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NAVAL AIR MATERIAL CENTER
PHILADELPHIA, PA.

NAVAL AIR EXPERIMENTAL STATION
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Cockpit Design Studies; Standard Cockpit Mockup: Components of Variance in Anthropometry

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ABSTRACT

The data of an anthropometric study of eleven morphological features on forty-two subjects was analyzed by the analysis of variance so as to obtain estimates of inter-subject, intra-subject, inter-anthropometrist, and intra-anthropometrist sources of variation and to determine the proportion of total variance contributed by each of these. The results indicate that unreliable variance (which consists of the last three sources mentioned above) contributes as much as one-fifth of the total variance in morphological features which involve movement of the shoulder joint (anterior and maximum arm reach) and in buttock-leg length and is negligible in features such as height and weight.

I. INTRODUCTION

In anthropometric studies only one of the universe of measurements for each morphological feature is sampled. Furthermore, numerous anthropometrists make the various measurements on the population sampled. Thus, there is a confounding of intra-subject, inter-anthropometrist, and intra-anthropometrist sources of variation in the measurements as unreliable variance. The contribution of one or more of these sources of unreliable variances to the total variation might be of such magnitude as to invalidate the application of these results in practical situations, e.g., fitting various personnel with clothing or other equipment. Accordingly, this investigation was undertaken to obtain estimates of the sources of variation mentioned above as well as that of the reliable variance (inter-subject variation) and to determine the proportion of the total variance contributed by each of these for a limited set of morphological features.

II. SUMMARY AND CONCLUSIONS

As a basis for selecting subjects for an investigation concerning the effects of the full pressure suit and other equipment on the performance of the pilot and on workspace dimensions, eleven morphological features had been selected as the ones most likely to be critical, viz., height, weight, sitting height, knee height, buttock-leg lenth, buttock-knee length, elbow-elbow breadth, bideltoid diameter, span, anterior arm reach, and maximum arm reach. Three measurements were taken for each of these eleven features on forty-two subjects by three anthropometrists, and the data was factor analyzed to determine the underlying basic factors. The results of this analysis are presented in reference (2).

By the use of an analysis of variance technique, which allowed the isolation of the various components of variance, a separate analysis was performed for each of the eleven morphological features and the proportion of total variance contributed by each of these was estimated. Intra-subject variance was least for height and weight and greatest for buttock-leg length and anterior arm reach; however, this variance was sizeable for maximum arm reach, elbow-elbow breadth, and bideltoid diameter. Conversely, inter-subject variance (reliable variance) was greatest in those features which contained negligible intra-subject variance and was least in those features which had large intra-subject variance. Intra-anthropometrist variance was non-existent except for weight, maximum arm reach, and anterior arm reach where it was a negligible percentage. Inter-anthropometrist variance was non-existent for all morphological features. However, this last result probably occurred because the inter-anthropometrist effect was compared against an experimental error term which was sizeable because of the inclusion of sampling errors.

Therefore, an approximate test of significance which allowed a deletion of sampling errors from the experimental error term was used and inter-anthropometrist variance was indicated to be present in maximum arm reach, knee height, buttock-knee length, anterior arm reach, and buttock-leg length. A summary of the results is presented in Table 2.

From the results obtained in this study it is apparent that unreliable variance can reach an alarming proportion in the measurement of some morphological features. One way to counteract this aspect would be to take more than one measurement on each feature for each subject so as to give a more reliable estimate of that feature. However, in large scale anthropometric studies this would be a very expensive procedure.

III. RECOMMENDATIONS

1. In conducting anthropometric studies it is recommended that more than one measurement be obtained on each subject for most morphological features. This would be especially important in the most variable ones such as buttock-leg length and measurements involving the shoulder joint, e.g., maximum and anterior arm reaches.

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IV. BACKGROUND

It is generally agreed that the reliability of anthropometric data varies directly with the body build of the subject, e.g., the dimensions of lean subjects are more accurately obtained than subjects with increasing amounts of subcutaneous fatty tissue. Likewise, measurements of morphological features such as height and sitting height are more reliable than those features which involve increasing amounts of subcutaneous tissue such as bideltoid diameter or elbow-elbow breadth. With regard to anthropometric studies on numerous subjects, it is obvious that the reliability of the results would increase with a decrease in the number of anthropometrists involved and with an increase in the amount of training received by the anthropometrist.

There has been some attempt in the past to determine which morphological features are most consistent. Gavan (1) reports a study based on measurements of sixty-two morphological features taken by six teams of anthropometrists on five subjects. There were at least ten measurements obtained for each feature; most were taken thirty times; and some were taken forty-nine times. No subject was measured by all teams. The average of the standard deviation and of the coefficient of variation were used as measures of consistency, i.e., the difference in repeated measurements when the subject and anthropometrist remain constant. This procedure allowed grouping of the morphological features into three consistency groups, high, medium, and low. However, this analysis results in a confounding of the four sources of variation, inter-subject, intra-subject, inter-anthropometrist, and intra-anthropometrist.

In order to avoid such confounding, a technique well suited to obtain estimates of each component of variance separately, the analysis of variance, was utilized in this study. The paradigm of the components of variance analysis of variance design used is given in Table 3 in the Appendix.

V. PROCEDURE

In preparation for this study three individuals trained together on practice subjects for a period of four weeks until the inter- and intra-anthropometrist variation was approximately constant. Each anthropometrist then measured fourteen subjects three times on each of eleven morphological features employing standard anthropometric techniques (5). These measurements were obtained within a period of one week and at about the same time each day. The forty-two subjects included civilian employees (37) and naval enlisted personnel (5) at the Air Crew Equipment Laboratory, who ranged in age from nineteen to sixty-eight (mean = 34.8; median = 33.5).

TABLE 1

Estimates of Components of Variance and the Percent of Total Variance Contributed by Each Appropriate Test

Appropriate Test

	Morphological Feature	Estimate of Intra-Subject Variance	Percent of Total	Estimate of Inter-Subject Variance	Percent of Total	Estimate of Intra-Anthropometrist Variance	Percent of Total
a)	Buttock-leg length	6.45	19.5	26.65	80.5	*	
b)	Height	.13	.3	37.07	99.7	*	
c)	Weight	1.05	.30	352.66	99.68	.07	.02
d)	Knee-height	.22	3.5	6.00	96.5	*	
e)	Buttock-knee length	.44	6.6	6.20	93.4	*	
f)	Elbow-elbow breadth	.88	9.2	8.67	90.8	*	
g)	Bideltoid diameter	.32	9.0	3.24	91.0	*	
h)	Max. arm reach	1.92	10.8	15.77	88.2	.18	1.0
i)	Span	1.76	4.4	40.67	95.6	*	
j)	Anterior arm reach	2.30	17.4	10.68	80.8	.23	1.8
k)	Sitting height	.57	5.9	9.09	94.1	*	

Approximate Test +

	Estimate of Intra-Subject Variance	Percent of Total	Estimate of Inter-Subject Variance	Percent of Total	Estimate of Inter-Anthropometrist Variance	Percent of Total	Estimate of Intra-Anthropometrist Variance	Percent of Total
a)	6.45	19.4	26.18	78.6	.67	2.0	*	
b)			no change					
c)			no change					
d)	.22	3.5	5.73	90.2	.40	6.3	*	
e)	.44	6.5	5.95	88.0	.37	5.5	*	
f)			no change					
g)			no change					
h)	1.92	10.4	14.45	78.6	1.33	10.0	.18	1.0
i)			no change					
j)	2.30	17.5	10.09	76.4	.58	4.4	.23	1.7
k)			no change					

\+ Refers only to the test of significance for the Inter-Anthropometrist effect.

* Not significant; therefore, considered non-existent.

Inter-Anthropometrist variance was non-existent according to appropriate test and is not included in that portion of the table.

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TABLE 2

Percentage of Total Variance
Contributed by Each Component of Variance

	Reliable Variance		Unreliable Variance	
Morphological Feature	Inter-Subject	Intra-Subject	Inter-Anthropometrist	Intra-Anthropometrist
Height	99.7	.3		
Weight	99.68	.30		.02
Span	95.6	4.4		
Sitting height	94.1	5.9		
Bideltoid diameter	91.0	9.0		
Elbow-elbow breadth	90.8	9.2		
Knee height	90.2	3.5	6.3	
Buttock-knee length	88.0	6.5	5.5	
Buttock-leg length	78.6	19.4	2.0	
Maximum arm reach	78.6	10.4	10.0	1.0
Anterior arm reach	76.4	17.5	4.4	1.7

VI. RESULTS and DISCUSSION

The results of the analyses are presented in Tables 1 and 2. It can be seen that the two major sources of variance are inter-subject (reliable variance) and intra-subject (unreliable variance) and, of course, have a reciprocal relationship. The intra-subject variation in this study was of an extrinsic nature (arising from variation in posture assumed when measurement was taken), except in weight, because of the short intervals between measurements. To determine intrinsic (real) intra-subject variation, longer time intervals would have been required.

The intra-anthropometrist effect contributed none or a negligible proportion of the total variance so that for practical purposes it can be disregarded. Likewise, the inter-anthropometrist effect was non-existent when compared against the appropriate experimental error term. However, this term was not precise because it contained the effect of sampling errors. Therefore, an approximate test was used (described in Appendix) which enabled the deletion of this effect to make the estimate of appropriate error more precise. With this adjustment, the inter-anthropometrist effect appeared in knee height, buttock-knee length, anterior arm reach, and maximum arm reach. This effect contributed the largest proportion of total variance in the last named feature (10 percent).

According to Table 2 the morphological features which are most reliable are height, weight, span, and sitting height; the least reliable are buttock-leg length, maximum arm reach, and anterior arm reach. The great variability seen in the arm reaches is to be expected inasmuch as movement of the shoulder joint varies in three dimensions. Any measurement involving this joint will tend to offer a sizeable amount of unreliable variance through both intra-subject and inter-anthropometrist sources of variation.

The best procedure by which to overcome this unreliability would be to obtain more than one sample of each measurement for each morphological feature, with some time interval between measurements, thereby increasing the reliability of the estimate. Such a procedure would be of special value in the conducting of anthropometric studies which are concerned with the solution of practical problems such as fitting various personnel with clothing or other equipment. However, this procedure would result in great expense. A compromise solution which would seem feasible would be to take only one measurement on those morphological features which have been indicated to be most reliable and to obtain two or more for the more variable ones.

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APPENDIX

Description of Statistical Analysis

The analysis of variance model used in deriving estimates of the components of variance for the eleven morphological features may be described as a partially hierarchal one (3, 4). The paradigm is shown in Table 3. There were three random effects, Subjects (which "nested" within Anthropometrists), Anthropometrists, and Trials, which represented Inter-Subject, Inter-Anthropometrist, and Intra-Anthropometrist sources of variation, respectively. The Subjects X Trials interaction within Anthropometrists is used to represent Intra-Subject variance because the entire experiment could not be replicated to give an estimate of experimental error. However, the very nature of the experiment seems to indicate that this interaction is non-existent. Therefore, σ^2_{ac} can be deleted from the Expected Value of Mean Square column in Table 3, leaving only σ^2_e. σ^2_e contains intra-subject variations and any other uncontrolled aspects in the experiment; however, inasmuch as the other sources of variation are considered by the Trials and by the Anthropometrist effect, σ^2_e should contain only intra-subject variations.

It is obvious from the table which effects are used as the appropriate error term for each test of significance. However, there is no test of the Anthropometrist effect unless the Trials X Anthropometrist interaction effect is non-significant. In all analyses this effect was non-existent. Inasmuch as the question of the pooling of non-significant interactions with the error term is far from settled at the present time, a "never pool procedure" was adhered to in making tests of significance. However, the Subjects X Trials interaction was used whenever it contained the same terms as the effect which was the appropriate error term, because it was based on greater degrees of freedom and, thus, it was a more reliable estimate. After all effects had been shown to be present or non-existent by tests of significance, all effects containing the same terms were pooled and estimates of the various components of variance and the percentage of total variation contributed by each of these was obtained.

In all eleven analyses the Anthropometrist effect was non-significant when tested by the Subjects within Anthropometrist effect. (Trials by Anthropometrist was non-existent in all eleven analyses). This effect contains sampling errors and is less precise than a within subjects effect. Therefore, an approximate test of the Anthropometrist effect was made by deleting the effects of sampling errors (σ^2_c) by the following F test: Anthropometrist mean square - Subjects within Anthropometrists mean square + Subjects X Trials within Anthropometrists mean square divided by Subjects by Trials within Anthropometrists mean square.

In terms of the Expected Value of Mean Square, after the non-significant components have been deleted, this F test is as follows:

TABLE 3

Components of Variance Paradigm

Source of Variation	df	Expected Value of Mean Square
Anthropometrist (b)	2	$\sigma^2 e + 14\sigma^2 ab + 3\sigma^2 c + 42\sigma^2 b + \sigma^2 ac$
Subjects within Anthropometrists (c/b)	39	$\sigma^2 e + 3\sigma^2 c + \sigma^2 ac$
Trials (a)	2	$\sigma^2 e + 14\sigma^2 ab + 42\sigma^2 a + \sigma^2 ac$
Trials X Anthropometrists (ab)	4	$\sigma^2 e + 14\sigma^2 ab + \sigma^2 ac$
Subjects X Trials within Anthropometrists (ac/b)	78	$\sigma^2 e + \sigma^2 ac$

$\sigma^2 a$ = Intra-Anthropometrist Variance; $\sigma^2 b$ = Inter-Anthropometrist Variance; $\sigma^2 c$ = Inter-Subject Variance: $\sigma^2 e$ = Intra-Subject Variance

$$\frac{\sigma^2_e + 3\sigma^2_c + 42\sigma^2_b - \sigma^2_e + 3\sigma^2_c + \sigma^2_e}{\sigma^2_e} \text{ which reduces to } \frac{\sigma^2_e + 42\sigma^2_b}{\sigma^2_e},$$

When this approximate test is used the Inter-Anthropometrist effect was significant in five of the morphological features. However, it must be emphasized that this test, even though theoretically sound in principle, must be considered as an approximation inasmuch as an appropriate test had been provided by the mathematical model. An experimental design in which all effects are within subjects effect would overcome this difficulty and give a precise error term for all effects, e.g., a treatments X subjects design (6). This design would require that the anthropometrists take two or more measurements on every subject. This possibility had to be excluded in the present study because the subjects were only available for a few sessions.

To illustrate the use of this statistical design, Tables 4, 5, and 6 present the data for the analysis of maximum arm reach measurements. This analysis is chosen because each of the four components of variance contribute to the total variation for this feature.

TABLE 4

Analysis of Variance
of
Maximum Arm Reach Measurements

Sources of Variation	Degrees of Freedom	Sum of Squares	Mean Square	F	P
Anthropometrist	2	244.02	122.01	2.70	>.05
Subjects within Anthropometrists	39	1765.32	45.26	23.70	<.001
Trials	2	18.90	9.45	4.95	<.01
Trials X Anthropometrists	4	8.82	2.21	1.16	>.05
Subjects X Anthropometrists within Anthropometrists	78	148.92	1.91		
Total	125	2185.98			

TABLE 5

Approximate Test
of
Anthropometrist Effect

$$F = \frac{122.01 - 45.26 + 1.91}{1.91} = \frac{78.66}{1.91} = 41.18 \qquad P < .001$$

TABLE 6

Estimates of Components of Variance
for
Maximum Arm Reach Measurements

Source of Variation	Mean Square	Components
Anthropometrist (b)	122.01	$\sigma^2_e + 3\sigma^2_c + 42\sigma^2_b$
Subjects within Anthropometrists (c)	45.26	$\sigma^2_e + 3\sigma^2_c$
Trials (a)	9.45	$\sigma^2_e + 42\sigma^2_a$
Subjects X Trials within Anthropometrists (e)	1.92	σ^2_e

		Estimate of Variance	Percent of Total
$\sigma^2_e =$		1.92	10.4
$\sigma^2_a =$	$\frac{9.45 - 1.92}{42} =$	.18	1.0
$\sigma^2_c =$	$\frac{45.26 - 1.92}{3} =$	14.45	78.6
$\sigma^2_b =$	$\frac{122.01 - 45.26}{42} =$	1.83	10.0
		18.38	100.0