AIRCREW/COCKPIT COMPATIBILITY: A MULTIVARIATE PROBLEM SEEKING A MULTIVARIATE SOLUTION

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SUMMARY

//Aircrew/cockpit compatibility depends on an interaction between the anthropometry of individual aircrew members and the geometry of the cockpit. Selection criteria in the past have attempted to deal with this interaction, but the model was too simple. This is a multi-variate problem which requires a multi-variate solution. Essentially the problem is one of charting the region of intersection between the anthropometric data domain and a set of rules or criteria which define 'operability'. The nature of this problem was demonstrated through computer simulated fitting trials of subjects in a number of cockpit-like geometries. The simulations clearly demonstrate that membership in a particular category of 'fit' depends on interactions between workspace and anthropometry which are geometry specific. Further, the simulations show that the establishment of analytical expressions to define class membership is complex and appears to require a non-linear approach. The consequences of these results are discussed in terms of establishing selection standards and determining design criteria for cockpits which are compatible with these standards. It is argued that cockpit design must be based on an extensive sampling of human characteristics in order that the full range of interactions, between various anthropometric dimensions and the workspace, is represented. //

1. INTRODUCTION

It is assumed that the purpose of applying anthropometric selection criteria is to screen out those candidates whose physical characteristics would be incompatible with the workspaces they must occupy or with the tools and equipment they must use in performing their duties. Obviously, selection criteria must reflect the limitations of the workplace environment if this goal is to be achieved. The link between operator selection and workspace geometry is inseparable; selection criteria should reflect the characteristics of the work environment, and workspace design should reflect anthropometric selection criteria. In practice this is seldom the case. Anthropometric selection criteria are often established solely within the domain of the anthropometric data, with apparently little acknowledgement that 'compatibility' depends on the interaction between the anthropometric characteristics of individual subjects and workspace geometry. Generally, selection criteria are based on regions of acceptance, typically established independently on each anthropometric variable of interest. Ranges for workspace design are similarly based.

This paper examines the effects of interactions between individual anthropometry and workspace geometry with a view to establishing the consequences of these interactions in developing selection strategies and guidelines for design. The problem of defining physical compatibility in the workspace, is essentially one of charting the region of intersection between an anthropometric data space and a set of rules or criteria which define 'operability' in a workspace. The non-linear multi-variate nature of this problem is demonstrated through computer simulated fitting trials of subjects in a number of cockpit-like geometries. The simulations make use of a simple sagittal plane manikin to represent the human skeletal form.

2. THE NEED FOR A MULTIVARIATE DISTRIBUTED APPROACH

Recent articles and letters in the human factors literature [1-3] have raised the issue of anthropometry and workspace design. Kleeman's contribution [3] supports the contention that perhaps all is not well with some of the established methods for applying anthropometric data to design, however, his suggestion to extend the design range from the more usual 5*th* and 95*th* percentile values to the 1*st* and 99*th* values may be begging the question. Perhaps the problem lies less with which percentile limits are chosen, but more with the way in which anthropometric data are applied.

The problems which result from assuming that anthropometric dimensions are perfectly correlated, is well documented [4-6] and it is recommended that multi-variate techniques be used in an effort to overcome limitations inherent in uni-variate methods [7]. Yet most traditional methods for the application of anthropometric data are uni-variate, so far as their ability to handle correlations between anthropometric variables is concerned. Falling within this category is the most common procedure for design, that is, the use of percentile data [8] mapped into the workspace domain through graphical procedures [7], drawing board manikins [9] or their computer generated counterparts [10-12].

Although the fallacy of the *average man* is well recognized [8], it would seem that an equally fallacious concept, the *n-percentile person*, is firmly entrenched within traditional methods. In making this claim it is accepted that few manikins, for example, are made entirely from segments of the same percentile, that is, all 5*th* or all 95*th* percentile values. Rather the criticism of these widely used methods stems from their limited, often non-existent, ability to represent the range of individual differences in the user population for any other than the most simple of workspace geometries.

A notable exception to this approach can be found in the work of Bittner et al. [13, 14]. They argue that if an anthropometric data base is conceptualized as an *n*-dimensional hyper-space, then a relatively small number of suitably chosen manikins could characterize the hyper-ellipsoid surface which encloses any given proportion of a user population. From a principle component analysis, the hyper-space was estimated to be approximately 4-dimensional Normal, giving rise to a 'CADRE' of 17 manikins. Although the 17-member CADRE is intended primarily for workspace design, it is possible that this approach could be adapted to the development of selection criteria. However, CADRE is founded on the belief that points on a hyper-surface which enclose a given proportion of the population data, will retain this property after transformation from the domain of the anthropometric data into the workspace domain. This may not be the case with certain workspace geometries. There exists the possibility that the requirement to manipulate the position of operators to satisfy various criteria such as vision and reach, will cause points lying within the enclosing surface in the space of the anthropometric variables to be mapped into regions external to the transformed enclosing surface in the workspace domain. Such a hypothesized region is illustrated in Figure 1 (Region A).

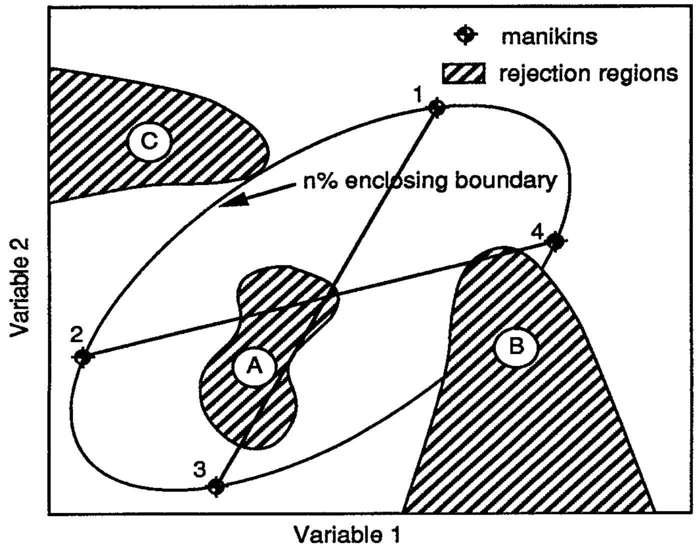

Figure 1. *Hypothesized rejection regions in anthropometric space.*

Even if closed regions of the type discussed above do not exist, there are other problems with CADRE. Sixteen manikins in CADRE are located on the hyper-ellipsoid enclosing surface, at the ends of an oblique axes system, which encloses 94% of the population data. The final manikin is located at the centroid. This provides for a sparse description of the enclosing surface, and a rejection region may not be sampled by the limited representation provided by CADRE (e.g. Region B in Figure 1). Although this problem could be addressed by a more detailed sampling of the enclosing surface, a final objection remains. Designing for a n-member CADRE constrains a rejection region to be tangent to the enclosing surface and never to cut it (e.g. Region C in Figure 1). Once the rejection region cuts the enclosing surface, the actual proportion of rejections can not be predicted by this n-member set. The net result is a conservative design, at least for those design areas not related to operator safety or critical performance. That is, actual rejection rates will generally be less than the 6% that might be expected from designing for manikins located on a 94% enclosing surface.

Therefore, in order to deal with the range of individual anthropometric differences and to know the rejection rates resulting from specific design or selection decisions, it is argued that not only is a multi-variate approach required, but this approach must sample throughout the entire data space. Such distributed multi-variate representations have been used in a number of areas related to workspace design and assessment [13, 15, 16]. The power of these methods comes from their representation, to an accuracy determined by the level of sampling and the fidelity of the modelling process, of the full range of interactions between anthropometric dimensions and the workspace.

3. THE SIMULATION PROGRAM

The Simulated Anthropometric Fitting Trial (SAFT) software is a PASCAL program for PC or PC compatible computers, which simulates an anthropometric compatibility check of human subjects in a simple seated workstation geometry. The simulation is based on the five-link sagittal plane manikin [15] shown in Figure 2. Manikins are defined by five anthropometric variables. Link lengths are calculated by a monte-carlo process which, by a random sampling throughout the anthropometric data space, matches the means, standard deviations and correlation matrix of the 5-dimensional distribution from which the variables are drawn. All variables are constrained to lie within 3.5σ of their mean value. This arbitrary truncation avoids the occurrence of extreme outlyers. Workspace geometries are defined in terms of a vision line, a seat adjustment ramp, seat geometry, instrument panel location, floor line, and a range of heel points for pedal location and adjustment.

The simulation attempts to fit each member of a group of manikins (up to 1900) into a workspace according to a set of rules; for example, eye on or above the vision line, seat reference point on the seat ramp, and heel on the floor line within a given range. Manikins are divided into categories according to their 'fit' in the workspace. Fit is defined in terms of reach to panel and floor, heel within the range of adjustment, and trunk and knee angles within defined ranges.

The manikin's posture is determined by the seat parameters used for the simulation (i.e. the seat back and seat pan angles determine the eye link, trunk link and thigh link angles). When each manikin is fitted into the workspace, the fitting algorithm first places each eye point and seat reference point (SRP) on the vision line and seat ramp line respectively. From this position, reach to the panel is tested. If the panel is within the manikin's reach no further seat adjustment is made at this stage. If the panel is outside the manikin's reach, up to 5 degrees of seat rotation about the SRP is used in an attempt to improve the situation. No translation of the SRP is allowed. Seat rotation halts when the reach criterion is satisfied. Any manikin that fails to reach the panel under maximum seat rotation, is held in this final posture for the lower body assessments.

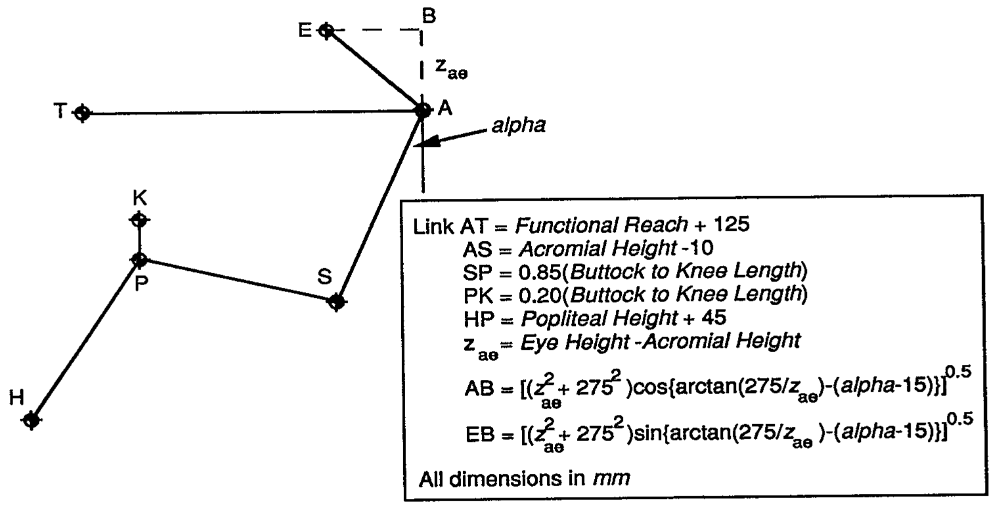

Figure 2. *Five link sagittal plane model used in SAFT.*

Once the panel reach assessment is complete, reach to the floor line is tested. If the heel point can not be located on the floor line, remaining seat rotation is used in an effort to find an intersection. Finally, the heel point is tested against the pedal adjustment range. Those manikins which fail to reach the rearmost heel position can use seat rotation, up to the maximum allowable, in order to come within range. Those manikins with heel points ahead of the forward limiting heel position, have their heel points brought back to this position. Trunk/thigh and knee angles are checked for range at this stage.

Manikins are classified into groups according to the compatibility test failed. There are four tests for acceptable fit, and manikins may fail one or more tests. The tests are:

Test 1- arm reach to the instrument panel;
Test 2- leg reach to the floor;
Test 3- heel point ahead of the rearmost allowable position; and
Test 4- thigh/trunk angle greater than 85 degrees and knee angle greater than 90 degrees.

4. PROCEDURE

Input data for the monte carlo simulation were obtained from the 1985 survey of Canadian Forces Aircrew [17]. While the data from this survey are for a largely male population, the principle results of the simulation should generalize to any population, regardless of nationality or gender. The correlation matrix, means, and standard deviations for the 5 variables used in SAFT are shown in Table 1.

Simulated fitting trials were run for two geometries. Seat ramp angles of 30 and 110 degrees were used. In both cases the vision line was set at 11 degrees below the horizontal, the trunk link angle (α) at 25 degrees and the thigh link angle (β) at 10 degrees (see Figure 3). The positions of panel, floor and heel ranges, were chosen to achieve approximately 10% rejection rates, from a population of 1900 manikins, for each of the 4 tests of 'fit'.

As a further test on the requirement for a distributed approach, a CADRE of 17 manikins were produced from the percentile values given in Bittner et al. [14] (see Table 2). The percentile values were first turned into z-scores and then into anthropometric values using the means and standard deviations from Table 1. Only the five variables required by SAFT were used in these calculations. Using the same vision angle and seat geometry (i.e. α and β) described above , and with a seat ramp angle of 30 degrees, a workspace was created (i.e. panel, floor and heel locations) that satisfied the complete set of 17 manikins on all tests of fit. This geometry was then tested using 10 independently created populations (N=1000) of SAFT manikins.

TABLE 1

Correlation matrix, means and standard deviations used for the monte carlo simulation in SAFT.

Correlations	Eye Ht. (Sitting)	Functional Reach	Buttock to Knee Lt.	Acromial Ht. (Sitting)	Popliteal Height
Eye Ht. (Sitting)		0.464	0.438	0.823	0.492
Functional Reach			0.721	0.488	0.752
Buttock to Knee Lt.				0.496	0.766
Acromial Ht. (Sitting)					0.491
***Mean*†**	80.6	79.4	60.9	60.6	45.1
***Standard Dev.*†**	3.43	3.88	2.77	2.85	2.27

† anthropometric variables in *cm*.

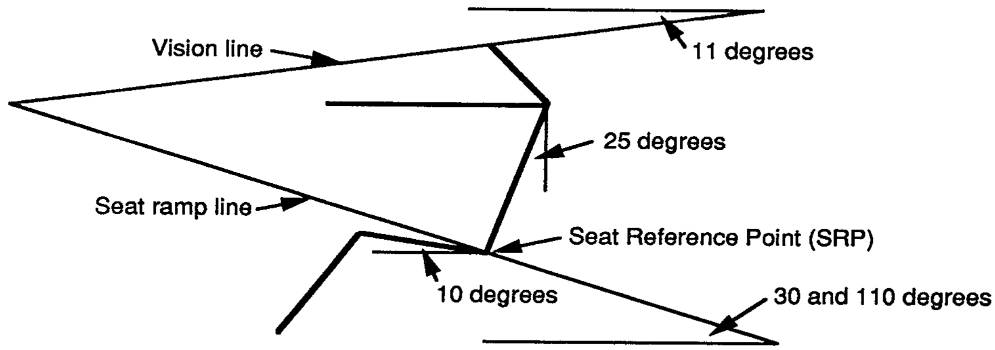

Figure 3. *SAFT workspace geometry.*

TABLE 2

Percentile values used to produce the 17 manikin set for CADRE.

Manikin	1	2	3	4	5	6	7	8	9
Eye Ht. (Sitting)	97.2	93.5	91.2	28.5	93.8	82.8	16.5	87.2	12.8
Functional Reach	97.3	76.3	89.6	92.2	68.2	51.6	58.0	22.9	77.1
Buttock to Knee Lt.	98.5	61.7	81.4	95.6	92.4	16.5	43.6	33.3	66.7
Acromial Ht. (Sitting)	95.7	90.0	86.9	36.8	91.4	75.5	22.0	82.5	17.5
Popliteal Ht.	97.6	63.8	96.7	90.7	66.7	58.6	38.3	11.7	88.3

Manikin	10	11	12	13	14	15	16	17
Eye Ht. (Sitting)	83.5	17.2	6.2	71.5	8.8	6.5	2.8	50.0
Functional Reach	42.0	48.4	31.8	7.8	10.4	23.7	2.7	50.0
Buttock to Knee Lt.	56.4	83.5	7.6	4.4	18.6	38.3	1.5	50.0
Acromial Ht. (Sitting)	78.0	24.5	8.6	63.2	13.1	10.0	4.3	50.0
Popliteal Ht.	61.7	41.4	33.3	9.3	3.3	36.2	2.4	50.0

5. RESULTS

The interaction between workspace geometry and anthropometry is demonstrated by the Test 1 (reach to panel) failures for seat ramp angles of 30 and 110 degrees (see Figure 4). For the 30 degree seat ramp angle, the surface of separation between manikins that pass Test 1, versus those that fail, can be described by a linear relation between *Eye Height (Sitting)* and *Functional Reach* (with a small effect due to *Acromial Height*). For this geometry, Test 1 failures have little or no dependency on the remaining anthropometric variables. A discriminant analysis [18] confirmed this claim (a linear discriminant function in *Functional Reach* and *Eye Height* achieved close to perfect discrimination). Note that the rejection region spans a large part of the range of both variables, hence, incompatibility is not simply a function of being *large* or *small* but rather depends on a critical combinations of the two variables. For the 110 degree seat ramp (typical of ejection seat geometry), the rejection region appears in a different part of the anthropometric domain. Again the separation boundary is largely linearly dependent on *Functional Reach* and *Eye Height*, although the partial overlap between the rejection and acceptance regions in Figure 4 suggests other dimensions are involved. A discriminant analysis showed that a linear discriminant function in *Functional Reach, Eye Height* and *Acromial Height* could precisely categorize the data into acceptable and rejection regions. Note from Figure 4, that the Test 1 failures for the 110 degree seat ramp geometry can be separated largely on the basis of *Functional Reach* alone.

Whereas panel reach depended on linear transformations of two or three anthropometric variables, the location of heel points on the floor line involves non-linear transformations (i.e. sine and cosine relationships) and depends on all five anthropometric variables. In Figure 5, the Test 3 failures are plotted against three of the five anthropometric variables used in SAFT. Examination of these data under various axes combinations and rotations, using a 3-dimensional data analysis package (MACSPIN 2.0 [19]), failed to disclose a simple structure for the boundary of separation between the Test 3 failures and the region of acceptable characteristics. Within the domains examined, the region of Test 3 failures and the region of acceptable anthropometric characteristics are highly confounded. Both standard discriminant analysis [18] and canonical discriminant [20] analysis were performed on these data. The Test 3 failures could not be separated from the acceptable region by either of these linear techniques. This is demonstrated in Figure 6, where the first two canonical variables are plotted for each category of fit. No other combination of canonical variables proved to more successful in separating the data. There is some evidence that the linear transformations of the canonical discriminant analyses have approximated the surface of separation in parts of the domain (i.e. there is an edge appearing between the *3rd* and *4th* quadrants in Figure 6), however, the surface of separation can not be described in terms of a single linear relationship. This is further demonstrated by Figure 7 which provides a view of the domain defined by the first three canonical variables.

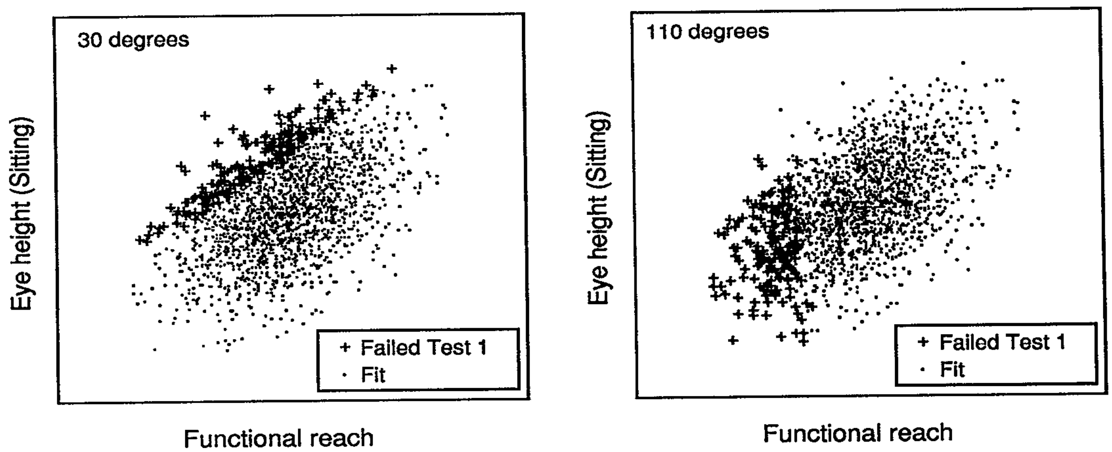

Figure 4. *Test 1 failures for 30 and 110 degree seat ramps.*

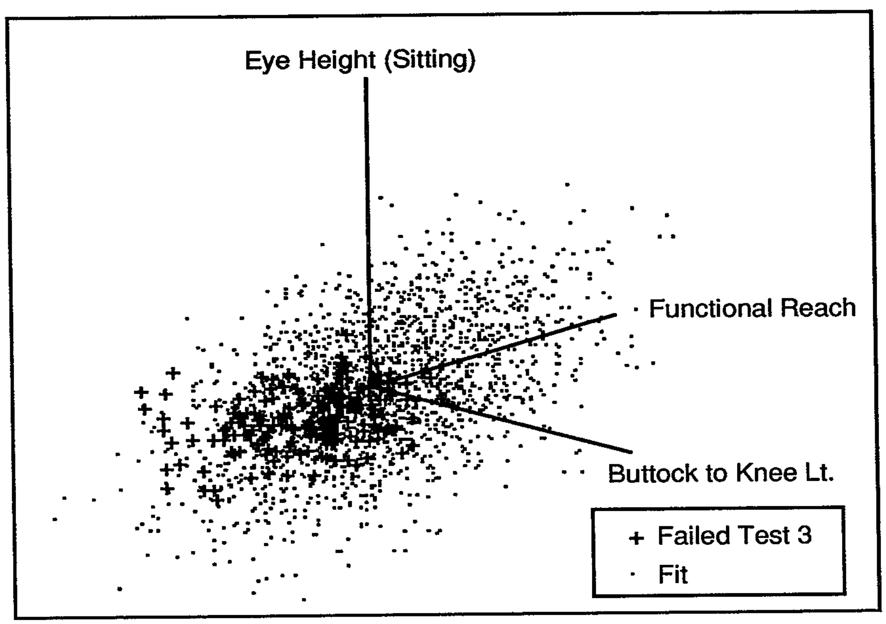

Figure 5. *Test 3 failures for the 30 degree seat ramp.*

The rejection rates for each of 10 independent populations of SAFT manikins are shown in Table 3. For a geometry that satisfied the CADRE 17-member set, it can be seen that Test 3 failures exceeds the nominal 5-6% rejection rate expected from the use of CADRE, while Test 1 failures fall considerably under this rate.

TABLE 3

SAFT rejection rates for a workspace geometry determined from the 17-member CADRE of manikins.

Run Number	1	2	3	4	5	6	7	8	9	10	Mean	S.D.
Test 1	2.0	1.5	2.4	2.4	2.3	1.8	2.4	2.3	1.9	2.4	2.1	0.32
Test 2	3.5	3.0	3.7	2.5	2.6	3.6	4.0	3.6	2.5	2.9	3.2	0.55
Test 3	11.6	9.7	12.5	10.4	12.8	11.3	10.1	11.0	12.4	9.1	11.1	1.26
Test 4	4.4	5.4	5.6	6.2	5.6	7.0	5.3	5.8	7.7	6.9	5.9	0.93

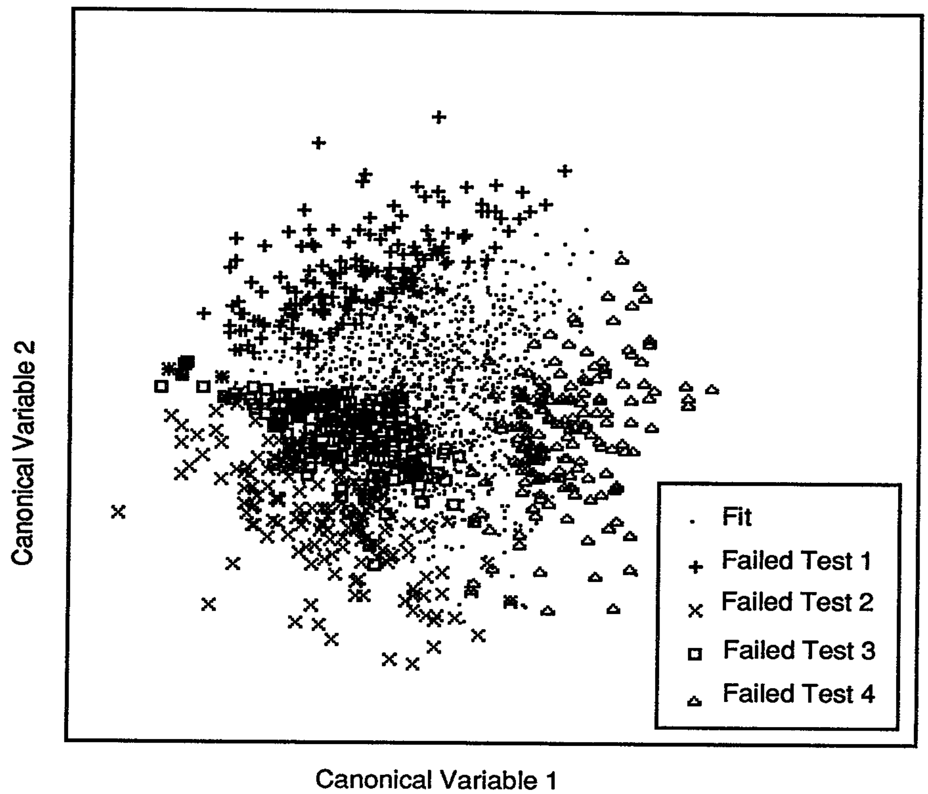

Figure 6. *Canonical discriminant analysis (30 degree seat ramp).*

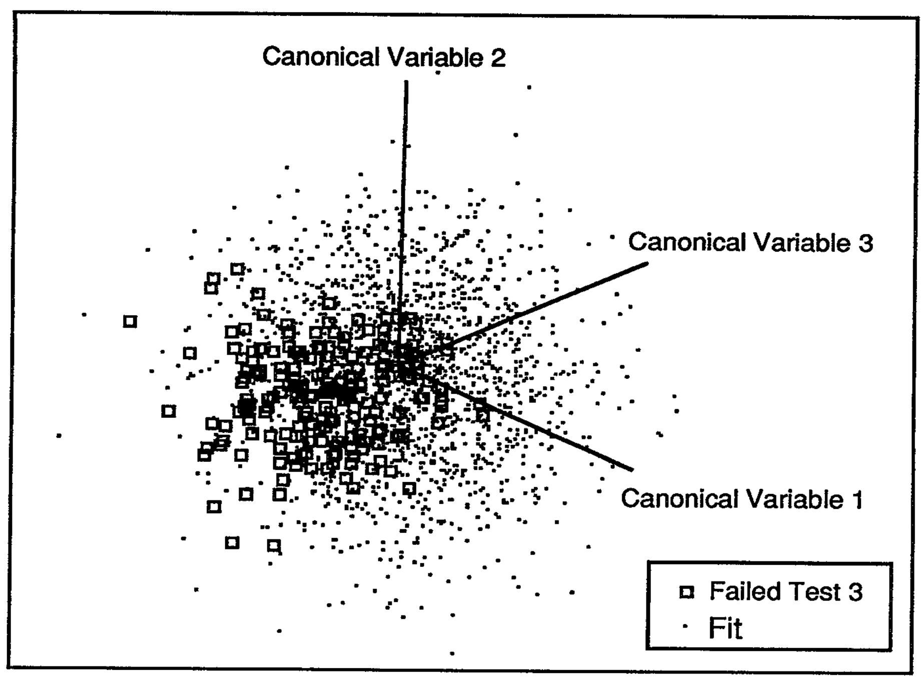

Figure 7. *Canonical domain for Test 3 failures (30 degree ramp).*

6. DISCUSSION

The application of SAFT to the relatively simple workspace geometries reported here, clearly demonstrates the 2 major claims of this paper: (1) that the anthropometric attributes that determine membership in a particular category of 'fit' is dependent on the specific workspace geometry; and (2) that rejection regions can be characterized by complex non-linear surfaces of separation within the anthropometric data space. Therefore, in view of these characteristics, it is not surprising that traditional techniques for the application of anthropometric data to design have been found to be inadequate in some situations [3]. The development of selection criteria, particularly those intended to ensure compatibility with existing workspace designs, is seen to be a related issue. In both design and selection, these complex interactions are not to be ignored.

The SAFT simulation program was written to demonstrate the nature of this problem and to create an environment where methods could be investigated for characterizing the regions of rejection for various workspace geometries. Although linear techniques such as discriminant analysis achieved good categorization for certain rejection regions (e.g. reach to panel), they failed for others (e.g. pedal reach). Some tentative efforts have been made to use neural network methods to partition the space. Early efforts have been encouraging, and there are plans to continue with this technology. Alternatively, it is possible that linear methods might be made to work if appropriate transformations are first made to the data. This avenue will also be explored further.

If it is accepted that 'compatibility' depends on the interaction between an operator's anthropometric characteristics and the workspace geometry, then it raises questions about the role of context free (i.e. geometry independent) selection criteria. On the other hand, selection criteria might be derived from the characteristics of one or more existing workspaces, or from geometries that are found in various design standards (e.g. [21]) or human engineering guidelines (e.g. [22]). Such geometry specific selection criteria may prove to be excessively restrictive if the rejection region of an old geometry is the acceptance region of a new geometry. This, however, should not be seen as a choice between one method or the other. It is suggested that an integrated approach to selection and design requires both approaches, that is: the establishment of a simple set of context free selection/design criteria; and the development of compatibility 'templates' for individual workspace geometries and the application of these templates in assigning operators to workspaces.

The context free selection/design criteria should be as simple as possible [23] and are intended to truncate the distribution of anthropometric characteristics and so avoid extreme outliers. As long as appropriate multi-variate and distributed methods are used, this strategy should provide the greatest freedom for designers. Ideally, these context free criteria should enclose a proportion of a target population which provides a suitable pool of operator candidates for training. If the purpose of these criteria is merely to avoid extreme outliers, then a simple uni-variate approach to setting rejection ranges may be adequate. This truncated multi-variate distribution then becomes the basis for future design exercises. Design for safety or critical performance of all future equipment should accommodate a nominal 100% of the operator population specified by these criteria. Alternatively, anthropometric limits will be established for those workspaces that do not achieve this goal. Future design efforts should also concentrate on developing workspaces that are more uni-variate in their compatibility requirements, for example, through the use of seat mounted controls and helmet mounted displays. Also certain geometries (e.g. panel reach for the 110 degree seat ramp- see Figure 4) can facilitate this process by reducing compatibility requirements to dependencies on single anthropometric variables.

The development of compatibility templates for specific workspace geometries is an essential adjunct to the use of the context free criteria in design. These templates should focus on those aspects of compatibility that are essential for the safe operation of the equipment or are essential for achieving a minimum acceptable level of performance. Each potential operator should be screened against the appropriate template before assignment to a specific workspace. These templates should only be required for existing workstations or for those new workspace designs that are unable to achieve critical operation by 100% of the operator population. In the short term, these templates will establish the effective selection criteria. Until such time as new geometries achieve critical operation by 100% of the context free distribution, the 'working' selection criteria will be established by the intersection of sets of acceptable anthropometric characteristics (i.e. the templates) derived from a specific group of workspaces. This group will include all workspaces on the operators' critical career path (i.e. training aircraft), plus a selection of operational workstations that might range from a single type, to all types in the inventory. If selection and design are tied together in this fashion, the process should evolve over time from an initial set of quite complex rules for selection, as established from the templates, to the simple context free criteria discussed above.

It has been argued throughout this paper that a multi-variate distributed approach must be taken in the application of anthropometric data to design. Such an approach is also critical in developing selection criteria, particularly in the establishment of compatibility templates. Although a CADRE of manikins chosen in the style of Bittner et al. [14], may be adequate for establishing the critical dimensions of a workstation, this limited representation of the data space has little interpretative power once rejection regions cut the enclosing boundary. This was demonstrated in the use of the 17-member CADRE to design a workspace which was subsequently tested against samples drawn from throughout the anthropometric data space. The discrepancy between the SAFT rejection rates (see Table 3) and the predicted 6% rejection rate for CADRE, suggests the existence of either Type A or B (Figure 1) rejection regions for this geometry. For those 'rejection' criteria that imply impaired operability rather than system failure or dangerous operation, the requirement to keep all such regions external to the enclosing boundary can result in overly conservative design solutions. Such conservatism is not without cost as it leads to greater size, larger ranges of adjustment and added complexity.

7. CONCLUSIONS

Although it is recognised that physical compatibility with a workspace is likely to depend on an interaction between an operator's anthropometric characteristics and workspace geometry, traditional methods for the application of anthropometric data to both design and the development of selection criteria appear to place little emphasis on this knowledge. The geometry specific nature of anthropometric compatibility, and the need for a non-linear multivariate approach to design, were demonstrated through the use of a computer simulation program called SAFT (Simulated Anthropometric Fitting Trial).

In view of these characteristics, it is suggested that a two tiered approach to selection/design is required, namely: the development of simple geometry free criteria for use in design and subsequently for selection; and a set of compatibility 'templates' for screening potential operators for their suitablity to occupy specific workspaces. In the short term, selection criteria would be determined from the intersection of some set, or subset, of the acceptable regions defined by these templates. Such criteria are likely to be complex, non-linear, multivariate functions of anthropometric variables. But if new workstations are designed in accordance with the simple geometry free criteria, then the requirements for selection should relax over time to match these same criteria. It is likely, however, that compatibility templates will still have to be developed for certain workspaces within a class of equipment, possibly due to constraints or trade-offs which occur in the design process. The restrictions imposed by these templates may become selection criteria for just that item of equipment (career streaming), or they may become part of the general criteria for selection ('fit to fly all'), depending on resource utilisation policy.

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