percentile ACROMIAL HEIGHT (SITTING), corrected for 'slump' (see (c) below), derived from the 1977 Australian tri-service anthropometric survey data for the combined AIRCREW group (Hendy 1979*c*);

(b) link AT allows for an increase in reach capability through an extension of the shoulder (Diffrient, Tilley and Bardagjy 1974);

(c) link AS includes a correction for torso shortening due to slump (Ryan 1970);

(d) links SP and PK were based on the ratio of BUTTOCK TO POPLITEAL LENGTH: BUTTOCK TO KNEE LENGTH with an empirical adjustment for leg extension (Churchill 1978); and

(e) link HP contains an empirical adjustment for footwear (25 mm) and leg extension (40 mm).

The link lengths used for the initial model were as follows:

link EB = 275 mm;

AB = EYE HEIGHT (SITTING) − ACROMIAL HEIGHT (SITTING);

AT = FUNCTIONAL REACH + 120 mm;

AS = ACROMIAL HEIGHT (SITTING) − 35 mm;

SP = 0·91 (BUTTOCK TO KNEE LENGTH);

PK = 0·17 (BUTTOCK TO KNEE LENGTH); and

HP = POPLITEAL HEIGHT + 65 mm.

3. CONCEPT OF USE

To see the aid in the proper context it is appropriate to consider, briefly, how the device might be used to solve a workplace design problem. Suppose a workplace is to be designed, or an existing one modified, in which the following aspects are of fundamental importance to the layout:

(i) the operator's eye position, or perhaps a line defining the limiting downwards angle of view;

(ii) the range and the method of seat adjustment;

(iii) the operator's reach to the panel;

(iv) the clearance between the operator's knee and various structures in the workplace; and finally

(v) the required range and nature of foot pedal adjustment.

The items (i) to (v) represent an initial set of design parameters that are common to many vehicular cabin designs.

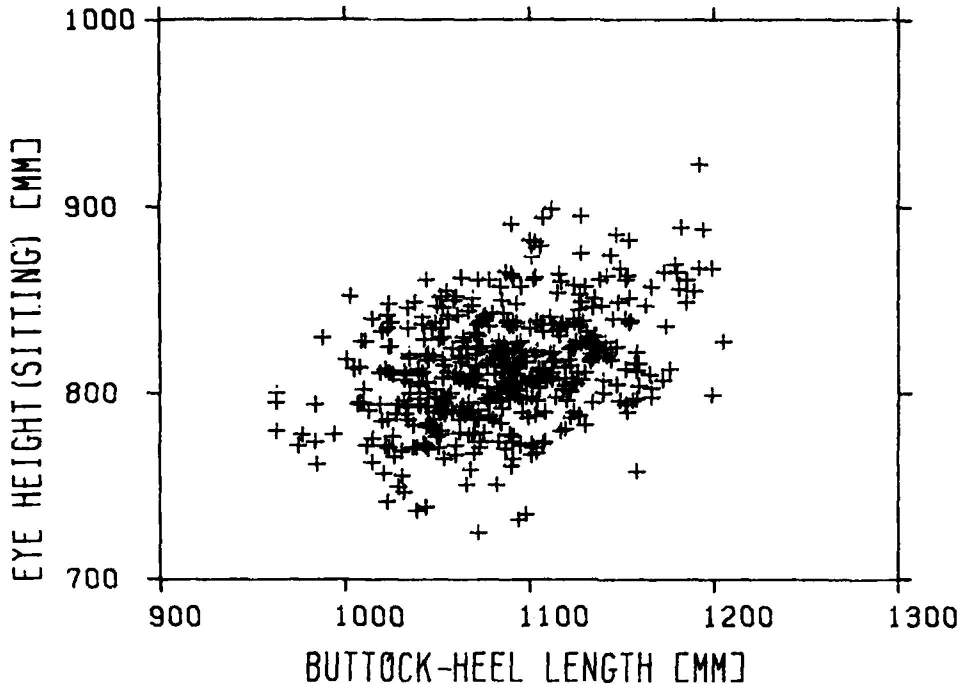


FIG. 2 : BIVARIATE DISTRIBUTION FOR EYE HEIGHT (SITTING) AND BUTTOCK TO HEEL LENGTH

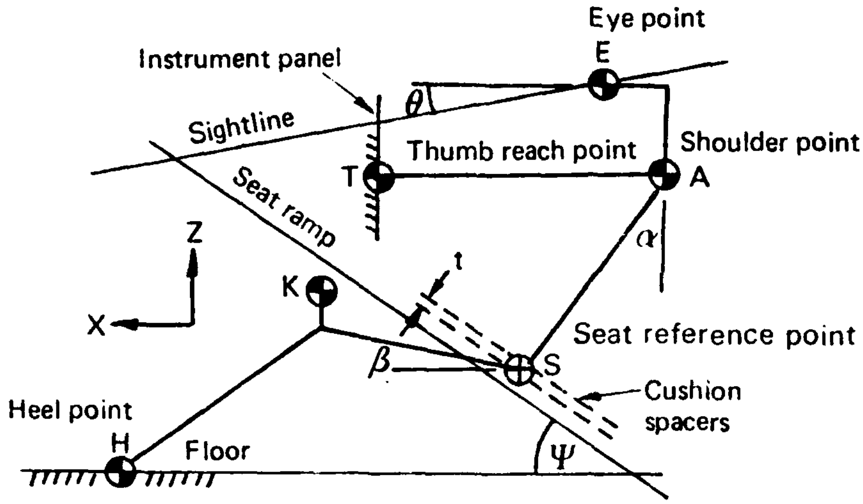


FIG. 3 APPLICATION OF THE GRAPHIC ANTHROPOMETRIC DESIGN AID TO WORK PLACE DESIGN

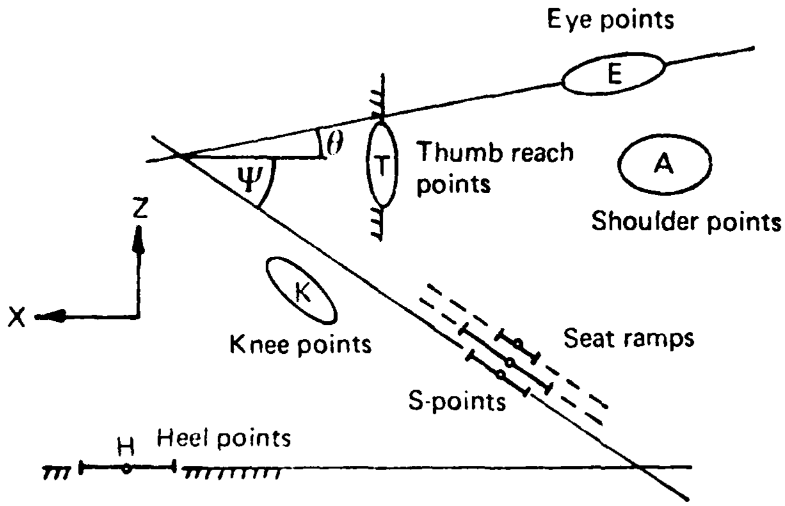


FIG. 4 DISTRIBUTIONS OF CARDINAL POINTS

In attempting to optimize a layout, the designer may require answers to questions such as:

(a) if a simple one-dimensional sliding seat adjustment is used, is there an optimum ramp angle for the mechanism; and

(b) what effect would limited pedal adjustment have on the range and method of seat adjustment?

Answers to these questions are not easily found by the conventional application of anthropometric data. If eye height and pedal reach are each important to the design then a seat that rose as it was moved forwards along the ramp may be appropriate. The 'best' ramp angle could be estimated, in this case, from the bivariate distribution of EYE HEIGHT (SITTING) and BUTTOCK TO HEEL LENGTH as indicated in Figure 2. But, what would happen to this ramp angle if the angle of view is more important than eye height, or if the ability to reach the panel must also be considered and what effect would leg flexion have? The graphic anthropometric design aid is intended to deal with this class of problem.

The way in which the aid might be used to optimize a workplace design can be illustrated by considering, briefly, the redesign of the CT-4A cockpit (Anderson and Hendy 1983). Note that 'optimum' would rarely be meant to imply mathematical precision, rather it will be the designer's assessment of a satisfactory trade-off between the various factors determining the workspace. However, given an appropriate cost function, use of the aid does lend itself to a true mathematical optimization. Within the accuracy of the model and the often arbitrary way in which the cost function would be constructed, the precision of a mathematical solution would be more apparent than real and would seldom be warranted. For the CT-4A the starting point for redesign was the following set of constraints:

A. a line defining the pilot's limiting downwards angle of view in the forward direction;

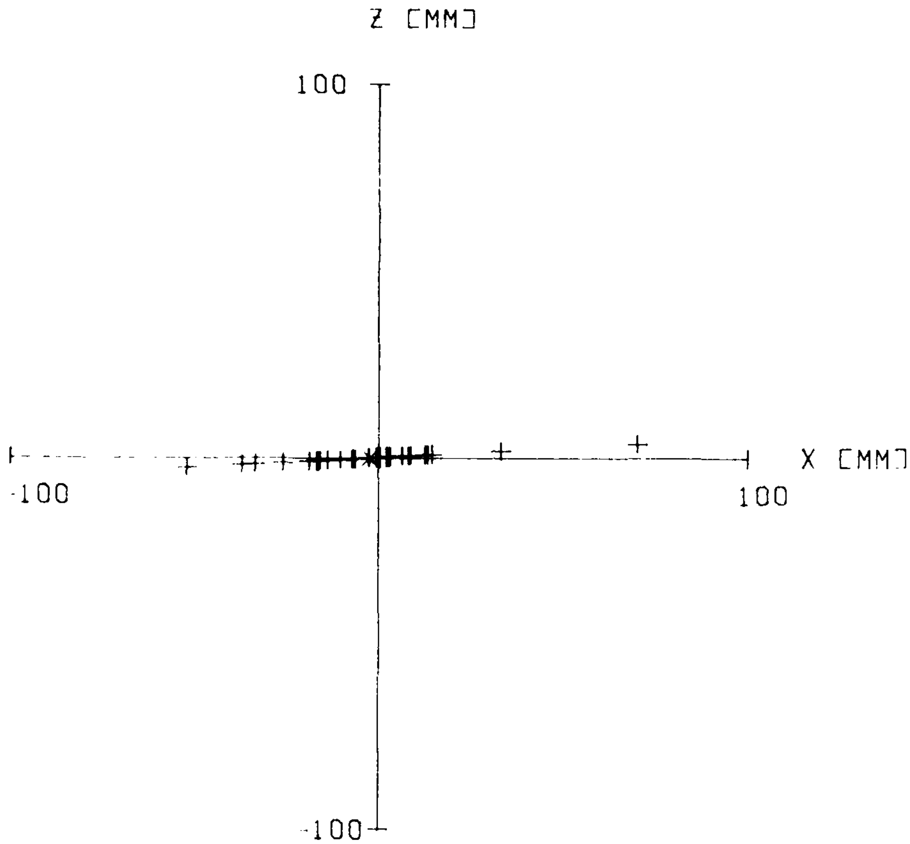
B. the positions of the instrument panel and the cockpit floor (already fixed by the existing fuselage structure): and

C. a simple, one degree of freedom, seat adjusting mechanism (with seat cushion spacers if necessary to allow a second degree of freedom).

The design strategy used for this project was as follows. Values were set for the thigh and backrest angles α and β, and unique solutions were sought to the problem of fitting the E- and T-points to the sightline and to the instrument panel, respectively, for each subject represented in the combined AIRCREW group data file (see Figure 3). It is not proposed to discuss the algorithms that were used to achieve these solutions, but geometrically it can be seen that a unique solution, jointly satisfying the E- and T-point requirements, can be obtained by sliding the model's E-point down the sightline until the T-point reaches a line corresponding to the instrument panel. Once the E- and T- points were fixed, the S-points were also plotted for each subject. At this stage the locations of the knee and heel points were not considered.

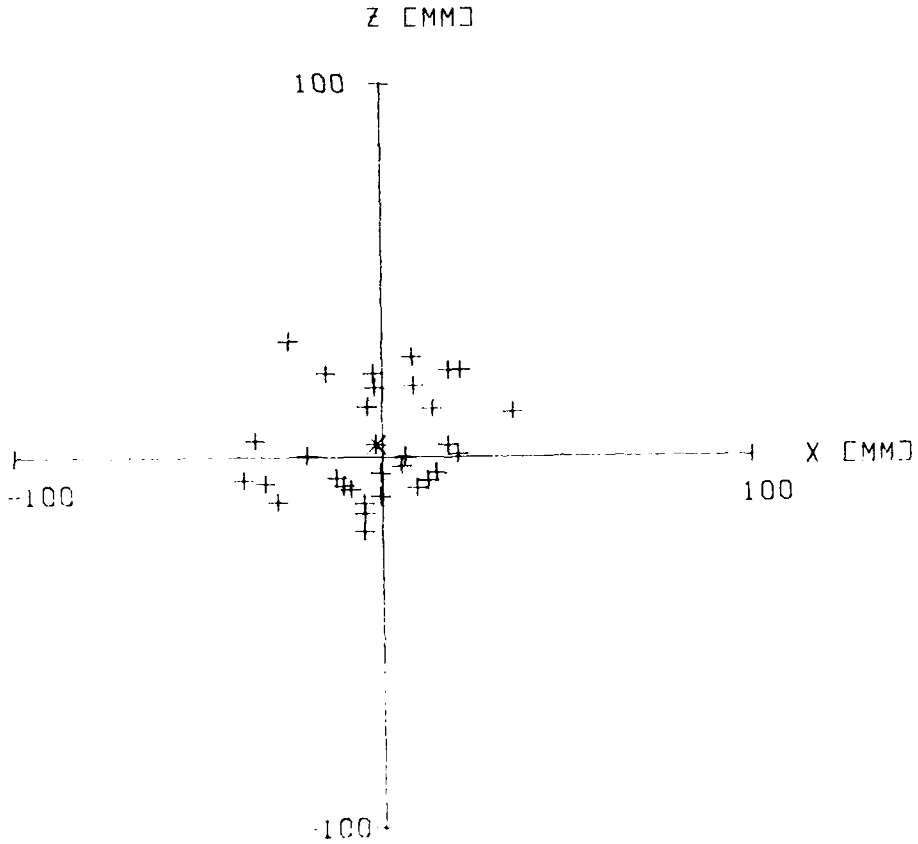
The plotted S-points formed a two-dimensional scattergram from which the coefficients, of equations of the form $z = mx + c_n$, were estimated. These equations described the locus of seat reference points for any given seat ramp angle and for n cushion spacers of thickness t (see Figure 3). The slope of the seat ramp equation m was determined by the angle ψ, but the positioning of these lines, from the choice of c_o, was at the discretion of the designer. The aim was, obviously, to have these ramps span the space occupied by the scattergram of S-points.

The next stage of the process was to constrain all S-points to fall on one of the seat ramp lines (i.e. $z = mx + c_n$: $n = 0, 1, 2, \ldots$). This was achieved by repeating the unique solution for the E- and T-points for each subject but this time the differences between the resulting S-point coordinates and the nearest seat ramp ($n = 0, 1, 2, \ldots$) were computed. All S-point positions were adjusted until they lay on a seat ramp line and the positions of all remaining points (E, A, T, K and H) were recomputed with respect to the now fixed S-points. This process produced scattergrams, in one and two dimensions, as represented schematically in Figure 4. Note that



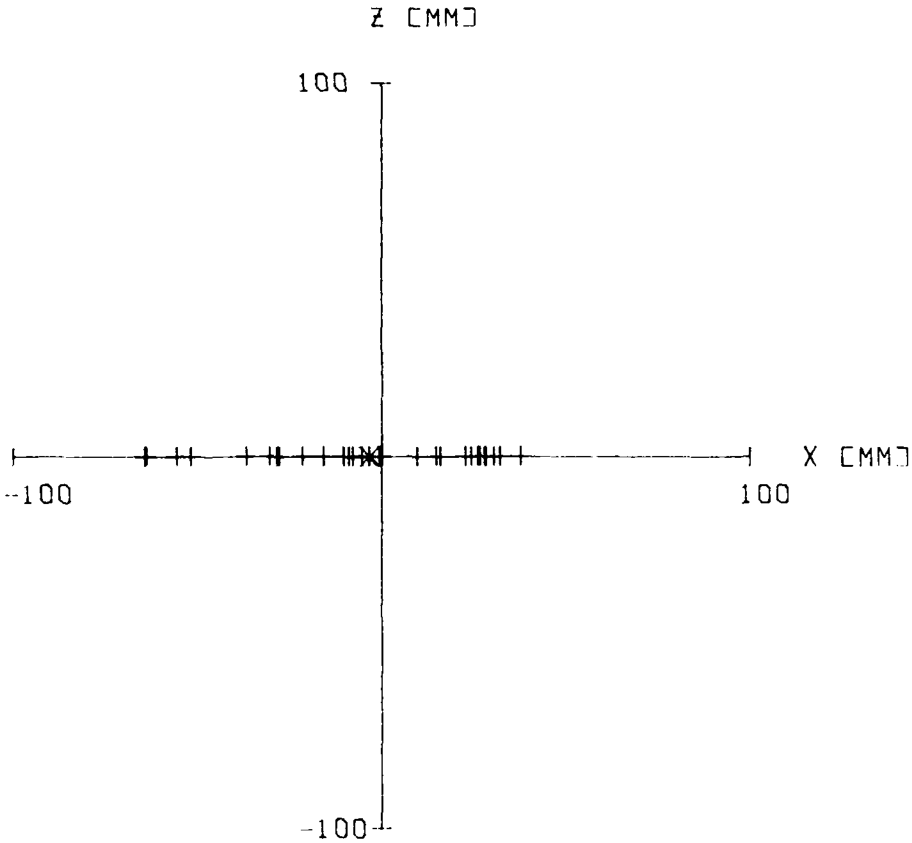
MEAN (X)	:	- 2.8	MM
STD. DEV. (X)	:	21.3	MM
MEAN (Z)	:	- 0.1	MM
STD. DEV. (Z)	:	1.1	MM
COVARIANCE	:	23.9	MM^2
CORREL. COEF.	:	1.0	

FIG. 14 : ERROR VECTOR FOR PREDICTED POSITION MINUS MEASURED POSITION ; HEEL (REVISED MODEL)



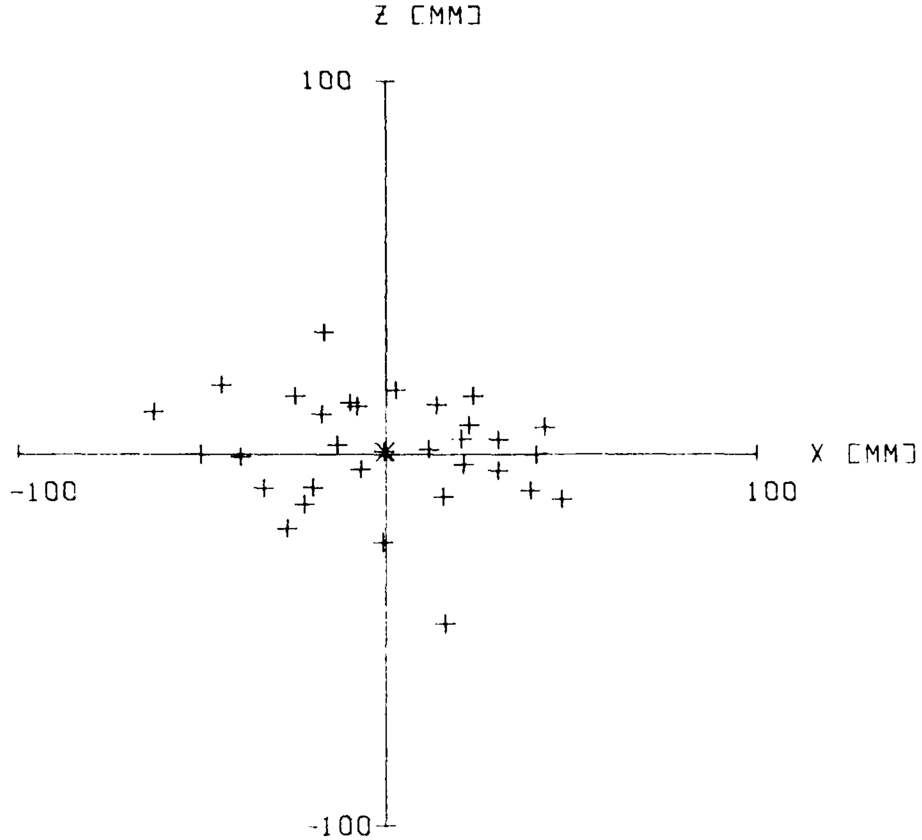
MEAN (X)	:	2.0 MM
STD. DEV. (X)	:	17.6 MM
MEAN (Z)	:	3.2 MM
STD. DEV. (Z)	:	14.0 MM
COVARIANCE	:	57.6 MM^2
CORREL. COEF.	:	0.2

FIG. 13 : ERROR VECTOR FOR PREDICTED POSITION MINUS MEASURED POSITION ; KNEE (REVISED MODEL)



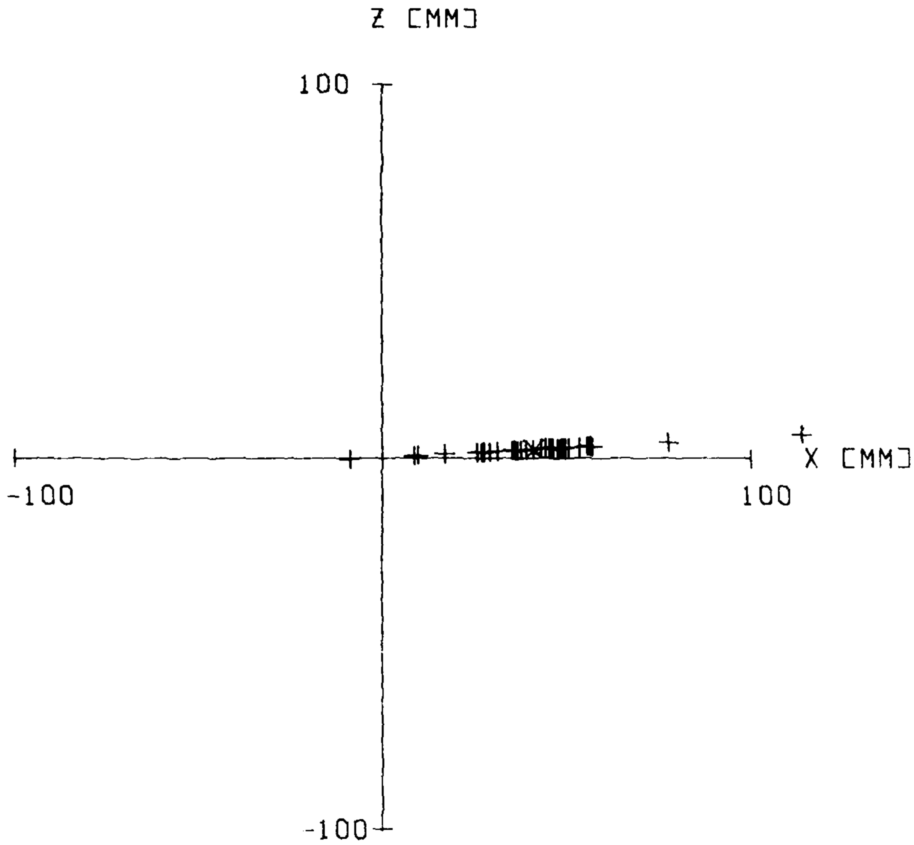
MEAN (X)	:	3.8	MM
STD. DEV. (X)	:	29.7	MM
MEAN (Z)	:	0.0	MM
STD. DEV. (Z)	:	0.0	MM
COVARIANCE	:	0.0	MM^2

FIG. 12 : ERROR VECTOR FOR PREDICTED POSITION MINUS MEASURED POSITION ; THUMB (REVISED MODEL)



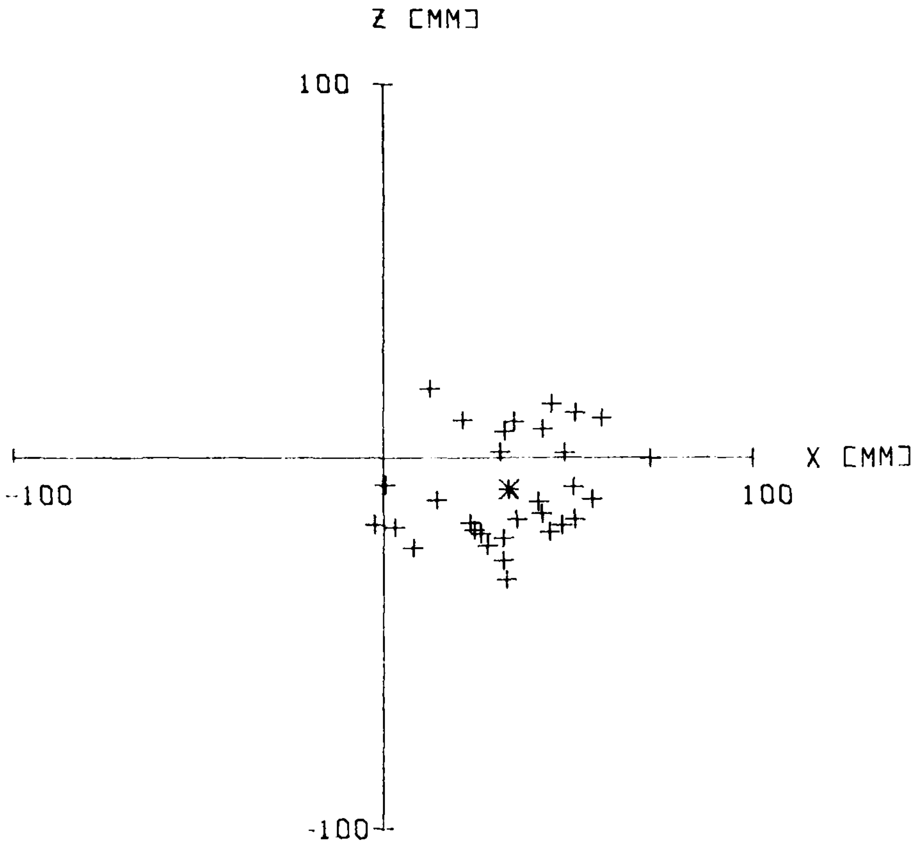
MEAN (X)	: - 0.7	MM
STD. DEV. (X)	: 29.1	MM
MEAN (Z)	: 0.6	MM
STD. DEV. (Z)	: 14.9	MM
COVARIANCE	: -74.7	MM^2
CORREL. COEF.	: - 0.2	

FIG. 11 : ERROR VECTOR FOR PREDICTED POSITION MINUS MEASURED POSITION ; EYE (REVISED MODEL)



MEAN (X)	:	40.9 MM
STD. DEV. (X)	:	21.3 MM
MEAN (Z)	:	2.1 MM
STD. DEV. (Z)	:	1.1 MM
COVARIANCE	:	23.7 MM^2
CORREL. COEF.	:	1.0

FIG. 10 : ERROR VECTOR FOR PREDICTED POSITION MINUS MEASURED POSITION ; HEEL (ORIGINAL MODEL)



MEAN (X) : 33.9 MM

STD. DEV. (X) : 17.9 MM

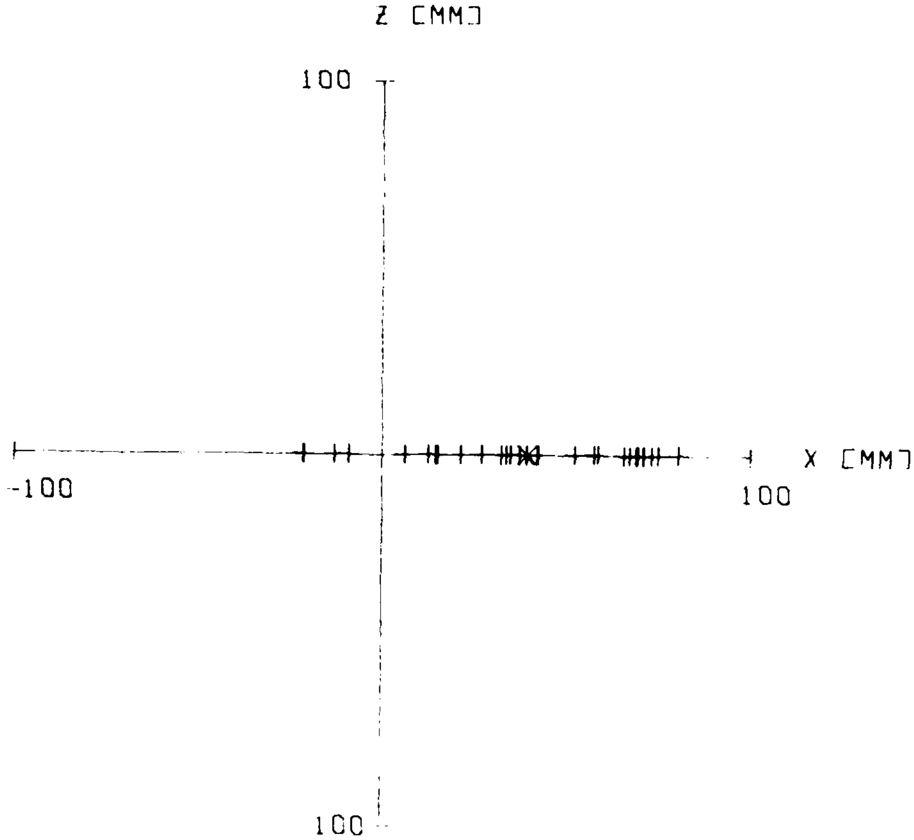
MEAN (Z) : - 8.7 MM

STD. DEV. (Z) : 13.9 MM

COVARIANCE : 60.9 MM^2

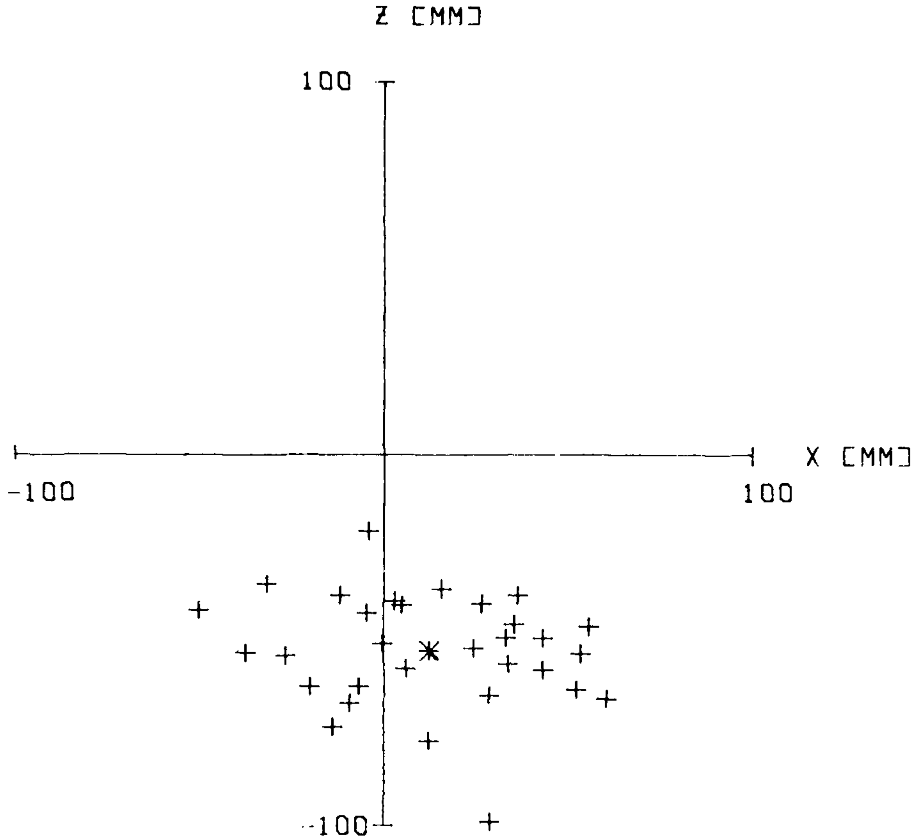
CORREL. COEF. : 0.2

FIG. 9 : ERROR VECTOR FOR PREDICTED POSITION MINUS MEASURED POSITION : KNEE (ORIGINAL MODEL)



MEAN (X)	:	39.2 MM
STD. DEV. (X)	:	29.7 MM
MEAN (Z)	:	0.0 MM
STD. DEV. (Z)	:	0.0 MM
COVARIANCE	:	0.0 MM^2

FIG. 8 : ERROR VECTOR FOR PREDICTED POSITION MINUS MEASURED POSITION : THUMB (ORIGINAL MODEL)



MEAN (X)	: 12.2	MM
STD. DEV. (X)	: 29.1	MM
MEAN (Z)	: -52.7	MM
STD. DEV. (Z)	: 14.9	MM
COVARIANCE	: -74.7	MM^2
CORREL. COEF.	: - 0.2	

FIG. 7 : ERROR VECTOR FOR PREDICTED POSITION MINUS MEASURED POSITION ; EYE (ORIGINAL MODEL)

as follows: measurement of cardinal points with the subject in full flying kit; conventional semi-nude anthropometry; and repeated measurement of cardinal points with the subject, again, in full flying kit.

4.3 Adjustment of the Model's Parameter Set

The error vectors for the function (*predicted position* minus *measured position*) were computed for each cardinal point, for all subjects. These error components are shown graphically in Figures 7 to 10.[1] The second set of cardinal point measurements was used in these computations. No attempt was made to take the mean, for each subject, of cardinal point measurements as bias was to be eliminated across, rather than within, subjects. Figures 7 to 10 indicate that in addition to random errors in the predicted points the initial set of model parameters resulted in substantial bias errors in the estimation of each of the cardinal points. It was considered appropriate to adjust the parameters of the model, by trial and error, to achieve a zero mean bias for each distribution of cardinal points.

To generalize, it appears that the first estimation of the model parameters allowed for excessive slump and arm stretch. In addition, the apparent increase in effective leg-link length, due to an increase in the angle of extension at the knee joint, was somewhat less than was estimated. This was not unexpected considering the arbitrary way in which the original estimates were obtained. The direction and magnitude of the trunk and arm reach errors were not surprising either as the five-point harness and the process of locking the inertia reel tend to encourage a more upright posture to be adopted than would be the case with most domestic or vehicular seats, including those fitted with conventional two- or three-point restraint harnesses. Further, the parachute harness, 'Mae West' and seat harness restrict the amount of shoulder rotation (extension) during reaching to a greater extent than would be experienced by an automobile driver or by a pilot, even if wearing a conventional two- or three-point safety belt.

A revised set of model parameters was chosen in order to reduce the bias observed with the initial set. The adjustments were made iteratively and from an examination of Figures 7 to 10 the magnitude and direction of the required adjustment was usually obvious. The revised parameter set was:

Link EB = 275 mm:

AB = EYE HEIGHT (SITTING)—ACROMIAL HEIGHT (SITTING) + 5 mm;

AT = FUNCTIONAL REACH + 90 mm;

AS = ACROMIAL HEIGHT (SITTING) − 15 mm;

SP = 0·85 (BUTTOCK TO KNEE LENGTH);

PK = 0·20 (BUTTOCK TO KNEE LENGTH); and

HP = POPLITEAL HEIGHT + 55 mm.

The error vectors were computed for this revised data set and are shown plotted in Figures 11 to 14. In all cases the mean bias errors have been reduced to values that are of the same order as the standard errors of the estimates (i.e. $\sigma/\sqrt{N}$) and are small in comparison with the standard

[1] Note that the error vectors for the heel positions in Figures 10, 14 and 20 lie on a line inclined at 3° upwards from the horizontal. This corresponds to the configuration of the heel rest surface of the CT-4A.

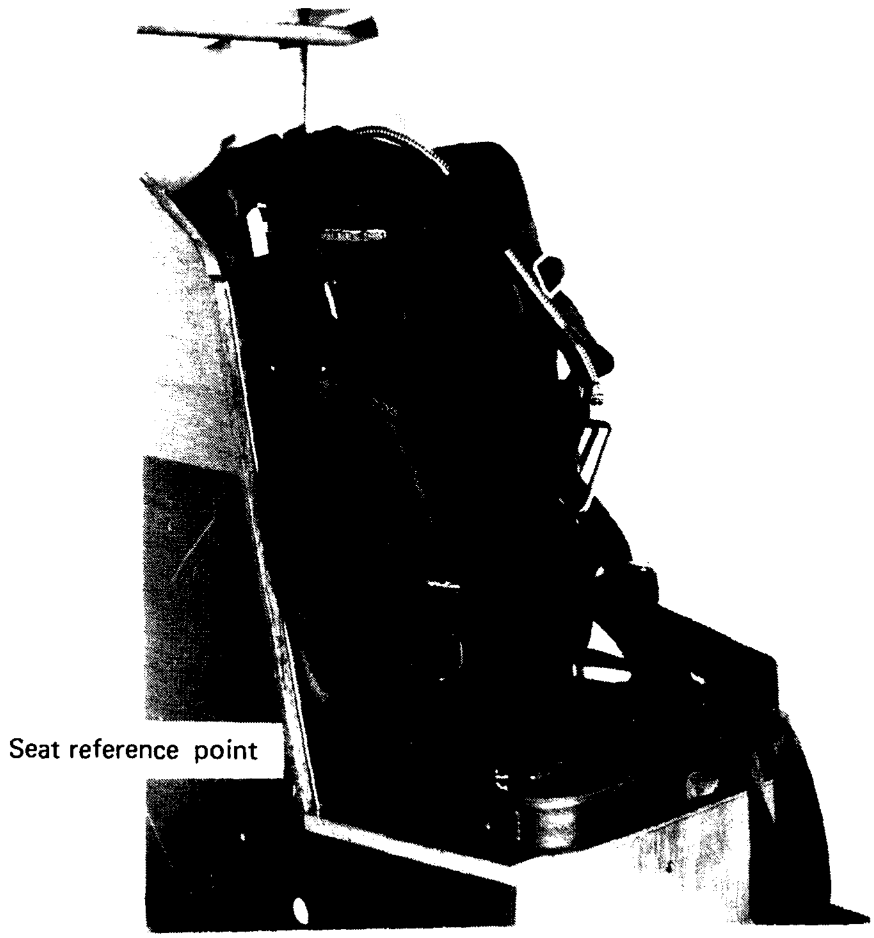


FIG. 6 LOCATION OF SEAT REFERENCE POINT

the subject was not required to maintain the fleshy region of the extended shoulder in contact with the wall. Generally, this region was clear of the end wall when the subject reached out. It is not known if a more rigorous constraint was used, in practice, during the 1977 survey and therefore it is possible that the techniques do differ in this respect.

4.2 Measurement of Cardinal Point Positions

For these measurements the subjects were seated in a special apparatus constructed to represent the seat and floor structure geometry of the CT-4A aircraft (see Figure 5). The five-point restraint harness fitted to the apparatus was made up from a GQ811 quick release box and lap straps, and a Teleflex Morse inertia reel with a shoulder harness of the type normally fitted to the CT-4A aircraft. A negative-g strap was made up from automobile safety belt fittings. This 'hybrid' five-point harness was intended to represent a modification proposed for the CT-4A based on the GQ811 harness. Although the hybrid harness is different from the standard Teleflex Morse CT-4A system, the differences are unlikely to bias the results significantly. Therefore, it is considered that measurements made of cardinal point positions will be valid for the hybrid GQ811 harness, the standard Teleflex Morse harness and indeed most other conventional five-point harness systems.

Subjects wore their personal issue clothing and equipment assemblies consisting of the following items:

(i) Nomex one-piece coveralls;

(ii) Nomex flying gloves;

(iii) Flying boots;

(iv) Mk 8 life preserver ('Mae West');

(v) HGU-2AP dual visor helmet or SP-4H general flying helmet; and

(vi) Canadian Flexipack parachute.

The procedure adopted for measuring cardinal point positions is described in Appendix III. To summarize, 6 cardinal point measurements were made for each of 31 instructor pilots. The subjects were seated in the special apparatus in full flying kit, wearing the five-point harness adjusted by each subject as if he were in an aircraft. When the subject was settled, and before measuring commenced, the shoulder harness was locked. The measurements were intended to represent the coordinates in two-dimensional cartesian space of the five cardinal points predicted by the aid, viz. eye, thumb, seat reference, knee and heel points. For convenience the horizontal component of the eye coordinates was inferred from the measured position of the nasal root depression. A 15 mm correction was applied to this measurement to give the estimated horizontal coordinate of the eye point. This correction was obtained from the difference between the mean values of CORNEA TO BACK OF HEAD and NASION TO BACK OF HEAD for RAF aircrew (Hobbs 1973). The value of 14·3 mm so obtained was rounded up to 15 mm. As the variances of these measures are small (standard deviations of approximately 6 mm), and assuming some correlation between the parameters, a constant correction of 15 mm is expected to be a sufficiently good estimate of the difference between these parameters for all subjects.

The seat reference point for the experimental rig was defined as the intersection of the forwardmost edge of the horizontally curved metal backrest with the seat cushion (see Figure 6). As the seat cushion was made of expanded polyethylene foam, which was essentially non-yielding, no allowance was made for cushion depression by the subject. The parachute pack filled the rounded depression in the backrest to the level of the forwardmost edge of the structure so that the seat reference point, as defined above, effectively treats the parachute as the backrest.

The cardinal points were measured twice for each subject so that an estimate could be made of the reliability of these measurements (see Section 5). The repeat measurements were made immediately following the session of conventional anthropometry. Therefore the sequence was

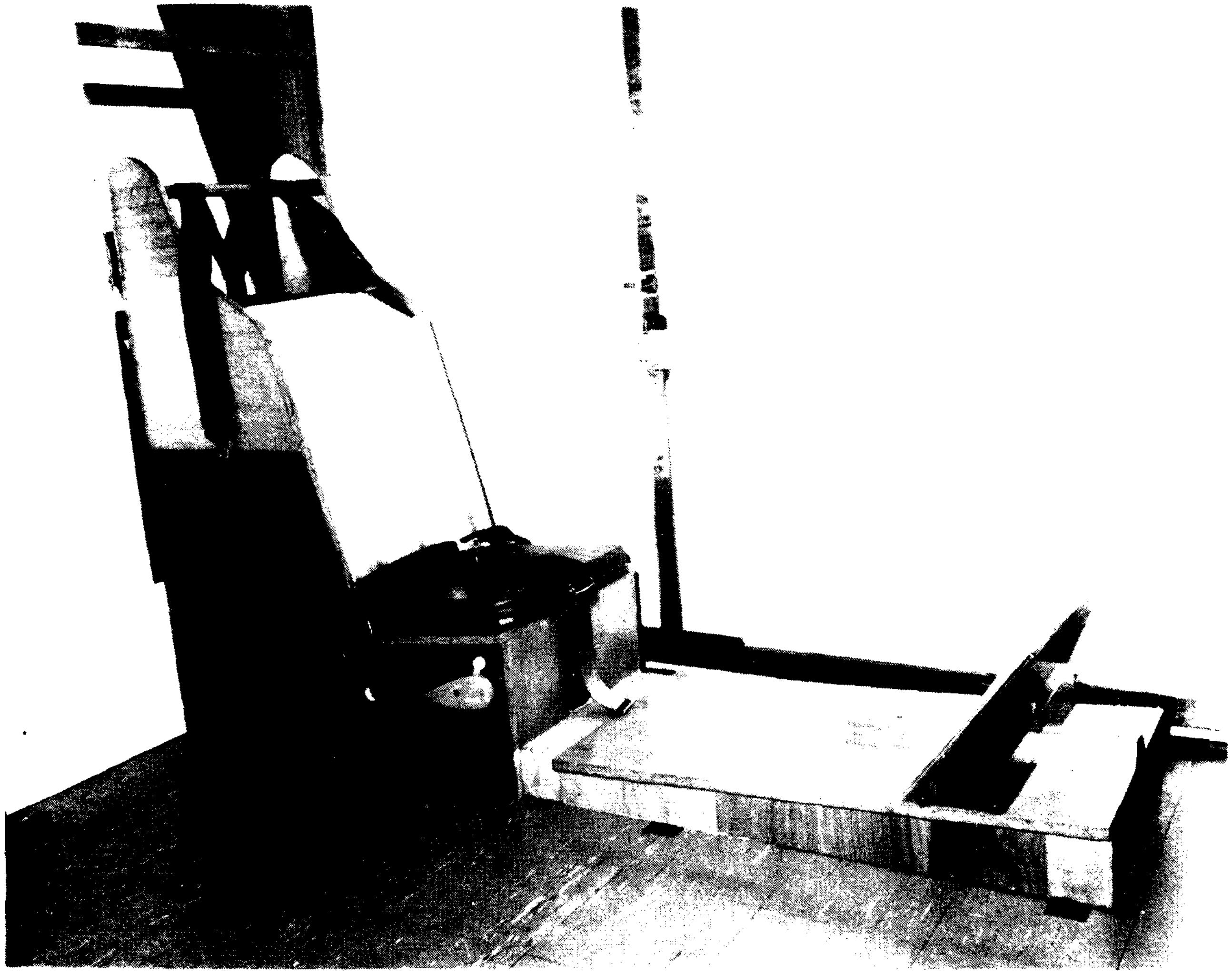


FIG. 5 APPARATUS REPRESENTING THE SEAT AND FLOOR STRUCTURE OF THE AIR TRAINER CT-4A AIRCRAFT

4.1 Conventional Anthropometry

Eight anthropometric measures were taken from the 31 instructor pilots using the equipment and procedures developed for the 1977 Australian tri-service anthropometric survey (Hendy 1979*b*). The variables measured were:

(i) EYE HEIGHT (SITTING);

(ii) ACROMIAL HEIGHT (SITTING);

(iii) FUNCTIONAL REACH;

(iv) BUTTOCK TO POPLITEAL LENGTH;[1]

(v) BUTTOCK TO KNEE LENGTH;

(vi) POPLITEAL HEIGHT;

(vii) KNEE HEIGHT;[1]

(viii) STOOL HEIGHT.

The data from the 31 subjects are shown in Appendix I together with the approximate percentile values estimated from the 1977 survey data.

Eleven of the subjects who participated in this validation experiment in 1980 were also measured in the 1977 survey. On each occasion the conventional anthropometric measures were made using the same equipment and, nominally, the same techniques and procedures. However a comparison of the two data sets for these individuals indicated that consistent differences exist, suggesting that despite the apparent similarities in techniques the subjects' postures were not the same on the two occasions. The three years difference in age was considered not to provide an explanation for these discrepancies. Appendix II lists the two data sets, the differences between 1980 and 1977 values and the means and standard deviations of the differences.

Two consistent trends are evident for the more recent data, viz. reduced sitting trunk height and increased functional reach. The apparent increase in 'slump' may be due to a subtle difference in instructions. In the 1977 survey subjects were asked to '. . . sit up straight to maintain an erect yet comfortable posture' (DSTO Trials Report 360, 1978), while in the present experiment subjects were asked '. . . to sit comfortably erect'. Perhaps this difference in emphasis in the instructions, or the subjects' greater awareness with the rig and the procedures, explains the apparently more relaxed posture in the recent measurements.

An explanation for increased functional reach is more elusive. In all measurements of functional reach made in the present survey, the subject's shoulder blades were '. . . symmetrically and lightly touching the perspex panel in the end wall of the measuring rig'. This position was confirmed by monitoring the region of contact of the subject's back with the perspex wall as shown by the image from the mirror behind the wall. However, when reaching out horizontally

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[1] These measurements were not taken in the 1977 survey. The following definitions apply. They should be read in conjunction with the 1977 survey Report (Hendy 1979*b*).

BUTTOCK TO POPLITEAL LENGTH: The subject sits erect, with feet flat on the floor and thighs parallel to the rear wall of the measuring rig. The subject is instructed: '. . . push your buttocks back until you have equal pressure of both buttocks against the perspex wall'. Both shoulder blades are symmetrically and lightly touching the perspex panel in the end wall of the measuring rig. With the sliding calipers measure the horizontal distance from the end wall to the underside of the tendon of the right biceps femoris muscle where it joins the calf (this is the popliteal).

KNEE HEIGHT: The subject sits erect, with feet flat on the floor, thighs horizontal and lower legs vertical (as determined by the upper and lower femoral and fibular marks respectively see Hendy 1979*b*). With the sliding calipers measure the vertical distance from the floor to the upper surface of the left thigh immediately above the popliteal.

the form of the S-point adjustment may be chosen by the designer. The adjustment could be vertical, horizontal or perpendicular to the ramp, and unidirectional (e.g. always upwards) or to the nearest ramp.

The above procedure was repeated for all representative values of the experimental variables. Typically these variables would include seat ramp angle ψ, thigh angle β, backrest angle α, range of pedal adjustment and the number of seat cushion spacers n. However, for the CT-4A the existing aircraft geometry limited the choice of experimental variables to ψ, β and n. These variables were manipulated until a suitable compromise was obtained between the expected reach capability of the user group, minimum range of seat adjustment and adequate angle of view.

Although this example of the CT-4A cockpit redesign was based on a seat which moved along a linear ramp, the locus of seat reference points does not need to be a straight line. Any path could have been described and a similar procedure applied. Likewise the seat reference points could be left free to vary in two dimensions in order that the total range of independent seat adjustment, necessary to satisfy particular design criteria, may be defined. It is the designer's prerogative to choose constraints which allocate the total variance of the system, appropriately, between the cardinal points of the model. For example, if the design is to achieve a minimum spread of eye points, the scatter normally associated with these points will be transferred to the other distributions. Similarly, if a fixed seat is used the eye and thumb point distributions will contain some of the variability that would otherwise contribute to the spread of S-points.

4. VALIDATION OF THE TWO-DIMENSIONAL MODEL

An experimental validation of the simple two-dimensional model described in Section 2 of this Report was conducted using 31 RAAF instructor pilots from Number 1 Flying Training School (1FTS) and the RAAF Academy, Point Cook. The validation, which is described in detail in the following sections, took the form:

(i) conventional anthropometry was used to measure the parameters necessary for the computation of the model link lengths;

(ii) the actual positions of the cardinal points predicted by the model were measured with each subject sitting, in flying kit, in a special apparatus; and

(iii) the differences between computed and measured points were used to make adjustments to the model as appropriate.

The validated model of stage (iii) above was used to evaluate a number of seating and pedal arrangements for proposed modifications to the RAAF CT-4A basic training aircraft. The same instructor pilots that were used in the validation of the model were placed in an accurate representation of the proposed CT-4A cockpit configuration in seat positions computed from the model. Comparisons of 'fit' in the pre-computed positions with those in subject-preferred positions provided a further aspect to the validation procedure (see Anderson and Hendy 1983, for further details). This present Report includes only those aspects of the formal validation described in (i), (ii) and (iii) above.

deviations. Any further refinements would result in, at most, one or two percent changes to parameters. Such 'fine tuning' was not considered to be justified.

5. FIDELITY OF THE MODELLING PROCESS

The procedure described in Section 4.3 above resulted in the adjustment of the model parameters to achieve suitably small errors in the estimates of the means of the cardinal point distributions. However, in keeping with the philosophy outlined earlier in this document, it is the spread of various individuals' cardinal points, about these central tendencies, that is considered to be important to the design process. Therefore, the fidelity of any model to represent the positions of real eyes, thumbs, knees etc. should be judged in terms of those boundaries that would be expected to enclose N-percent of these real cardinal points. In Sections 5.1 to 5.5 the theoretical basis for computing such boundaries for the specific situation represented by the CT-4A cockpit geometry is described; while in Section 5.6 the application of this theory to the simple two-dimensional model is discussed. The derived boundaries are not strictly general but they do provide a guide to the errors that might be expected from the use of the model in geometrically related layouts.

5.1 Errors Associated with the Prediction

Suppose that a direct measurement is made of the position in xz-space of a cardinal point (e.g. the eye) for the jth subject. Let this measurement be represented by a vector $\mathbf{M}_{ij}$ (see Figure 15), such that:

$$\mathbf{M}_{ij} = \mathbf{M}_j + r_{ij}, \tag{1}$$

where:

(i) $\mathbf{M}_j$ is the expected value of $\mathbf{M}_{ij}$ for the jth subject (i.e. the mean of $\mathbf{M}_{ij}$ over i); and

(ii) r_{ij} is a random vector associated with the uncertainty in measuring the position of the point represented by $\mathbf{M}_{ij}$.

Consider two independent estimates of $\mathbf{M}_{ij}$, viz. $\mathbf{M}_{mj}$ and $\mathbf{M}_{nj}$. Then (see Figure 16):

$$\mathbf{M}_{mj} = \mathbf{M}_j + r_{mj}, \tag{2}$$

and

$$\mathbf{M}_{nj} = \mathbf{M}_j + r_{nj}. \tag{3}$$

Now compute a *measurement error* vector $(m_j)_{mn}$, such that:

$$\begin{aligned}(m_j)_{mn} &= \mathbf{M}_{mj} - \mathbf{M}_{nj} \\ &= (\mathbf{M}_j - \mathbf{M}_j) + (r_{mj} - r_{nj}) \\ &= r_{mj} - r_{nj}.\end{aligned} \tag{4}$$

It is expected that $(m_j)_{mn}$ would be distributed with zero mean and non-zero variance if averaged over all $m \neq n$ for the jth subject. When averaged in this way, $(m_j)_{mn}$ would provide a measure of the intra-subject variability associated with the measurement of cardinal point position in xz-space.

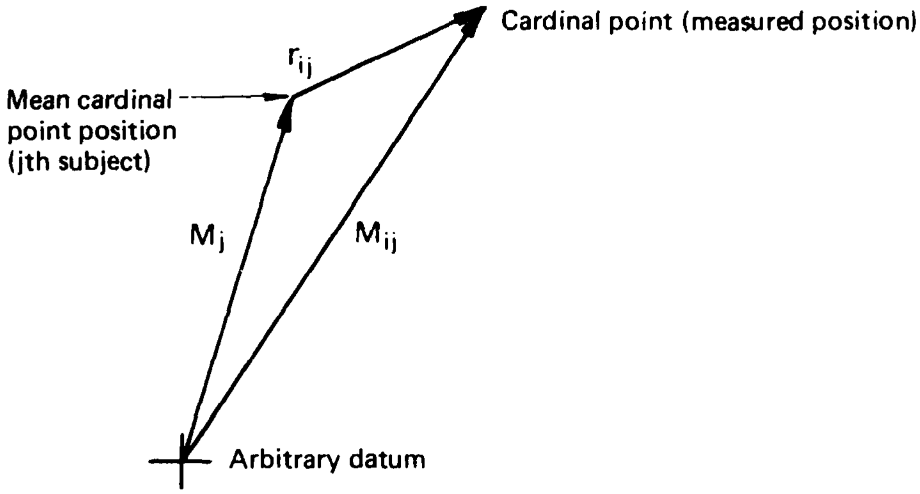


FIG. 15 MEASUREMENT VECTOR FOR THE jTH SUBJECT

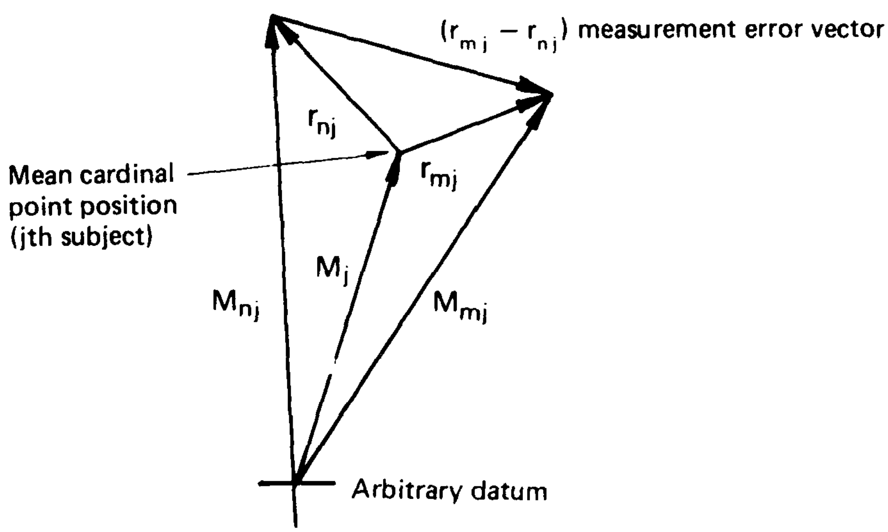


FIG. 16 INDEPENDENT ESTIMATES OF CARDINAL POINT POSITION FOR THE jTH SUBJECT

Similarly $(m_j)_{mn}$ could be averaged over j with m and n fixed, i.e. averaged over subjects. Again $(m_j)_{mn}$ would be expected to be distributed with zero mean and non-zero variance. However, when averaged over j with m and n fixed, $(m_j)_{mn}$ would provide a measure of the variability associated with the determination of cardinal point position, but containing both inter- and intra-subject effects.

Suppose $\mathbf{P}_{ij}$ is the model prediction of the position in xz-space of a cardinal point for the jth subject. $\mathbf{P}_{ij}$ is the result of applying the model to a single set (the ith) of observations of the jth subject's anthropometric data. Hence, $\mathbf{P}_{ij}$ is the predicted position of the point measured directly by the vector $\mathbf{M}_{ij}$. Let:

$$\mathbf{P}_{ij} = \mathbf{P}_j + s_{ij}, \tag{5}$$

where:

(i) $\mathbf{P}_j$ is the expected value of $\mathbf{P}_{ij}$ for the jth subject (i.e. the mean of $\mathbf{P}_{ij}$ over i), and

(ii) s_{ij} is a random error vector associated with the uncertainty in predicting the point $\mathbf{P}_{ij}$.

Note that the model in this case is deterministic and therefore the uncertainty in predicting $\mathbf{P}_{ij}$ is vested, entirely, in the anthropometric data on which the model draws. This would not be the case if the model were stochastic.

Now compute a *prediction error* vector p_{ij}, such that:

$$\begin{aligned} p_{ij} &= \mathbf{P}_{ij} - \mathbf{M}_{ij} \\ &= (\mathbf{P}_j - \mathbf{M}_j) + (s_{ij} - r_{ij}). \end{aligned} \tag{6}$$

The procedure described in Section 4.3 of this Report does not guarantee that $(\mathbf{P}_j - \mathbf{M}_j)$ will be zero; rather, the adjustments made to the model are only intended to reduce the expected value ($\mathbf{E}[\mathbf{P}_j - \mathbf{M}_j]$) to a negligibly small quantity when averaged over j. Therefore it is expected that $(\mathbf{P}_j - \mathbf{M}_j)$ would contribute to the variance of p_{ij} but would not contribute a bias. Hence, taking expected values averaged over subjects and assuming that r_{ij}, s_{ij} and $(\mathbf{P}_j - \mathbf{M}_j)$ are mutually independent:

$$\begin{aligned} \mathbf{E}[p_{ij}] &= \mathbf{E}[(\mathbf{P}_j - \mathbf{M}_j) + (s_{ij} - r_{ij})] \\ &= \mathbf{E}[\mathbf{P}_j - \mathbf{M}_j] + \mathbf{E}[s_{ij}] - \mathbf{E}[r_{ij}] \\ &= 0. \end{aligned} \tag{7}$$

Substituting $\bar{p}$ for $\mathbf{E}[p_{ij}]$, the variance term is given by:

$$\mathbf{E}[(p_{ij} - \bar{p})^2] = \mathbf{E}[((\mathbf{P}_j - \mathbf{M}_j + s_{ij} - r_{ij}) - \bar{p})^2]. \tag{8}$$

Note that $\mathbf{E}[(p_{ij} - \bar{p})^2]$ contains both inter- and intra-subject variation associated with both the model prediction and with the underlying process that the model is attempting to represent. Therefore, writing:

$$\rho_{ij} = (\mathbf{P}_j - \mathbf{M}_j) + s_{ij},$$

Equation (8) can be written as:

$$\mathbf{E}[(p_{ij} - \bar{p})^2] = \mathbf{E}[((\rho_{ij} - r_{ij}) - \bar{p})^2]. \tag{9}$$

Here, ρ_{ij} is an error vector which collects together the error terms introduced by the modelling procedure while r_{ij} represents the variability associated with the process of applying anthropometric data to a design, i.e. r_{ij} does not provide a measure of the validity of the model itself. For clarification of this point refer to the definition of r_{ij} (Equation (1)) and consider that r_{ij} represents all sources of error associated with specifying the *actual* position in xz-space of a subject's cardinal points. Therefore, it is appropriate to partition out the component due to r_{ij}

from the prediction error vector when reporting on the fidelity of the model, but to include all sources of variance when commenting on the final application of the model to design. Note that the component of variance due to r_{ij} is common to all methods of workplace design which have anthropometric data as their basis.

5.2 Sum of Independent Bivariate Processes

In Section 5.1 independent vectors in two-dimensional cartesian space have been added and subtracted to form functions which express the errors associated with the measurement and prediction processes. It will be assumed that these vectors terminate in points in xz-space which are distributed according to a bivariate process. Further, it will be assumed that, in general, the covariance of the bivariate process may be non-zero.

Consider two independent processes $\{x_1, z_1\}_i$ and $\{x_2, z_2\}_j$. Suppose that $\{x_1, z_1\}_i$ is distributed with mean $(\bar{x}_1, \bar{z}_1)$ and variances $(\sigma^2_{x_1}, \sigma^2_{z_1}, \sigma^2_{x_1 z_1})$. Similarly, $\{x_2, z_2\}_j$ is distributed with mean $(\bar{x}_2, \bar{z}_2)$ and variances $(\sigma^2_{x_2}, \sigma^2_{z_2}, \sigma^2_{x_2 z_2})$. Suppose new variables $\{u, v\}$ are formed, where:

$$u = x_1 \pm x_2,$$

and (10)

$$v = z_1 \pm z_2.$$

Then, taking expected values, the means $(\bar{u}, \bar{v})$ of the combined process are:

$$E[u] = E[x_1 \pm x_2],$$

i.e. $\bar{u} = \bar{x}_1 \pm \bar{x}_2,$

and (11)

$$E[v] = E[z_1 \pm z_2],$$

i.e. $\bar{v} = \bar{z}_1 \pm \bar{z}_2.$

Similarly, the variances of the combined $\{u, v\}$ process are given by:

$$E[(u - \bar{u})^2] = \sigma^2_{x_1} + \sigma^2_{x_2} \pm 2\sigma^2_{x_1 x_2},$$

i.e. $\sigma^2_u = \sigma^2_{x_1} + \sigma^2_{x_2};$

and (12)

$$E[(v - \bar{v})^2] = \sigma^2_{z_1} + \sigma^2_{z_2} \pm 2\sigma^2_{z_1 z_2},$$

i.e. $\sigma^2_v = \sigma^2_{z_1} + \sigma^2_{z_2}.$

Note that the results represented by Equations (11) and (12) assume that the constituent processes $\{x_1, z_1\}_i$ and $\{x_2, z_2\}_j$ are independent.

The covariance of the combined $\{u, v\}$ process is:

$$E[(u - \bar{u})(v - \bar{v})] = E[(x_1 - \bar{x}_1)(z_1 - \bar{z}_1) + (x_2 - \bar{x}_2)(z_2 - \bar{z}_2) \pm (x_1 - \bar{x}_1)(z_2 - \bar{z}_2) \pm (x_2 - \bar{x}_2)(z_1 - \bar{z}_1)],$$

i.e. $\sigma^2_{uv} = \sigma^2_{x_1 z_1} + \sigma^2_{x_2 z_2}.$ (13)

Again note that it is assumed, in Equation (13), that the contributing processes are independent.

5.3 Constant Ordinal Contours for a Bivariate Distribution

As stated in the introductory paragraph to Section 5 of this Report, the aim of this analysis is to generate boundaries in xz-space which would be expected to enclose N-percent of a given population of real eyes, thumbs etc. There is a variety, an infinite number in fact, of contours which could be drawn to enclose N-percent of any given distribution of points. For this analysis the probability density function (pdf) of the distribution describing the characteristics of the sample will be inferred and a contour, at a constant ordinal value of this bivariate describing function, will be drawn to enclose the required proportion of the pdf.

Suppose that some attribute is distributed according to a bivariate Normal pdf of zero mean value and equal variances σ^2. Then the probability that the value of this attribute, as described by the pdf, lies between values ω and $\omega + d\omega$ in distance from the origin is given by the Rayleigh pdf (Bendat 1958), $p(\omega)$, such that:

$$p(\omega) = \frac{\omega}{\sigma^2} \exp\left[-\frac{\omega^2}{2\sigma^2}\right]. \tag{14}$$

The cumulative probability function, $\mathbf{P}(\omega \leqslant \mathbf{R})$, is obtained from Equation (14) by integration to give:

$$\mathbf{P}(\omega \leqslant \mathbf{R}) = 1 - \exp\left[-\frac{\mathbf{R}^2}{2\sigma^2}\right], \tag{15}$$

and by transposing:

$$\frac{\mathbf{R}}{\sigma} = \mathbf{R}_\sigma = \sqrt{2}\left\{\ln\left[\frac{1}{1 - \mathbf{P}(\omega \leqslant \mathbf{R})}\right]\right\}^{1/2}. \tag{16}$$

The normalized radii which define circular enclosing boundaries for three proportions of interest are given below (by substitution in Equation (16)):

$\mathbf{P}(\omega \leqslant \mathbf{R})$	$\mathbf{R}_\sigma$
0·99	3·03
0·95	2·45
0·90	2·15

Note that circular contours, drawn at the normalized radii presented above, will enclose the respective proportions of the bivariate Normal pdf. As these contours have fixed $\mathbf{R}_\sigma$ they correspond to constant ordinal values, due to the circular symmetry of the equal variance bivariate Normal describing function.

5.4 Axes Rotation and Scaling

In order to apply the results derived from Equation (16), any given bivariate Normal process must be described, by suitable axes rotation and scaling, in terms of new variables which have a pdf with circular symmetry.

Suppose that a new cartesian axes system (x', z') is formed by rotation of an existing system (x, z) through an angle θ. Any point in xz-space can be represented in the $x'z'$-space as follows:

$$\begin{bmatrix} x' \\ z' \end{bmatrix} = \begin{bmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{bmatrix} \begin{bmatrix} x \\ z \end{bmatrix}. \tag{17}$$

Therefore under axes rotation the expected values $(\bar{x}', \bar{z}')$ become:

$$\mathbf{E}[x'] = \mathbf{E}[x \cos\theta + z \sin\theta],$$

i.e.

$$\bar{x}' = \bar{x} \cos\theta + \bar{z} \sin\theta; \tag{18}$$

similarly:

$$\bar{z}' = -\bar{x} \sin\theta + \bar{z} \cos\theta. \tag{19}$$

The variances $(\sigma_{x'}^2, \sigma_{z'}^2)$, are given by:

$$\mathbf{E}[(x' - \bar{x}')^2] = \mathbf{E}[((x - \bar{x}) \cos\theta + (z - \bar{z}) \sin\theta)^2],$$

i.e.

$$\sigma_{x'}^2 = \sigma_x^2 \cos^2\theta + \sigma_z^2 \sin^2\theta + \sigma_{xz}^2 \sin 2\theta; \tag{20}$$

similarly:

$$\sigma_{z'}^2 = \sigma_x^2 \sin^2\theta + \sigma_z^2 \cos^2\theta - \sigma_{xz}^2 \sin 2\theta. \tag{21}$$

The covariance term $\sigma_{x'z'}^2$ under the rotated axes is:

$$\mathbf{E}[(x' - \bar{x}')(z' - \bar{z}')] = \mathbf{E}[((x - \bar{x}) \cos\theta + (z - \bar{z}) \sin\theta) \times \\ (-(x - \bar{x}) \sin\theta + (z - \bar{z}) \cos\theta)],$$

i.e.

$$\sigma_{x'z'}^2 = \tfrac{1}{2}(\sigma_z^2 - \sigma_x^2) \sin 2\theta + \sigma_{xz}^2 \cos 2\theta. \tag{22}$$

But putting $\sigma_{x'z'}^2 = 0$ in Equation (22) and solving for $\theta = \theta'$ gives

$$\theta' = \tfrac{1}{2} \tan^{-1} \frac{2\sigma_{xz}^2}{(\sigma_x^2 - \sigma_z^2)}. \tag{23}$$

Hence an axes rotation of θ', as given by Equation (23), creates new independent variables $\{x', z'\}$.

The final manipulation required is to scale (x', z') so that the distribution described in terms of these independent variables has circular symmetry. Consider a joint pdf $p(x', z')$ where the independent variables $\{x', z'\}$ are distributed Normally with zero means and unequal variances $(\sigma_{x'}^2, \sigma_{z'}^2)$. Contours at constant ordinal values would describe elliptical paths with major and minor axes aligned with the cartesian axes. Now create a new variable x^* such that:

$$x^* = \frac{\sigma_{z'}}{\sigma_{x'}} x', \tag{24}$$

where x^* has been scaled so that it will be distributed Normally with zero mean and variance $\sigma_{z'}$.

A contour at a constant ordinal value of the joint pdf, $p(x^*, z')$, would satisfy the equation:

$$\mathbf{R}^2 = (x^*)^2 + (z')^2. \tag{25}$$

In Equation (25), **R** is the radius of the circular path traced out by the contour.

Hence, from Equations (24) and (25), solving for z', we have:

$$z' = \pm\sigma_{z'}\sqrt{\mathbf{R}_\sigma^2 - \left(\frac{x'}{\sigma_{x'}}\right)^2}, \tag{26}$$

where:

$$\mathbf{R}_\sigma = \frac{\mathbf{R}}{\sigma_{z'}}. \tag{27}$$

Equation (26) describes the required contour in terms of the original independent variables $\{x', z'\}$.

5.5 Partitioning of Variances

Suppose that the graphic anthropometric design aid is applied to the anthropometric data gathered from a group of subjects to produce distributions, in xz-space, of predicted cardinal point positions. These distributions must be augmented by the variances associated with the prediction process and the underlying design process before one may be confident in drawing boundaries said to enclose N-percent of real eyes, thumbs etc. The additional variance terms may be isolated from the data for the prediction and measurement error vectors by considering the constituent independent components of these vectors.

From Equation (4) it is seen that the measurement error vector $(m_j)_{mn}$ is obtained by taking the difference between two random error components. Therefore if the r_{ij} process is distributed with variability described by σ_r^2, then $(m_j)_{mn}$ will be distributed according to $2\sigma_r^2$ (see Section 5.2). Note that in this context σ_r^2 may represent variance in either the x or z directions or covariance.

Similarly, the prediction error vector p_{ij} consists of sums and differences of independent random processes (see Equation (6)). By grouping together those components introduced by the modelling procedure, p_{ij} can be reduced to a function of two vectors ρ_{ij} and r_{ij} (see Equation (9)). Hence, if the variance terms of p_{ij} and ρ_{ij} are σ_p^2 and σ_ρ^2 respectively, it follows from Section 5.2 that:

$$\sigma_p^2 = \sigma_\rho^2 + \sigma_r^2. \tag{28}$$

σ_ρ^2 and σ_p^2 may represent either variance or covariance terms, as is the case for σ_r^2.

Equations (8) and (9) indicate that the ρ_{ij} vector contains a component s_{ij} due to the uncertainty in predicting the position of a cardinal point from anthropometric data. This component will already be present in any distribution produced by applying group data to a deterministic model. Augmentation of these distributions by the full extent of σ_ρ^2 would therefore be inappropriate as the variance due to s_{ij} would be included twice. Unfortunately there is no satisfactory way of explicitly isolating this component σ_s^2. But it was seen in Section 5.1 that s_{ij} is the random error component resulting from a deterministic mapping of the subject's anthropometric data. Therefore, it seems reasonable to expect that generally s_{ij} would be produced in a similar way to r_{ij} as both are strongly dependent on the subject's anthoprometry. Hence, a 'best' estimate of σ_s^2 might be to assume that $\sigma_s^2 = \sigma_r^2$.

5.6 Generation of Confidence Limits

The boundaries to be drawn are by nature confidence limits in that they purport to describe a region enclosing N-percent of real cardinal point positions, taking into account all major sources of variance. Two such confidence limits will be drawn for each distribution of cardinal points. The inner boundaries will be constructed with all sources of variance considered to be due to the modelling procedure (i.e. augmented by $(\sigma_\rho^2 - \sigma_\varsigma^2)$) while the outer boundaries will include the variance due to the underlying process (i.e. σ_r^2) as well.

The steps necessary to generate these confidence limits are summarized as follows:

(i) apply the graphic anthropometric design aid to the anthropometric data from a subject group of interest;

(ii) calculate the means, variances and covariances ($\bar{x}_1$, $\bar{z}_1$, $\sigma_{x_1}^2$, $\sigma_{z_1}^2$, $\sigma_{x_1 z_1}^2$) of the resulting distribution of predicted cardinal point positions;

(iii) augment the variances and covariances by the relevant additional error sources (see above) to give the parameter set for the augmented distribution ($\bar{x}$, $\bar{z}$, σ_x^2, σ_z^2, σ_{xz}^2);

(iv) calculate the axes rotation (from Equation (23)) necessary to reduce the covariance to zero;

(v) compute new variances for the independent variables (from Equations (20) and (21)) under the axes rotation;

(vi) calculate a set of points in terms of these independent variables, which describe the elliptical contour enclosing N-percent of the augmented distribution (from Equation (26)), choosing a suitable value of $\mathbf{R}_\sigma$ from Section 5.3; and finally

(vii) plot the set of points describing the enclosing ellipse against the original cartesian axes by an axes rotation equal but opposite to that used in step (iv) (using Equation (17)).

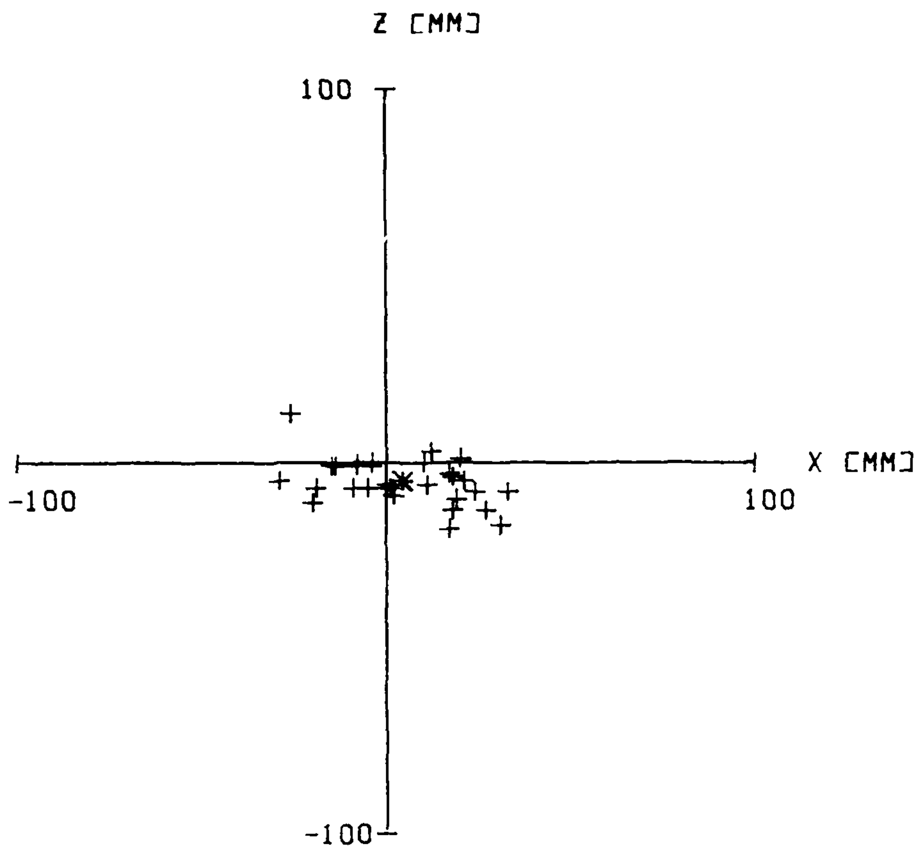
This procedure is to be carried out for each of the predicted cardinal point distributions.

5.7 Results

The distributions of *prediction error* vectors p_{ij}, and *measurement error* vectors $(m_j)_{mn}$, are shown plotted in Figures 11 to 14 and Figures 17 to 20 respectively. In each of these Figures summary statistics are presented from which the dominant variance terms may be successively isolated using, with one exception, the procedures above. The results of this process are shown in Tables 1 to 4.

The one departure from the previously described method concerns the adjustment of the variance, in the x-direction only, for predicted eye position. Whereas a best estimate of σ_ς^2 had been obtained by assuming $\sigma_\varsigma^2 = \sigma_r^2$ for all other cases, the random error component in the x-direction for the predicted eye position is due entirely to the resolved component of Acromial Height variation. The resolved component is in the order of $10 \cos 65°$ (see Hendy 1979*c*), i.e. 2·6 mm, and therefore, for this specific case, the s_{ij} component is seen to be insignificantly small when compared with the other components of ρ_{ij}.

Note from Tables 2 and 4 that the problem has been reduced to a single dimension for thumb and heel positions. The reason is self evident for heel position as these points were constrained to lie on a plane surface, i.e. a surface representing the floor structure of the CT-4A cockpit. The floor of the CT-4A is inclined at 3° upwards from the horizontal and although the 3° has been ignored in all calculations ($\cos 3° = 0 \cdot 9986$) the points have been plotted along the inclined surface (see, for example, Figure 20) in all relevant figures.



MEAN (X) : 4.3 MM

STD. DEV. (X) : 16.8 MM

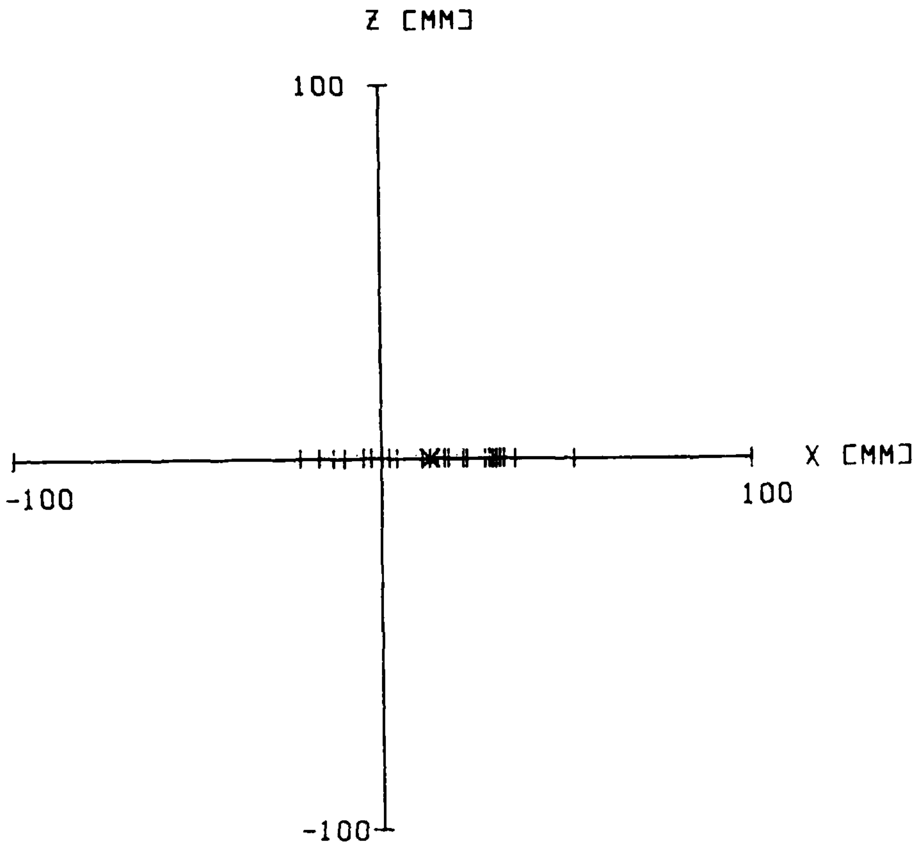
MEAN (Z) : - 5.0 MM

STD. DEV. (Z) : 6.2 MM

COVARIANCE : -43.0 MM^2

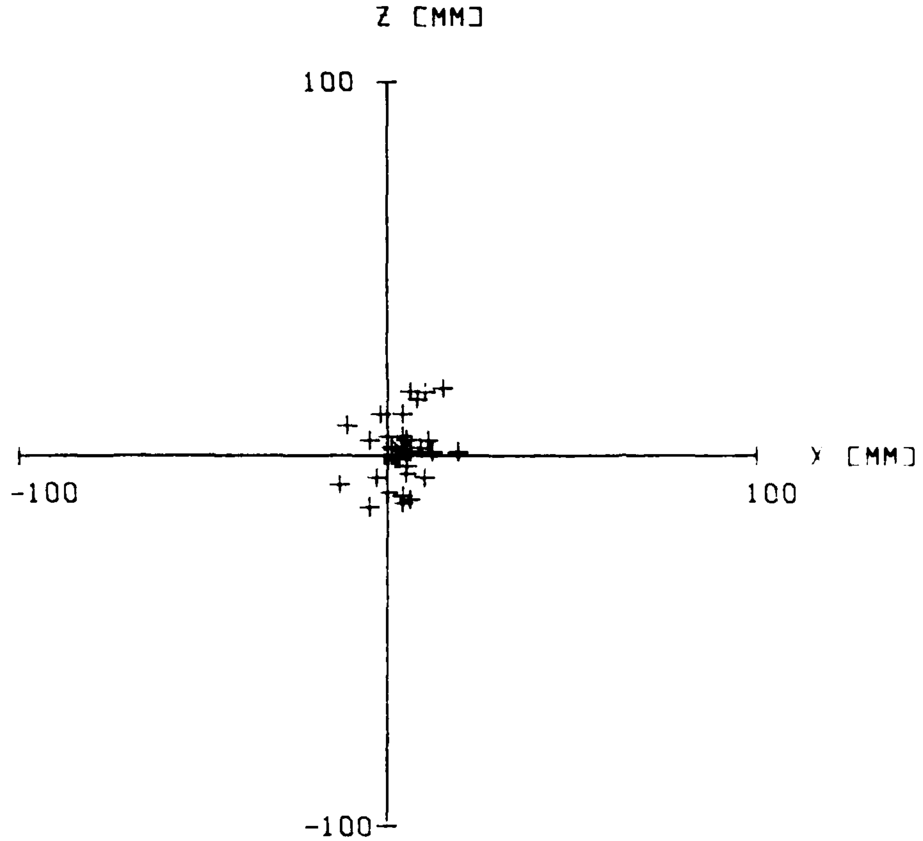
CORREL. COEF. : - 0.4

FIG. 17 : MEASUREMENT ERROR VECTOR ; EYE



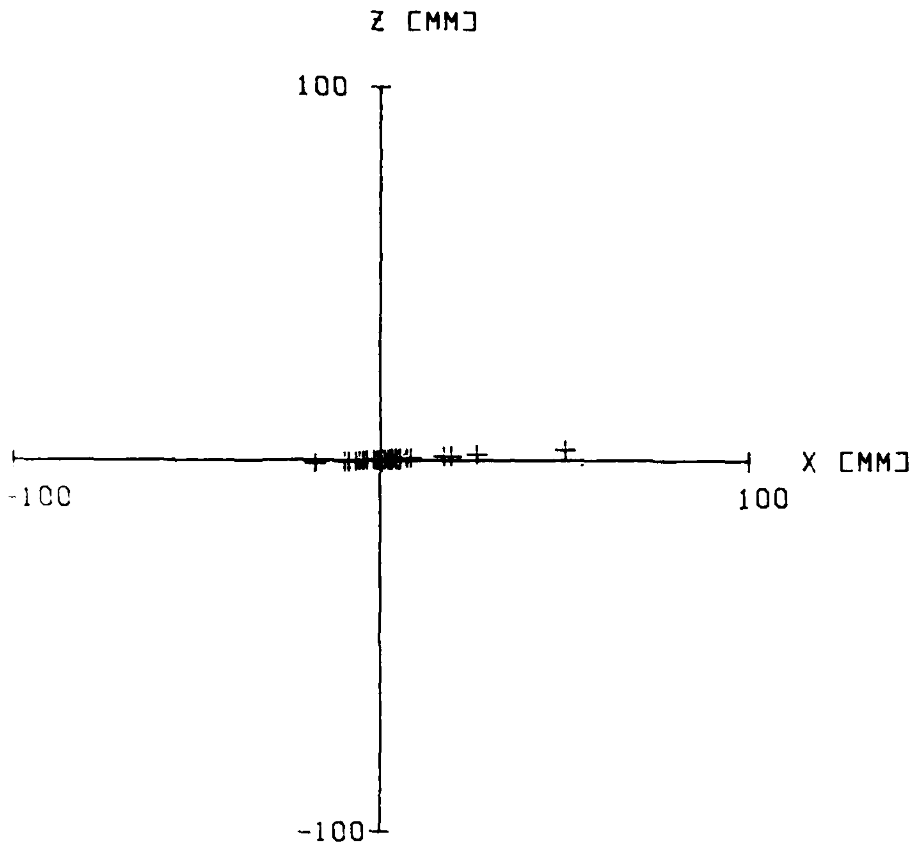
MEAN (X)	:	13.0	MM
STD. DEV. (X)	:	18.8	MM
MEAN (Z)	:	0.0	MM
STD. DEV. (Z)	:	0.0	MM
COVARIANCE	:	0.0	MM^2

FIG. 18 : MEASUREMENT ERROR VECTOR ; THUMB



MEAN (X)	:	3.5 MM
STD. DEV. (X)	:	6.8 MM
MEAN (Z)	:	1.2 MM
STD. DEV. (Z)	:	8.8 MM
COVARIANCE	:	16.4 MM^2
CORREL. COEF.	:	0.3

FIG. 19 : MEASUREMENT ERROR VECTOR ; KNEE



MEAN (X)	:	2.5	MM
STD. DEV. (X)	:	12.1	MM
MEAN (Z)	:	0.1	MM
STD. DEV. (Z)	:	0.6	MM
COVARIANCE	:	7.6	MM^2
CORREL. COEF.	:	1.0	

FIG. 20 : MEASUREMENT ERROR VECTOR ; HEEL

TABLE 1

Partitioning of Variances; Eye

	x	z	xz
$2\sigma_r^2$	282·2	38·4	−43·0
σ_r^2	141·1	19·2	−21·5
$\sigma_\rho^2+\sigma_r^2$	846·8	222·0	−74·7
σ_ρ^2	705·7	202·8	−53·2
$\sigma_\rho^2-\sigma_\zeta^2(\sigma_\zeta^2=\sigma_r^2)$		183·6	−31·7

TABLE 2

Partitioning of Variances; Thumb

	x	z	xz
$2\sigma_r^2$	353·4		
σ_r^2	176·7		
$\sigma_\rho^2+\sigma_r^2$	882·1		
σ_ρ^2	705·4		
$\sigma_\rho^2-\sigma_\zeta^2(\sigma_\zeta^2=\sigma_r^2)$	528·7		

TABLE 3

Partitioning of Variances; Knee

	x	z	xz
$2\sigma_r^2$	46·2	77·4	16·4
σ_r^2	23·1	38·7	8·2
$\sigma_\rho^2+\sigma_r^2$	309·8	196·0	57·6
σ_ρ^2	286·6	157·3	49·4
$\sigma_\rho^2-\sigma_\zeta^2(\sigma_\zeta^2=\sigma_r^2)$	263·5	118·6	41·2

TABLE 4

Partitioning of Variances; Heel

	x	z	xz
$2\sigma_r^2$	146·4		
σ_r^2	73·2		
$\sigma_\rho^2+\sigma_r^2$	453·7		
σ_ρ^2	380·5		
$\sigma_\rho^2 \quad \tau_\varsigma^2(\sigma_\varsigma^2 = \sigma_r^2)$	307·3		

For thumb position, the rationale is less obvious. The major predictive power of the simple two-dimensional model, in the case of thumb tip reach, is considered to be confined to the horizontal extent alone. Therefore less emphasis has been placed on the z-component of the thumb vector although the value used (the link AT extends horizontally from the acromion (see Figure 1)) is considered to be an appropriate choice. For this reason no attempt was made to confirm the vertical component of thumb tip reach during the validation procedure. Hence, enclosing boundaries are presented only for the x-component of thumb tip reach.

The enclosing boundaries are shown in Figures 21 (for N = 90%) and 22 (for N = 99%) plotted against the distributions of predicted cardinal point positions. The data used to generate these plots were from the combined AIRCREW group (Hendy 1979*c*) following the procedures, with the exception already noted, of Section 5.6. Generally, the inter-/intra-subject variances dominate the enclosing boundaries, although exceptions are to be found in the horizontal component of eye position and the component of knee position orthogonal to link SP (Figures 21 and 22). The large inter- intra-subject variances have also masked the contribution due to σ_r^2. As was noted previously, σ_r^2 represents an error or uncertainty component common to all design procedures that are based on anthropometric data. Although largely overshadowed by other contributing variances in Figures 21 and 22, the σ_r^2 component (here contributing to the outer boundaries in Figures 21 and 22) would assume greater significance when employing design strategies aimed at minimizing the spread of certain cardinal points, e.g. a design for a constant eye point. In the limiting case, when the design strategy has reduced the effects of all inter- intra-subject variability to zero, one is left with a residual variance of $(\sigma_\rho^2 \quad \sigma_\varsigma^2)$ and σ_r^2 determining the spread of cardinal points.

6. EXTRAPOLATION OF THE TWO-DIMENSIONAL MODEL BASE TO OTHER GEOMETRIES

The development and validation of the simple two-dimensional model described in Section 2 has been based on the backrest angle appropriate to the CT-4A, i.e. 15°. Although it was stressed earlier in this Report that minimal properties of articulation are vested in this simple model, it was intended that the model should be usable in other geometrically related situations. It is considered that if the model were to be extrapolated, for backrest angles other than 15°, the fixed

APPENDIX II (Continued)

Subject Number		Eye Height (Sitting)	Acromial Height (Sitting)	Popliteal Height	Functional Reach	Buttock Knee Length	Stool Height
	1980	845	648	452	823	591	437
18	1977	855	663	455	793	595	428
	Difference	10	15	3	+30	4	+9
	1980	775	592	449	794	589	441
19	1977	818	612	459	784	590	422
	Difference	43	20	10	+10	1	+19
	1980	802	599	463	836	607	441
26	1977	822	610	469	811	620	438
	Difference	20	11	6	+25	13	+3
	1980	793	609	468	841	632	439
29	1977	811	602	463	776	632	420
	Difference	18	+7	+5	+65	0	+19
	1980	805	607	464	821	606	456
31	1977	828	619	473	799	601	452
	Difference	23	12	9	+22	+5	+4
Mean difference		29·6	24·4	9·1	+35·0	0·6	+9·4
Standard dev. of diff.		17·5	22·2	8·0	25·8	5·6	16·2

APPENDIX II

Comparison of 1977 Measurements with 1980 Measurements

Subject Number		Eye Height (Sitting)	Acromial Height (Sitting)	Popliteal Height	Functional Reach	Buttock-Knee Length	Stool Height
	1980	776	582	404	770	573	391
2	1977	786	584	426	713	570	382
	Difference	−10	−2	−22	+57	+3	+9
	1980	765	564	449	825	612	445
6	1977	817	625	458	816	607	412
	Difference	−52	−61	−9	+9	+5	+33
	1980	768	562	473	896	622	453
8	1977	836	625	478	811	620	443
	Difference	−68	63	−5	+85	+2	+10
	1980	787	597	443	803	594	430
11	1977	808	609	459	787	599	414
	Difference	−21	−12	−16	+16	−5	+16
	1980	787	570	447	812	637	434
15	1977	814	606	468	806	638	421
	Difference	27	36	21	+6	−1	+13
	1980	806	603	464	884	629	447
17	1977	840	646	468	824	635	431
	Difference	34	43	4	+60	−6	+16

APPENDIX 1 (Continued)

Subject No.		Eye Height (Sitting)	Acromial Height (Sitting)	Popliteal Height	Knee Height	Functional Reach	Buttock-Knee Length	Buttock-Popliteal Length	Stool Height
23	Measure	725	529	401	501	757	556	456	381
	Percentile	1	1	1	—	15	1	—	6
24	Measure	742	576	437	554	793	605	495	393
	Percentile	1	8	20	—	50	40	—	15
25	Measure	792	580	423	533	796	602	517	395
	Percentile	25	10	7	—	50	40	—	20
26	Measure	802	599	463	584	836	607	513	441
	Percentile	40	30	70	—	90	50	—	85
27	Measure	804	618	475	606	869	644	530	467
	Percentile	40	60	85	—	98	92	—	98
28	Measure	769	605	451	578	774	642	535	427
	Percentile	7	40	50	—	30	91	—	70
29	Measure	793	609	458	582	841	632	527	439
	Percentile	25	40	60	—	92	85	—	85
30	Measure	777	557	418	531	813	587	492	385
	Percentile	10	2	4	—	75	20	—	9
31	Measure	805	607	464	588	821	606	503	456
	Percentile	40	40	70	—	80	50	—	95

Note: All measurements are in millimetres.

APPENDIX 1 (Continued)

Subject No.		Eye Height (Sitting)	Acromial Height (Sitting)	Popliteal Height	Knee Height	Functional Reach	Buttock Knee Length	Buttock-Popliteal Length	Stool Height
11	Measure	787	597	443	560	803	594	512	430
	Percentile	20	25	30		60	25		75
12	Measure	768	573	422	529	801	593	518	402
	Percentile	7	7	6		60	25		25
13	Measure	746	542	439	561	804	593	502	439
	Percentile	1	1	25		60	25	—	85
14	Measure	809	619	466	610	801	632	520	458
	Percentile	50	60	70		60	85	—	96
15	Measure	787	570	447	582	812	637	527	434
	Percentile	20	5	40		70	90	—	80
16	Measure	777	562	424	541	814	587	492	401
	Percentile	10	3	8		75	20	—	25
17	Measure	806	603	464	597	884	629	516	447
	Percentile	40	30	70		99	80	—	90
18	Measure	845	648	452	560	823	591	507	437
	Percentile	85	90	50		80	25		80
19	Measure	775	592	449	573	794	589	489	441
	Percentile	10	20	40		50	20		85
20	Measure	767	618	406	522	772	559	466	381
	Percentile	6	60	1		25	2		6
21	Measure	768	582	438	564	778	617	519	413
	Percentile	7	10	25		30	60		50
22	Measure	809	608	478	601	867	618	523	458
	Percentile	50	40	85		98	60		96

APPENDIX I

Anthropometry of RAAF Instructor Pilots Used in the Validation Experiment

Subject No.		Eye Height (Sitting)	Acromial Height (Sitting)	Popliteal Height	Knee Height	Functional Reach	Buttock-Knee Length	Buttock-Popliteal Length	Stool Height
1	Measure	766	580	414	546	802	600	497	406
	Percentile	6	10	3	—	60	40	—	30
2	Measure	776	582	404	528	770	573	472	391
	Percentile	10	10	1	—	25	7	—	15
3	Measure	734	540	415	512	780	579	481	389
	Percentile	1	1	3	—	40	10	—	10
4	Measure	813	613	499	610	860	641	527	453
	Percentile	50	50	98	—	97	91	—	93
5	Measure	752	548	437	575	838	645	542	432
	Percentile	2	1	20	—	90	93	—	75
6	Measure	765	564	449	570	825	612	509	445
	Percentile	5	3	40	—	85	60	—	90
7	Measure	763	544	418	535	826	593	504	399
	Percentile	4	1	4	—	85	25	—	25
8	Measure	768	562	473	594	896	622	521	453
	Percentile	7	3	80	—	99	70	—	93
9	Measure	745	528	455	575	838	624	531	443
	Percentile	1	1	50	—	90	75	—	85
10	Measure	739	536	405	529	769	598	486	387
	Percentile	1	1	1	—	25	30	—	10

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8. CONCLUSIONS

This Report describes a concept for the application of anthropometric data to workplace design. The emphasis of this approach has been on the use of a strategy which retains individual variability in a largely unmodified fashion. The main body of this Report is concerned with the description and validation of a graphic anthropometric design aid which is intended to facilitate this approach. The two-dimensional model base for the aid, although simple in structure, depends on the types of anthropometric variable available from most surveys. A penalty of the simple nature of the two-dimensional model is the limited range of geometries in which the aid can be used, although this limited set of geometries would be expected to include many seated workstations (e.g. aircraft cockpits, vehicular cabins). The aid provides a convenient procedure for the rapid evaluation of a variety of workstation configurations with the ability to manipulate total system variance to the advantage of overall design. For example, a seat adjustment method might be optimized for minimum population eye spread, minimum foot pedal adjustment or some combination of both.

In Section 5.7 the extent of the added variance due to the modelling procedure is demonstrated. As a by-product of the validation method, an estimate of the inter-/intra-subject variability associated with the adoption of a given sitting posture was obtained. This source of variability is seen to be common to all methods of applying anthropometric data to the workplace design, i.e. it is not specific to the type of model used for the design aid. Enclosing boundaries were generated including all known variances due to the inter-/intra-subject anthropometric variability, model error and subject positioning error. These boundaries were said to enclose the space that would be occupied by N-percent (N = 90% and 99%) of *real* eyes, thumbs, knees, heels etc. In general these enclosing boundaries are dominated by the inter-/intra-subject anthropometric variability. This would not necessarily be the case if employing a strategy that minimized the spread of a particular cardinal point.

Although the design aid's simple two-dimensional model base was developed and validated for a specific geometrical arrangement, a method is presented to extrapolate the model's parameters for use in different situations. The form of the extrapolation concerns the method of calculating predicted eye position for backrest angles different from the value of 15° used in the validation experiment. It is suggested that although the extrapolated model is not strictly a general model, valid conclusions can be based on its use for seated workstation design over a range of backrest angles in the range from 15° to 30°.

in anthropometric technique between the 1977 measurements and those taken in 1980. The revised link lengths are as follows:

$$\begin{aligned}
\text{link AT} &= \text{FUNCTIONAL REACH} + 125\ \text{mm};\\
\text{AS} &= \text{ACROMIAL HEIGHT} - 10\ \text{mm};\\
\text{SP} &= 0{\cdot}85\ (\text{BUTTOCK TO KNEE LENGTH});\\
\text{PK} &= 0{\cdot}20\ (\text{BUTTOCK TO KNEE LENGTH});\\
\text{HP} &= \text{POPLITEAL HEIGHT} + 45\ \text{mm};\\
z_{ae} &= \text{EYE HEIGHT} - \text{ACROMIAL HEIGHT};\\
\text{AB} &= \sqrt{z_{ae}^2 + 275^2}\cos\{\arctan(275/z_{ae}) - (\alpha - 15)\};
\end{aligned}$$

and

$$\text{EB} = \sqrt{z_{ae}^2 + 275^2}\sin\{\arctan(275/z_{ae}) - (\alpha - 15)\}.$$

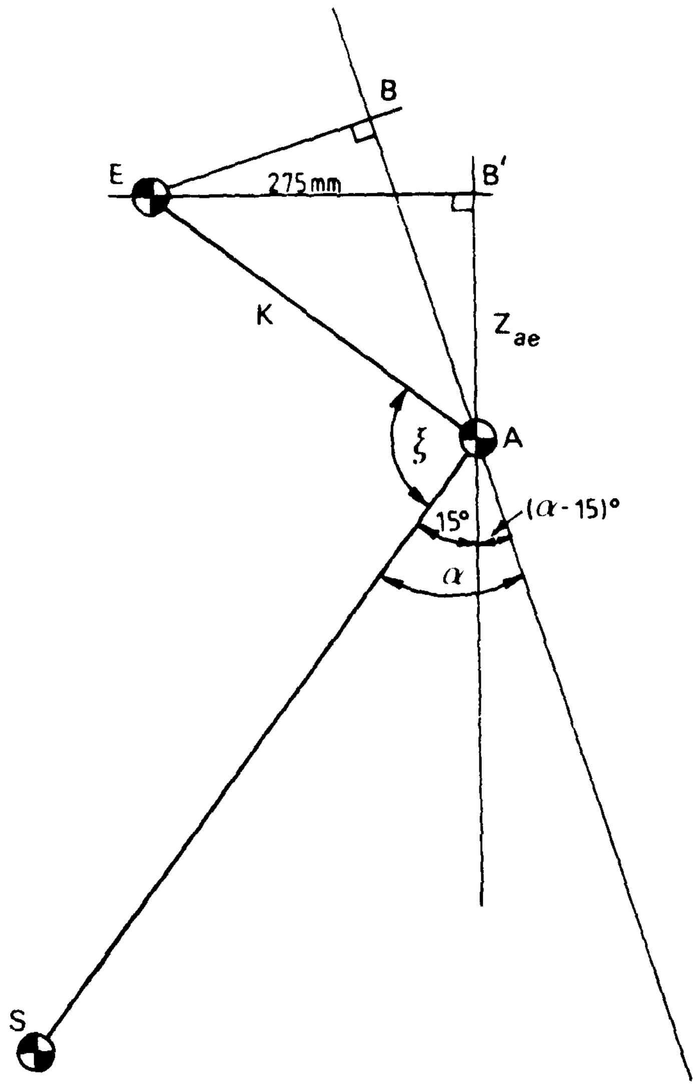
In each case these link lengths were derived from the parameter set presented in Section 4.3 of this Report adjusted, where appropriate, by the mean differences of Appendix II. These link values are considered to be a best estimate of the two-dimensional model base for use with the 1977 survey data.

7. DISCUSSION

There are two aspects to the work presented in this Report which should not be confused. The first, and perhaps more durable, of the ideas presented is the departure from the use of pooled data in design in favour of a procedure which retains individual variability. In this way it is hoped to address, directly, the concept of designing for N-percent of users. The second aspect, the model which is the basis for the anthropometric design aid, is separate. The specific model described in this Report is one method of implementing the basic philosophy, but it is not the philosophy itself. The model is not considered to be an optimal configuration as it can be, and should be, further refined to be more accurate and less geometry-specific.

To the extent that the design strategy advocated in this Report depends on individuals, the conclusions to be drawn from implementing this strategy are also specific to this same group of individuals. However, if the sample of subjects which provided the data gives a sufficiently unbiased estimate of the parent population from which the sample was chosen, then the conclusions that are drawn are appropriate to the complete user group. Therefore the procedures advocated in this Report are seen to be consistent with the requirements of design for an existing indentifiable user group.

But what of designs intended for a future population? If there is reason to suspect that some future population will differ from a *known* group for which data exists, some modification of the anthropometric variables may be required. Typically, recent Western populations have been found to be anthropometrically larger with successive generations (Tanner 1968) suggesting that some scale factor should be applied in the calculation of all link lengths to achieve consistency with the extrapolated central tendencies of the data. A general scaling of known group data, in an effort to predict the characteristics of some future user group, requires that the original emphasis on sets of *individuals'* data be modified. The scaled data would no longer represent the individuals of the original known group but could, perhaps, be considered to describe M manikins (M is the number of subjects in the original group) representing all the inter-subject variation that one might expect to exist in the hypothesized future group. Such an assumption appears to be tenable



$$AB = \sqrt{Z_{ae}^2 + 275^2}\ \cos\left\{\arctan\left(275/Z_{ae}\right) - (\alpha - 15)\right\}$$

$$BE = \sqrt{Z_{ae}^2 + 275^2}\ \sin\left\{\arctan\left(275/Z_{ae}\right) - (\alpha - 15)\right\}$$

FIG. 24 ALTERNATIVE COMPUTATION OF MODEL EYE POSITION length eye link ($EB = 275$ mm) may not be appropriate. Two ways of achieving a more general model include:

(i) the validation of the model at backrest angles covering the expected design range by evaluating EB for zero mean bias at various angles (α) and interpolating between; or *alternatively*

(ii) the adoption of a strategy, for determining the coordinates of the eye point (E), which is sensitive to changes in α.

The second of these alternatives was chosen to avoid the protracted gathering of experimental data required by (i).

To gain some insight into the magnitude of change expected in links EB and AB as α is varied from 15° to 30°, the AMRL 50th percentile manikin was used (McConville and Laubach 1978) in arbitrary, but representative, seated postures. The validity of the procedure and the resulting conclusions are largely dependent on the fidelity of the manikin's head and neck articulation.

The initial efforts at positioning the manikin at various backrest angles suggested that over the range $15° \leqslant \alpha \leqslant 30°$ a construct that maintained vector AE constant in magnitude and at a fixed angle (for any one individual) to the link SA may be appropriate. Use of the manikin, in this way, cast further doubt on the validity of maintaining a fixed link length for EB. Figure 23 illustrates the results of applying such a strategy. The steps taken in developing this figure are as follows:

(a) for 15° rake angle, link SA_{15} was drawn of length equal to the 50th percentile ACROMIAL HEIGHT (McConville and Laubach 1978) less a correction of 10 mm for slump;

(b) the manikin was positioned so that the eye point lay on a vertical line corresponding to a link length $E_{15}B$ of 275 mm and a link length $A_{15}B$ approximately equal to the difference between the 50th percentile values of EYE HEIGHT and ACROMIAL HEIGHT (McConville and Laubach 1978);

(c) $E_{15}A_{15}$ and $\angle SA_{15}E_{15}$ were measured and these values were used to draw A_iE_i for $i = (20°, 25°, 30°)$ such that:

$$A_iE_i = \text{constant} = K,$$

and

$$\angle SA_iE_i = \text{constant} = \zeta; \text{ and finally}$$

(d) the manikin was positioned at each backrest angle in an attempt to match manikin eye position (E_i) with the computed position (E_i).

For the four angles of α chosen, it was possible to place the manikin's eye position overlying, or close to, the computed position while maintaining a *representative* manikin posture (see Figure 23).

The geometrical construct that is recommended to generalize the two-dimensional model to a practical range of angles ($15° \leqslant \alpha \leqslant 30°$) is shown in Figure 24. By this process the link lengths AB and BE are both dependent on backrest angle while maintaining $|AE|$ and $\angle SAE$ constant within each individual representation. The final step in generalizing this model is to adjust the parameter set used for link length calculation to account for the apparent differences

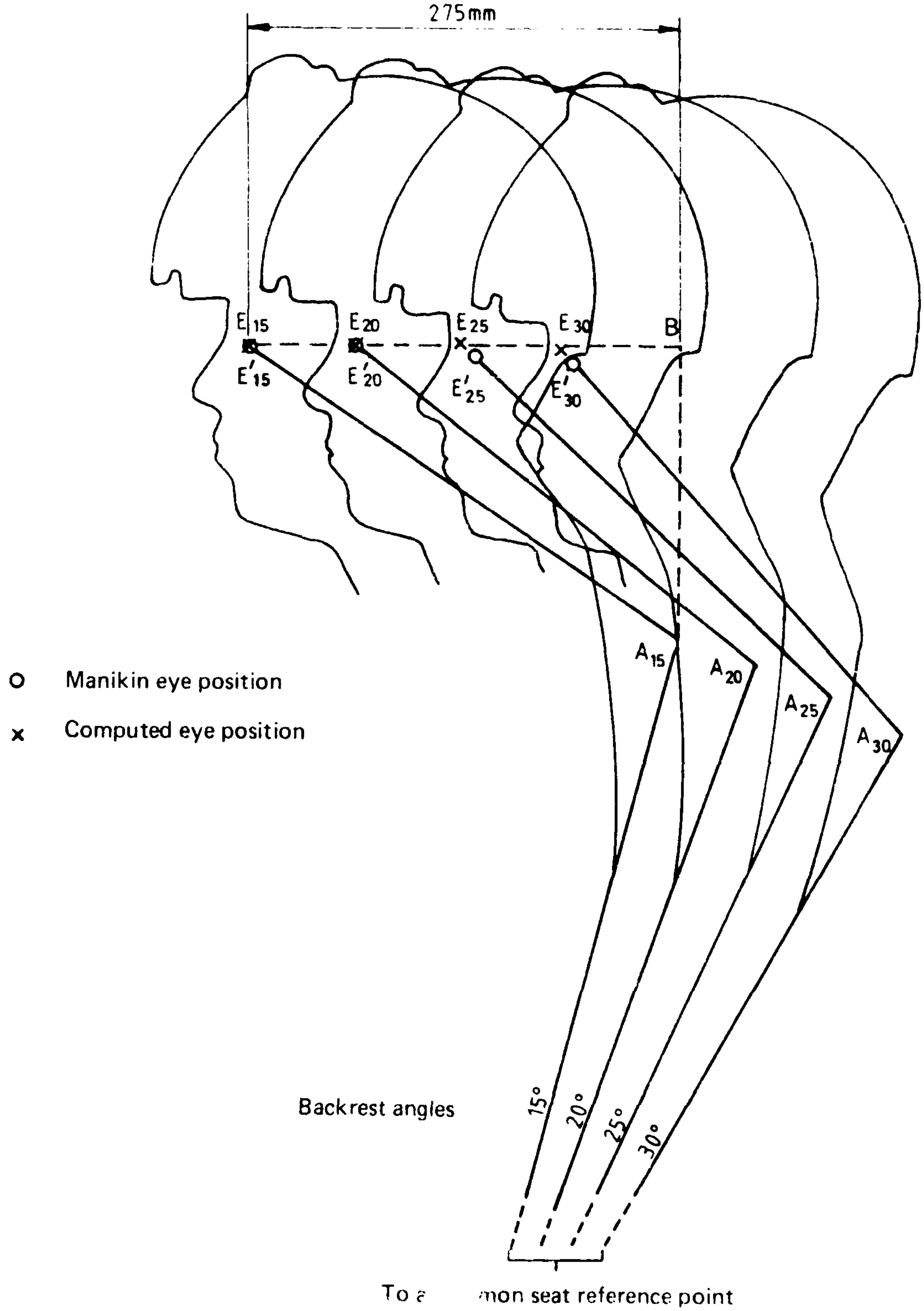
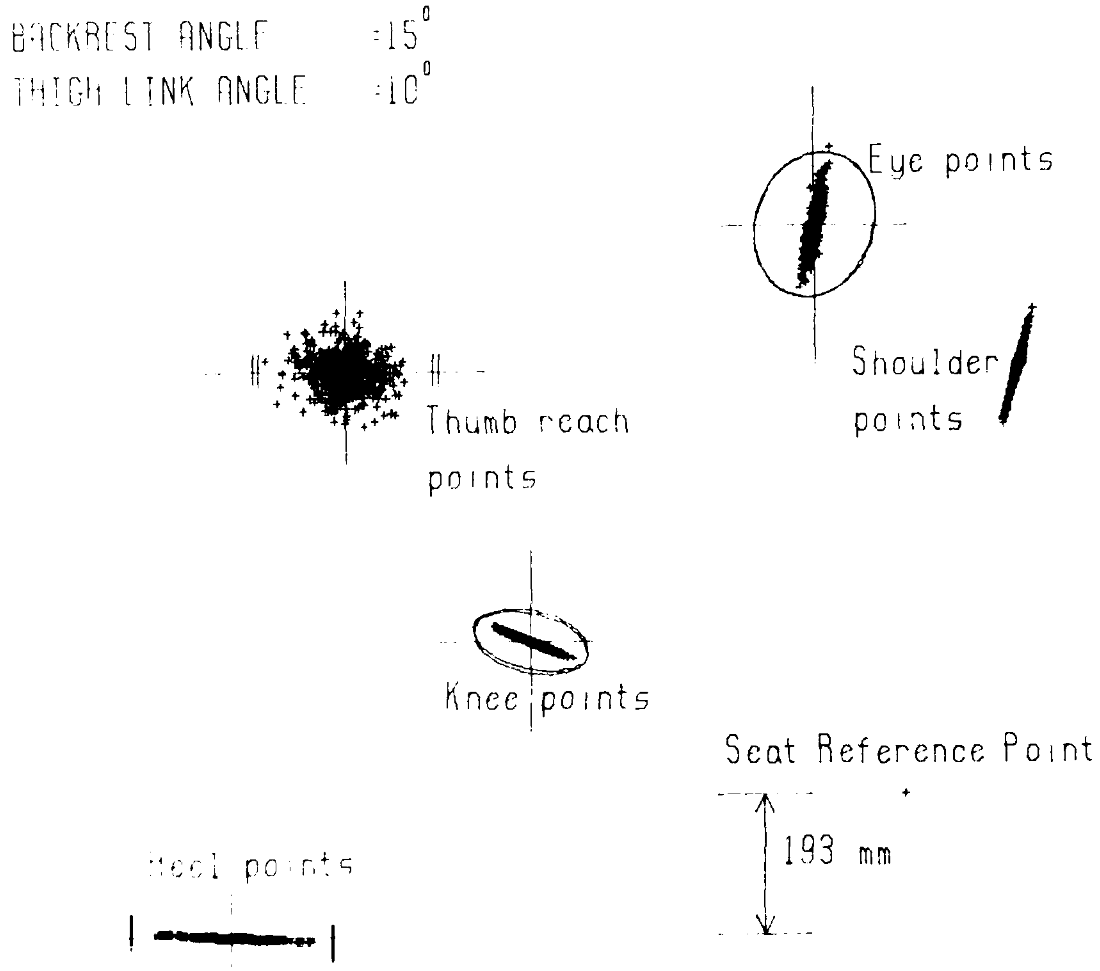


FIG. 23 COMPARISON OF EXTRAPOLATED MODEL EYE POSITION WITH THE AMRL MANIKIN EYE POSITION



... BOUNDARIES EXPECTED TO CONTAIN 99% OF 'REAL'
... POINT POSITIONS

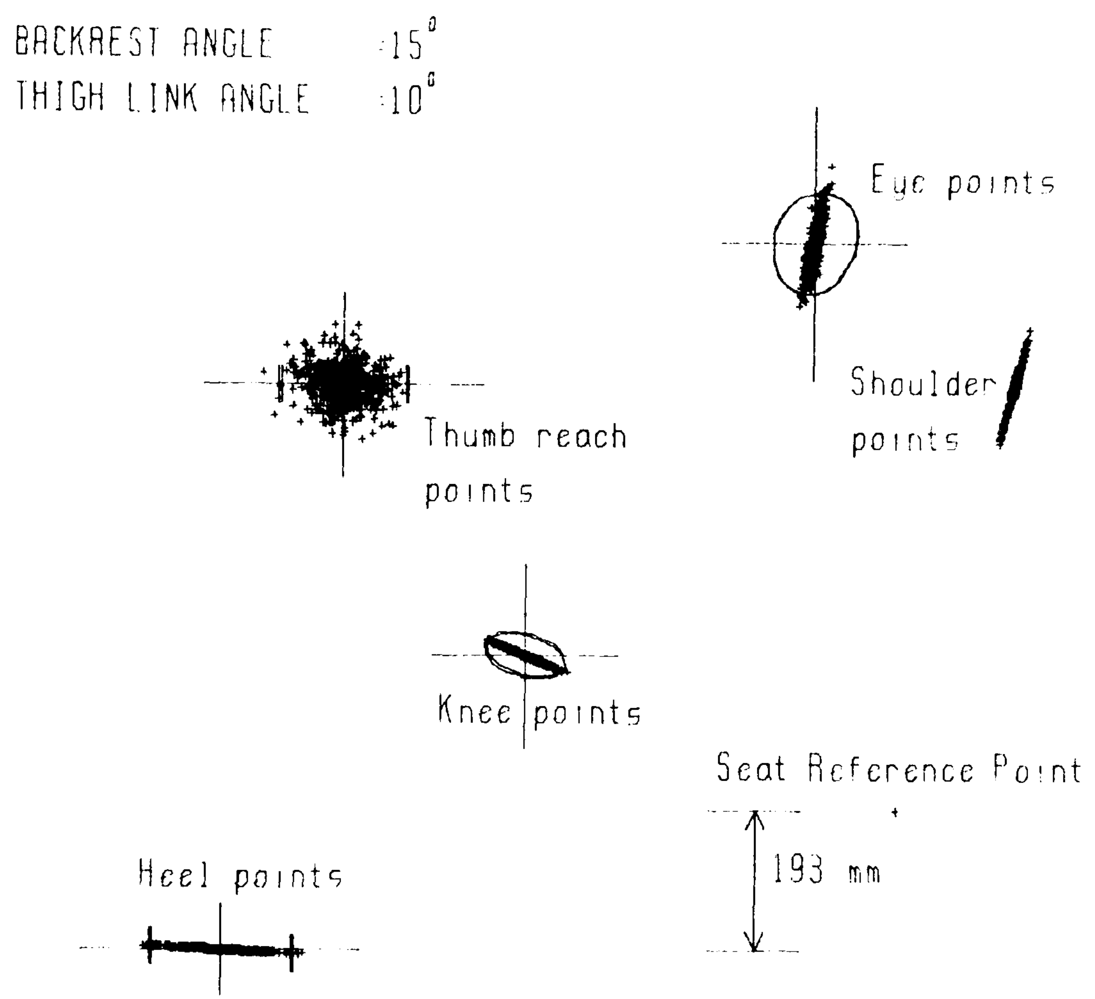


FIG. 21 : ENCLOSING BOUNDARIES EXPECTED TO CONTAIN 90% OF 'REAL' CARDINAL POINT POSITIONS

APPENDIX III

Description of Cardinal Point Measuring Procedure

The subject is asked to don his flying kit and adjust it as if he is about to go flying. He is asked to sit in the measuring apparatus and strap-in to the device as he would in an aircraft. The inertia reel is then locked. The sliding footrest is adjusted so that with the heel of the subject's boot at the corner formed by the footrest and the floor of the apparatus, the line (in a sagittal plane) joining the seat reference point (SRP) to the point on the underside of the tendon of the right biceps femoris muscle where it joins the calf (i.e the popliteal) is at an angle of +10 to the horizontal.

The subject is asked to look straight ahead at the reflection of his pupils in the mirror opposite. To help the subject maintain this position a perspex cursor is raised in front of the subject until a line scribed on the perspex, the reflection of this line and the reflection of the center of the subject's left pupil, all coincide.

NASION POINT: With the subject looking straight ahead at the reflection of his pupils in the mirror opposite, the datum edge is moved horizontally to make light contact at the most posterior point of the nasal root depression. Record the horizontal distance of the datum edge from the end wall.

EYE HEIGHT (SITTING): With the subject looking straight ahead at the reflection of his pupils in the mirror opposite, the datum edge is brought up until it coincides with the reflection of the center of the subject's left pupil in the mirror opposite. Record the height of the datum edge from the floor.

THUMB TIP REACH: The subject extends the left arm forward horizontally, the hand pronated with the tip of the index finger touching the extended thumb (which is held in the plane of the extended arm). The subject is asked '. . . to reach against the harness as if you were trying to reach the instrument panel, but not to the point of discomfort'. The datum edge is moved horizontally until contact is made with the tip of the left thumb. Record the distance of the datum edge from the end wall.

KNEE POINT: With the subject's feet flat on the sliding footrest, the datum edge is brought down to make light contact with the highest point of the left knee directly above the popliteal. Record the height of the datum edge from the floor and the horizontal distance of the datum edge from the end wall.

HEEL POINT: Record the horizontal distance, measured from the end wall, of the intersection of the footrest and floor plane of the special apparatus.

SEAT REFERENCE POINT: The horizontal and vertical coordinates of the seat reference point were measured with respect to the end wall and floor of the anthropometric measuring rig.

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16. Abstract

In recent workplace design projects at ARL, a procedure for the use of anthropometric information has been developed which relies on the use of sets of anthropometric data from individuals rather than the conventionally used pooled data. This Report describes a graphic anthropometric design aid which has been devised to assist in the implementation of this procedure. The aid predicts the positions, in side elevation, of certain cardinal points which are considered to be important to the design process, viz. the eye, thumb tip reach, knee point, seat reference point and heel point. This Report also contains details of the design aid's validation, the concept of the aid's use and the fidelity of the aid within the design process.

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