ANTHROPOMETRY FOR PERSONS WITH DISABILITIES: NEEDS FOR THE TWENTY-FIRST CENTURY

Task 2: Analysis and Recommendations

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PREFACE

This document is the final report of Task 2 of the "Anthropometric Research Review" undertaken by Anthropology Research Project, Inc. (ARP) for the U.S. Architecture and Transportation Barriers Compliance Board (Access Board), and administered by the U.S. Department of Education under Contract No. QA96001001. The authors thank David Yanchulis, Research Coordinator at the Access Board, for his cooperation and support. They are grateful, also, for the many hours of painstaking work by ARP staff members Belva Hodge for producing and Ilse Tebbetts for editing this report.

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INTRODUCTION

Under Task 1 of contract No. QA96001001, an annotated bibliography concerned with the anthropometry of people with disabilities, and its applications to the design of facilities, workspaces, and equipment, was completed. It appears in this report as an appendix. The objective of Task 2 is to assimilate the information gathered in Task l, to identify further anthropometric research needed to update guidelines and standards for accessible design, and to recommend the means of carrying out such studies.

The bibliography compiled in Task 1, while by no means exhaustive, incorporates a large body of anthropometric data on more than 11,000 persons of every age and a wide variety of disabilities. Unfortunately, most of the studies were conducted on specialized populations, many of them foreign. Dimension definitions and measurement techniques vary from study to study and, in many cases, samples were very small. In a recently published review of the anthropometry of people with disabilities (Kumar, 1997), A. Goswami examined six international studies of people with lower limb disorders and discovered that, for a combined total of 58 body size descriptors measured in the studies, not a single dimension was found in common. Goswami also could not find a single study that attempted to standardize either body landmarking or measurement procedures. These and similar findings are illustrative of the current state of affairs in regard to anthropometry of this group of individuals. Thus, while there is a great deal of existing anthropometric data, any attempt to combine them into a useful database would be futile.

Examination of the literature further reveals virtual unanimity among experts in the field regarding the undesirability of applying data from non-disabled populations to the design of equipment and spaces intended to accommodate populations with the full range of abilities and disabilities. This would be true of data from any non-disabled population, but is exacerbated in the U.S. by the fact that most existing anthropometric data on U.S. adults comes from military personnel. So poor is the status of applied anthropometry on U.S. civilians that the last major survey containing significant data applicable to design was completed in 1962 (Stoudt et al., 1965). This nationwide stratified random sample of men and women measured 14 anthropometric dimensions that can be used for the design of workspaces. Since that time three other large civilian surveys have been conducted but none contain anthropometric dimensions useful in design. As a result, many texts and guidebooks intended for interior and product designers in the U.S. are based on body size information collected from highly fit military populations.

The most recent of such comprehensive studies was conducted on U.S. Army personnel (Gordon et al., 1989). Although over 200 dimensions were measured on a group of 9,000 ethnically diverse soldiers, the data from this survey lack the range of variability found in the population of interest here. To examine this contention, a comparison was made for workspace dimensions from the Army survey and a compilation of seven separate studies of people with disabilities. Using the coefficient of variation (CV) as the statistic to compare the degree of variability, Table 1 presents the differences for 11 variables. The CV is a dimensionless statistic expressed in percent, so comparisons across dimensions that vary in magnitude are still valid.

TABLE 1

Coefficients of Variation (CV) for Selected Anthropometric Dimensions: Several Samples of Persons with Disabilities and U.S. Army Males

DIMENSION	PERSONS WITH DISABILITIES[1]			ARMY	DIFFERENCE
	Min and Max CV	No. of Studies	Average CV		
Mass-Weight	**5.5-20.4**	**7**	**11.1**	**14.1**	**-3.0**
Stature-Sitting	**2.9-8.3**	**6**	**6.6**	**3.9**[2]	**2.7**
Shoulder Height, Sitting	**6.9-11.0**	**4**	**9.3**	**5.0**	**4.3**
Elbow-Rest Height	**12.7-29.2**	**6**	**20.0**	**11.8**	**8.2**
Thigh Clearance	**18.3-33.0**	**4**	**22.7**	**7.5**	**15.2**
Shoulder Width	**4.6-8.9**	**5**	**6.8**	**4.5**[3]	**2.3**
Elbow-Elbow Breadth	**4.4-13.4**	**5**	**8.7**	**8.0**[4]	**0.7**
Popliteal Height	**7.9-10.2**	**4**	**8.9**	**5.7**	**3.2**
Buttock-Knee Length	**5.4-8.0**	**2**	**6.7**	**4.9**	**1.8**
Buttock-Popliteal Length	**7.0-10.4**	**4**	**8.6**	**5.3**	**3.3**
Hip Breadth	**7.8-25.8**	**4**	**14.4**	**5.9**	**8.5**

[1] Disabled data computed from means and standard deviations given by Goswami (Kumar, 1997).
[2] Sitting height value used. [3] Biacromial Breadth value used. [4] Forearm-Forearm Breadth value used.

Except for weight, the group with disabilities shows as much as twice the variability of the non-disabled sample in some cases. One reason for this result is, of course, the great number of disabilities, which, in turn, can cause a wide variety of changes in body size, posture, and function. This has led many investigators to a second finding relevant to Task 2: Anthropometric data obtained from individuals with a particular disability should not be used to draw up designs and standards for individuals with different disabilities. Nor are they applicable to a general U.S. population of people with disabilities.

The principal way to achieve good design is through the application of anthropometric data. In order to be effective, however, the data must not only be appropriate to the design at hand but must also be descriptive of the target user population. As noted above, much if not all the anthropometry so far collected on groups with disabilities involves specialized populations (Damon and Stoudt, 1963; Goswami et al., 1987; Molenbroek, 1987), and therefore has limited application for federal agencies that must concern themselves with the general U.S. population of individuals with a wide variety of disabilities.

NEAR-FUTURE RESEARCH NEEDS

In the best of all possible worlds, a major nationwide anthropometric survey of individuals with disabilities should be conducted. Such a study would be designed to collect information including body sizes, reach capabilities, range of joint motion, strength, and visual field data from several thousand children and adults, aged 2 and older with a wide variety of disabilities. The resulting database would be widely useful to engineers, architects, designers, and medical personnel as well as to the Access Board. Such an undertaking would, of course, be extremely costly. It is recommended here as a long-term goal that may ultimately be achieved, perhaps with funding from other interested groups. The current Civilian and European Surface Anthropometric Resource (CAESAR) program[1] is an example of how government and non-government organizations can pool resources to achieve a common goal. This anthropometric survey will obtain data from several thousand non-disabled civilians in the U.S. and abroad.

For the time being, we recommended a pilot study whose purposes would include:

- providing specific data on a general U.S. population of people with disabilities for use by the Access Board in updating their Accessibility Guidelines.

- providing the groundwork to support expanded anthropometric surveys in the future by establishing sampling strategies, and standardizing measuring and data handling procedures.

An anthropometric survey of this population presents a variety of challenges not encountered in similar studies of non-disabled subjects but, on the whole, planning and organization are the same for both. The major tasks to be completed in the planning stage of any survey are the following:

- Select the target population.
- Establish a sampling strategy.
- Select and define variables to be measured.
- Establish and test measuring techniques.
- Determine allowable errors for measuring each variable.

The planning tasks will be discussed in some detail in the following sections, largely in terms relevant to the requirements of the proposed pilot study.

1 For more information on the combined funding approach to CAESAR, contact Gretchen Stokes, SAE International, 400 Commonwealth Drive, Warrendale, PA 15096-0001, 412-772-8583.

THE TARGET POPULATION

Perhaps the most difficult problem presented by this population is its diversity. Disabilities may be caused by a wide variety of diseases and injuries as well as genetic and congenital conditions. For purposes of the Access Board, we recommend that the proposed survey be limited to people who use wheelchairs. We make this recommendation for two reasons. First a modestly sized pilot study cannot adequately address the full range of anthropometric diversity, so it makes sense to focus on that portion of the range which is most different from the non-disabled population, and that portion of the range which is most challenging from the perspective of the designer or architect. The individuals who use wheelchairs fit both these criteria. Second, a major survey may well structure its sampling plan (see below) to proportionately reflect groups which use a variety of mobility aids. If this is done, wheelchair users might be statistically “outnumbered”, and the result would be that reach ranges, for example, would not reflect their needs. In a concrete example of this effect, in the U.S. military, females represent about 8% of the total population. For many dimensions women represent the smaller end of the distribution. If they were measured in proportion to their representation in the military, and then the product or workspace design were created to accommodate the 5^{th} percentile through the 95^{th} percentile of the total population, nearly all the women would be excluded from the design because they fall disproportionately into the lowest 5 percent. What the military does instead is to measure men and women separately, and specify design targets which accommodate both men and women. This approach is likely to be effective in the present context, where people who use wheelchairs may be expected to fall at one end of the distribution of many dimensions, and where they may represent a minority of the total population of people with disabilities.

Trying to limit the scope of the pilot study, which should be exploratory in nature, we would also suggest restricting the survey group to an adult population aged 18 and over. The primary reason for this is to reduce diversity in the target population to a reasonable level. Human growth, whether or not there are disabilities involved, produces obvious and enormous anthropometric changes. Because of the anthropometric changes with age, sampling by age (see below) would require very small categories (a year or two) which would dramatically increase the sample size. In addition, methods to gain access to samples of children, measurement procedures and data analysis would all be different from the methods, procedures and analyses developed for adults. Certainly, children are candidates for future studies, and when the time is appropriate, their needs would be better served by a study targeted for their special requirements.

Recruitment of appropriate subjects must be carefully planned for, even when such subjects are widely available. In this case, appropriate subjects are not widely available. Arrangements will have to be made to seek out appropriate subjects in places where they are likely to be found in some numbers. One goal of major nationwide surveys is to maximize the diversity of the target population in the sample, not only with regard to sex, age, and racial/ethnic diversity but also with regard to geographic spread. For this preliminary study – and, perhaps even for larger future studies – geographic diversification is not likely to add anything useful to the variability of the sample. Thus, it should be possible for any qualified investigator living in or near a large city to recruit enough subjects within easy driving distance. The most likely locations would include large-hospital physical rehabilitation programs, nursing homes, and universities that enroll appreciable numbers of students with disabilities.

SAMPLING STRATEGIES

Sampling involves the process of selecting a group of individuals thought to be representative of an entire population. To put it another way, the small number of individuals in a given sample must reflect a significant amount of the variability extant in the entire population. Accurate sampling is critical to the creation of a database that can be applied successfully to the purposes for which it is intended. As has been noted, the variability of the target population in this country is very great.

There are a number of sources of information on the size of various U.S. populations with disabilities, including the National Health Interview Survey (NHIS), as well as publications of various associations representing specific disabilities but these reports do not give the kind of breakdowns that would be useful in developing a sampling plan. A review of the literature leads inevitably to the conclusion reached by J.A. Sanford (1996), “There appears to be no single data source that directly assesses the prevalence of mobility impairments in the U.S. population.”

Ordinarily in sampling for anthropometric surveys, a multi-dimensional matrix is drawn up to make sure that all critical sources of anthropometric variability are accounted for in the eventual sample. In the Army’s most recent anthropometric survey, for example, (Gordon et al., 1989), the matrix included sex, race and age. This is because these three demographic parameters account for much of the anthropometric variability in a non-disabled population. While the matrix approach is useful for the population of interest here, the same three parameters are not particularly effective. This is because the type of disability has much more to do with eventual body size and shape differences than does race. Age and sex are still important in describing a population of people with disabilities, so those parameters remain. Indeed, sex is generally important enough that, for anthropometric purposes, designers do well to consider males and females separately, rather than combining them into an appropriately representative population.

Age is a continuous variable, along which anthropometric dimensions change continuously. What this means is that unlike sex, where one is either a male or female, a 35-year-old may not be anthropometrically different from a 36-year-old. Yet, individuals in their 30’s are anthropometrically distinct from individuals in their 60’s. As a result, when using age in a sampling plan, some arbitrary divisions are needed. For the pilot study, we recommend dividing the population roughly into quartiles. Such divisions might be, for example: 18-25, 26-38, 39-50, and 51and over. There would be anthropometric distinction between the groups, but the distinctions are not so fine as to defy practical significance. To find the exact dividing points for age, one would research the age distribution of the population of wheelchair users, and place approximately 25% of the age distribution in each sampling unit. If such data are not available, then one would use the breakdown of the U.S. Census figures by age.

Dividing the wheelchair population into significant groups is also problematic. One approach is that suggested by Kumar (1997) in Table 2. When developing this into a sampling strategy for a pilot study, one would select the most frequent 4 or 5 conditions, and group the rest into a category "Other". For a full-scale survey, with a more complex sampling strategy, and a larger overall sample size, one would be able to use more specific categories, and reduce the number in the "Other" group. Following this scenario, a sampling matrix might look like the one shown in Table 3. This is based on a total sample of approximately 250 subjects of a single sex. The figure would be repeated for the other sex, for a total of 500 subjects.

TABLE 2

Frequency of Medical and Physical Conditions Necessitating Wheelchair Use

CONDITION	PERCENT
Arthritis	28
Organic nervous disorder	14
Cerebral vascular disease	13
Bone injuries and/or deformities	11
Lower limb amputation	9
Cerebral palsy	8
Traumatic paraplegia	7
Respiratory and cardiovascular disease	5
Obesity, congenital errors, spinal injury	5

TABLE 3

Hypothetical Sampling Matrix

AGE	ARTHRITIS	ORGANIC NERVOUS	CEREBRAL VASCULAR	BONE INJURIES	OTHER	TOTAL
18-25	17	9	8	7	21	62
26-38	18	9	8	7	21	63
39-50	17	9	8	7	21	62
50-65	18	8	9	8	22	65
TOTAL	70	35	33	29	85	252

Kumar's distribution is based on data which were gathered in the U.K. In the literature search undertaken to compile the annotated bibliography, we did not discover similar information for the U.S. Such information is critical if medical condition is to be used as a sampling parameter. It may be the case that another organization will carry out a questionnaire survey yielding appropriate information about: 1) the level and type of mobility aid used; 2) medical causes for using a mobility aid; and 3) other related demographic information. (A sample questionnaire is seen below.) If such a survey is done before planning for the pilot study is complete, then the resulting questionnaire

SAMPLE QUESTIONNAIRE

Age:____

Race/Ethnicity:____

City/Town:____

Occupation: ____

Type of Mobility Aid: _______________________________________

Hand propelled or electric:____________________________________

Medical Condition requiring Mobility Aid:_______________________

What objects do you have trouble reaching:

Home Work Public Places

Your height:____

Your weight:____

If you use an electric mobility aid, how could the placement of the controls be improved?_____________________________________

If you use a wheelchair, how is it sized for you? Too short, too tall, too wide, too narrow, etc._____________________________________

Have you ever had an injury attributable to your mobility aid? Please describe.

____

data could be used. If another agency or researcher does not conduct such a survey, then we would recommend the questionnaire survey step prior to the beginning of the pilot anthropometric study.

Dividing the population of people who use wheelchairs into reasonable sampling units can be done in a number of ways. The key is to select a demographic parameter that has anthropometric significance, and then be sure the sampling matrix reflects the proportions of the population in each of the categories.

We have used the number 500 in our hypothetical sampling plan. This was selected to show how a sampling matrix could be developed. Let us now look more specifically at how many individuals should be measured, either in a pilot study or in a larger nationwide survey. In the extreme case, one could measure every wheelchair user, or every person in the U.S. with any kind of disability, and thus know exactly the anthropometric characteristics of that population. Such an approach is obviously prohibitively expensive, and not necessary. At the other extreme, one could measure a single wheelchair user, and assume his or her dimensions to be representative of the group as a whole. At a certain level, a single person could represent the whole group, in the sense that a single person could demonstrate that people using wheelchairs do not have an arm reach of 10 feet. This approach would estimate the population at a very low level of precision. It would also represent the population at a low level of confidence, in the sense that having measured only one, how could we be sure that there are no other individuals with a reach of 6 feet? Increasing our sample from one to some other number, would increase our confidence (since we would feel better about having more than one subject), and possibly increase our precision as well (since we would have more than one, and could observe that several individuals had a reach of less than 10 feet). These two concepts, precision and confidence, have been incorporated into a formula that allows statistical estimations of a sample size. For a specified level of precision at a specified confidence level, we know in advance how many subjects need to be measured. The formula is:

$$n = \frac{\left(zS_x\right)^2}{C^2}$$

Where: z is z-score associated with a particular confidence level,
S_x is the standard deviation of the dimension in question, and
C is the desired precision

There are no hard and fast ways to determine an acceptable level of precision, just as there are no fixed ways of determining an acceptable confidence level. Statistical confidence has often been set at 95%, but this has more to do with tradition than any practical consideration. Indeed, 80% may be sufficient for many applications, and less than 80% might be sufficient for a pilot study. Similarly, precision is often targeted at 1½ % of the mean, but this figure is not sacred. Given that each of these parameters is flexible, it is sometimes useful to start with a sample size that is practically achievable, and then calculate back to find what levels of precision and confidence are associated with that n.

The other issue in calculating sample size, or the confidence and precision associated with a sample size, is the selection of a dimension. Note that in the formula, the S_x is the standard deviation associated with a particular dimension. Generally, in searching for a worst case (largest n) solution, a dimension with a high standard deviation is chosen. Typically, this is a circumference with a high correlation with weight (*e.g.,* waist or hip). In the case of dimensions needed for ADAAG applications, circumferences are inappropriate. Here, the worst case dimension, of those needed for this application, would likely be one of the reaches. If the resulting n is unacceptably high (in view of budget considerations, for example) one could select a somewhat less variable dimension (one with a lower SD) which would sacrifice some degree of confidence and precision in favor of lower costs. With regard to the proposed survey, one might, for example, have 1½% precision for body breadth and settle for 2½% precision in the reaches.

The assumption in this approach is that we know what the standard deviation is. In studies of non-disabled individuals it is a simple matter to choose the standard deviation for a particular dimension from a similar population, or from an earlier study of the same population. These do not vary that much, and a good approximation is all that is needed for the formula to be effective. In the case of a population of wheelchair users, however, there is no such reliable resource for which to pluck SD's for given dimensions. A standard deviation from one of the published studies could be used, but all of these are from small or specialized samples that do not represent the entire U.S. population with the full range of disabilities. In the final analysis, however, we would have little choice, since those surveys are all that we have. We would use these values with caution, however, recognizing that they may be inadequate representations of the actual values.

Based on our experiences with anthropometric data collection, we believe that for a pilot study an n of 500 would be adequate. We think that it would show that the techniques are valid, and give a reasonably precise estimate of the mean values for the dimensions in the population, at a reasonable confidence level. A sample larger than 500 would just add to the expenses and the logistic difficulties. As it is, 500 will present some challenges in subject acquisition, but we believe that subject acquisition is potentially such a problem for a full-scale survey, that it is important in a pilot study to explore the magnitude of the problem. A sample smaller than 500 would be easier to collect, of course, but given the large variability in the population, a smaller n might not provide enough precision to form a useful interim database.

The sampling approach described above is a stratified random sample. This is not the only legitimate sampling method available. In *Sampling and Data Gathering Strategies for Future USAF Anthropometry,* Churchill and McConville (1976) describe simpler sampling strategies that can be perfectly reliable for limited purposes. One such is called a U-shaped sample: "When analysis of a design problem makes it clear that a design which accommodates both small and large men will of necessity accommodate those in between, it makes sense to sample only small and large men. This may be particularly true for *arm-reach envelope studies* (italics ours), for example, where the sample size is severely restricted because of the considerable time required to obtain the data from each subject. In this case, useful results more than compensate for the difficulties of selecting subjects and obtaining information." The authors suggest also the use of W-shaped samples that add subjects representative of medium sized individuals. In the case of the pilot study described here one might select subjects from the following arm-length categories:

Male Arm Length (thumbtip reach)	Female Arm Length (thumbtip reach)
up to 29"	up to 26.5"
30-32"	28.5-29.5"
over 34"	over 31"

Since arm length correlates very well with other linear measurements of the body, such as sitting height, this W-shaped sample is likely to work for the accessibility measurements as well. The choice of a sampling strategy is one of many determinations to be made by the investigator during the planning phase of the proposed survey.

SELECTION OF VARIABLES

Our own review of the ADAAG requirements, plus that of our subcontractor KRW, reveals that the single most needed anthropometric datum, by far, is arm length. Sitting height is also important for drawing up standards listed in the ADAAG, as are some dozen other assorted variables such as grip strength and foot length. Planning and executing even a relatively small anthropometric survey is a costly undertaking and if it is to be done, the addition of a reasonable number of variables for which there will clearly be other uses, such as wheelchair design, will not significantly add to the cost. For this survey we suggest variables that fall into five categories:

- basic body size descriptors
- reach and functional reach measurements
- arm and hand strength measurements
- field of vision measurements
- wheelchair/user measurements

A tentative list of variables to be measured would be as follows:

A. Acromion height, sitting; arm length (acromion to fingertip); biacromial breadth; buttock-heel length; eye height, sitting; foot breadth; foot length; knee height, sitting; maximum elbow span; sitting abdominal breadth; sitting chest depth; sitting height from chair; weight
B. Reaches: all reaches measured forward, vertically, and out to the side; fingertip reach [toggle switches, buttons]; thumbtip reach [knobs]; grip reach [whole-hand operations]
C. Hand strength [operating equipment]; arm strength [transfers]
D. Field of vision [up, sideways, down]
E. Measurements of chair and user (floor to top of head, side to side, back to front, height to armrest, height to seat) [accessibility]

The two most basic dimensions measured in every non-disabled population are height and weight. Neither of these are used directly in the design of clothing, equipment or workspaces. They are taken for a number of other reasons having to do with comparability of samples and garment sizing indicators. Weight is included here as a recommended dimension because a variety of engineering problems require body weight. Stature (standing height) seems not to be relevant to a population that does not stand, but height to the top of the head while sitting in the wheelchair is potentially useful.

MEASURING TECHNIQUES

The Body Size Descriptors

These measurements serve as basic population descriptors and are applied in the design of workspaces and the physical environment, as well as the sizing of personal items and equipment. Except for body weight, this group of measurements is made up of simple point-to-point distances in one or another of the principal body axes and some geometrically more complex circumferences and surface contours; they are typically obtained manually using an anthropometer, measuring tape, and a variety of special calipers. Modern technology currently provides alternate ways to obtain accurate and reliable data of this type. Among them are the Faro Arm (Faro Technologies, Inc.) which is a portable coordinate measuring system. It consists of a probe on the end of a 6 degree-of-freedom arm, which is linked to a laptop computer. The user touches the probe on a body landmark, presses a button, and the location of the point in three-dimensional space is recorded automatically in the computer software. Software later allows the calculation of point-to-point distances and other dimensions. Such a device might be useful here because some subjects in the proposed study may not be able to assume the rigid standardized postures often used in traditional anthropometry, and the Faro Arm probe might be able to access some critical body areas difficult to reach in seated subjects.

Reach

For reach and field-of-vision measurements, Air Force methodology is, once more, instructive. Since 1990, investigators at Wright-Patterson Air Force Base have been engaged in testing accommodation of aviators seated in the cockpits of a variety of aircraft. (Kennedy and Zehner, unpublished) In many ways, the problems presented by this project are similar to those faced by the Access Board and by designers of workspaces intended to accommodate wheelchair users. Among the seven major areas of accommodation this long-running AF project is specifically concerned with is “hand reach to, and actuation of, controls.”

The functional reach dimensions listed above can all be measured in the traditional way by keeping the back, shoulder, and buttocks against the back of the seat and stretching the arm along a scaled wall chart (to the thumbtip, to the forefinger resting on the pad of the thumb, or the tip of the middle finger). Alternatively, the Faro Arm might be touched to the wall or reference plane (possibly the back of the chair), and then touched to the tip of the finger.

Air Force investigators take arm reach measurements one step farther, in that they measure arm reach in three “zones.” Reach Zone 1 requires that the operator’s shoulders be fully restrained by harnesses with the pilot held against the seat back by the inertial reel. Zone 2 requires use of the harness, but the operator is free to move his/her shoulders and torso forward and to the sides to a comfortable limit permitted by the total restraint system. Zone 3 specifies that the inertia reel be unlocked and the shoulders and torso permitted to move forward and to the sides as necessary for maximum reaches. Though it is not altogether clear that these kinds of distinctions should be made in conducting reach measurements on people using wheelchairs, there is certainly the possibility that the principle will be relevant.

Field of Vision

This is another area critical to cockpit accommodation. Air Force anthropologists measure maximum upward and downward lines of sight, forward and to the sides using a carpenter's inclinometer fitted with a sight tube to measure visual angle. The sight tube is equipped with cross hairs at each end. An Abney Level can also be used.

Strength

The ability of wheelchair users to operate equipment in work and living spaces depends not only on reach but also on sufficient hand strength to grasp and manipulate controls. The design and placement of grab bars are also guided by strength capabilities, chiefly in the hands and arms. Strength can be measured in a number of ways with pushing, pulling and twisting perhaps the most relevant to the present case. ADAAG standards currently specify that door opening and operation of assorted other control mechanism require no more than 5 pounds of pushing or pulling force, for example. Strain gauges that can be instrumented for direct computer readout, are probably the means of choice for taking these measurements.

Wheelchair/User Measurements

Accommodation and accessibility standards for individuals using mobility aids are worse than useless unless they take into account the wheelchair and its user as a single unit. Measurements from and to the most protruding points, whether they be located on the chair or on the user, are not difficult to make using either traditional manual instruments or a Faro Arm. The difficulty arises in the multiplicity of chairs and scooters on the market today. Investigators undertaking to make such measurements would have to do some research to determine at least the largest of such mobility aids and/or those with the highest seats in order to obtain results useful in creating guidelines for accessibility. One source of such information is a 1995 study (KRW Inc.) conducted for the U.S. Architectural and Transportation Barriers Compliance Board which incorporates a listing of more than 125 models of scooters and power chairs along with their lengths, widths, wheel base lengths, and seat heights.

From a sampling point of view, these chairs are very challenging. Ordinarily, one designs to accommodate a certain percentage of the population, or designs to a specific value (95th percentile forward arm reach, for example). This point is determined not only by the total range of variability, but by the frequency. Thus the relative number of certain chair types is very important. For example if a very large chair were infrequently purchased and used, it would have little effect on the value of the 95th percentile. However, if a very large chair were purchased often, then it would have the effect of raising the 95th percentile, and in turn, changing the design target. Thus it is not enough to know that the range in chair height is 30 to 39 inches. We would need to know the effective numbers of the chairs at various heights in the population of wheelchair users.

This need not be especially complicated, particularly for the pilot study. By measuring people in their chairs, one would automatically get a random sample of the chairs that people buy, in the approximate frequency in which they are seen in the population. In creating the sampling plan and subject acquisition plan, one would exercise caution to make sure that no bias in chair type is introduced. An example of one such bias might be conducting a pilot test in a geographic area where a certain type of chair is more readily available. If it develops in the pilot study that chair variability cannot be accommodated in this way, then the follow-up full study would have to include chair type as a parameter in the sampling plan. This would introduce complexity, however, and should be avoided if at all possible.

Measurer's Handbook

Crucial to achieving the second goal of the proposed survey is the creation of a measurer's handbook that would serve to ensure that future studies produce data that could be used to expand the original database. Such a handbook should include clearly worded definitions of the dimensions measured, detailed descriptions of the methods used to measure them, landmark descriptions would also be included, and illustrations to enhance the measurement descriptions. An example page is shown in Figure 1.

OVERHEAD FINGERTIP REACH, SITTING

ORIGIN-TERMINATION: Floor — dactylion III, right.

PROCEDURE: Subject sits erect on a flat surface with the right arm and hand extended vertically overhead as far as possible, and the palm of the hand facing forward. The back does not touch the wall. Grasp the subject's wrist to guide the arm into a vertical position. Some subjects will not be able to fully extend the arm into this position without discomfort. In these cases, do not force the arm any higher than it can comfortably go without changing the position of the torso. The sitting surface and the subject are arranged so that the wall-mounted scale is at the subject's right side. Stand at the left of the subject and use a block to establish, on the wall-mounted scale, the vertical distance between the floor and the tip of the middle finger (dactylion III). The computer will subtract the height of the seat from this measurement. The measurement is made at the maximum point of quiet respiration.

CAUTION: Do not permit the subject to hyperextend the wrist.

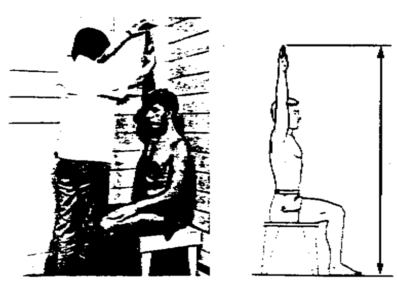

FIGURE 1

Sample Page from Measurer's Handbook

Data Entry

We have found through experience that an online data entry and editing system dramatically reduces the amount of observer error present in the final data set. The system we use was developed for the ANSUR survey and has been used extensively since that time. In this software, measured values are entered into a laptop computer, and are checked for reasonableness as they are entered. A suspicious value is flagged, and can be remeasured while the subject is still available. In this way, many types of measurement error can be reduced. The process is documented in detail in Churchill et al., (1988). We recommend such a system for any data collection effort for a population of wheelchair users.

Establish Allowable Error

Because anthropometric data are used in the design of workspaces, and equipment, excessive error in the data can result in badly designed workspaces and unsuitable products. Observer error is a fact of life in almost any scientific endeavor. Though it cannot be eliminated entirely, it can be considerably reduced.

Error analysis of anthropometric data is usually done after the data collection has been completed. While this gives the user of the data the information necessary to judge the effects of error on his/her use of the data, it does not allow observer error information to be used during data collection to improve the quality of data collection. The approach used in the Army's 1987-1988 anthropometric survey and the one recommended here was to establish an allowable observer error for each dimension.

Standards for allowable error are established by a team of expert anthropologists conducting repeat measurements of the selected dimensions, and analyzing the inter- and intraobserver differences. Error allowances will differ: larger ones will be established for functional reach measurements, for example, than for breadths which tend, on the whole, to be more easily repeatable.

Allowable errors are used for two purposes. They are first used during the initial training period as an indicator that measurers have successfully learned their tasks. Team members make practice measurements on a group of subjects to learn their assigned dimensions. Intraobserver and interobserver error results are calculated regularly to assess the ability of each measurer to repeat measurements within fixed limitations, and the ability of each pair of measurers to achieve interobserver consistency.

LONG-TERM RESEARCH

As urgency dictates and funds permit, future anthropometric surveys should be undertaken to:

- expand the working-adult database created during the pilot study.
- expand the over-65 population whose members may well be the most common users of wheelchairs, and who certainly represent the fastest growing demographic sector of US society.
- survey an appropriate children's population to keep up with design needs stemming from the trend toward mainstreaming in our schools.

Two other considerations for future study warrant mention: linkage and range-of-joint motion (ROJM) studies useful for the creation of dynamic human modeling software, and compilation of a three-dimensional database of individuals with disabilities obtained by use of scanning equipment.

DIGITAL HUMAN MODELS

Studies involving the biophysical aspects of wheelchair propulsion involve the anthropometric description of body links – lengths, breadths, and depths of body segments – that are important to the construction of dynamic computer models. Based upon concepts usually credited to Dempster (1955), the body is divided into segments defined by the major joint centers of the body. Although the true center of rotation remains unknown for most joints, especially for the more complex joints such as the hip and shoulder, anthropologists measure the length of various links by palpation of bony landmarks surrounding a given joint. For example, the segment called the lower leg link would extend between the center of the lateral malleolus at the ankle and the center of the lateral femoral epicondyle at the knee. While neither of these two points is located precisely at the center of rotation projected to the lateral surfaces of the respective joints, they can be reliably palpated and landmarked. Proceeding similarly, the linkage lengths for an entire body may be marked and measured. Such data can be treated statistically much like any other body size descriptor and when combined with ROJM data can be used to construct a scaled, dynamic computer model. Such models can represent an individual of specific dimension, or can represent whole groups of individuals. Motion around the linkage center is based upon ROJM data incorporated in the model's database. A number of such models are currently available for non-disabled analogues (e.g. JACK, CREWCHIEF, SAFEWORK, and RAMSIS) and some, reportedly, reflect elements of true 3-D motion.

Other physical properties of the whole body and of body segment can also be included in these models. Currently available non-disabled data include the center of gravity of the whole body, as well as its segments. Moments of inertia also are known. This class of measurements is used to estimate body dynamics in response to impact or instability, for example, and have the potential of contributing a great deal to the simulation of auto accidents or other events which would be unethical to investigate with human subjects.

Modeling individuals and their disabilities presents particular problems because the very data which make the models appear realistic (e.g., the range of joint motion, the centers of gravity and moments of inertia for body segments, etc.) are potentially different, and largely unknown, for this population. It is for this reason that collecting such data on this population is of critical importance.

3-D SHAPE DIGITIZATION

Currently in the forefront of measuring methodology for anthropometric studies is 3-D shape digitization. The first such instrument used by the Air Force was a small low-density laser scanner which rapidly passed over the head and face and, in combination with computer graphics software, produced a 3-D digital image on a computer screen. The Air Force, the Army, and NIOSH now all use larger scanners capable of producing 3-D images of the whole body and could digitize volumes large enough to include a positioned wheelchair user (in many, but not all, wheelchair models). Among the advantages of 3-D measurement is that resulting images record not only the size of objects (including the human body) but also their shape. Three-dimensional data from these scanners will also be extremely useful in providing shape to the digital human models. Large quantities of 3-D scan data have not yet been collected on any population (with disabilities or without) so the potential usefulness of the data is largely unexplored.

CAPABILITIES, RESOURCES, AND FACILITIES

Any organization charged with the responsibility of carrying out an anthropometric survey such as the proposal suggested here should have the following capabilities:

- a track record for the conduct of reputable research in applied anthropometry.
- experience in planning and organizing anthropometric surveys.
- hands-on experience with the measurement of all classes of anthropometric dimensions.
- hands-on experience with experimental subjects and human use considerations.
- experience in the area of field data collection, on-line data editing, and data processing.
- experience with data analysis techniques.
- experience with human measurement instrumentation.
- experience in training measurers and minimizing observer error.
- experience in dealing with people with disabilities.
- access to an appropriate population.
- experience in producing high-quality technical reports.

The resources needed are relatively minimal. Specifically the organization needs to have: 1) computer equipment sufficient to data entry and data storage needs; 2) a variety of appropriate anthropometric equipment; and 3) access to any specialized equipment the survey might require.

No large fixed facility should be required to conduct the proposed study, since it is envisioned that measurement would take place in the field, and once arrangements have been made, test sites at selected and prearranged locations could be established. At most, a temporarily empty room would be required.

It is often useful for long-term budgetary planning to have rough estimates of the cost of a project. We provide such an estimate here, with the proviso that many of the factors which will materially affect the cost of this research program are yet indeterminate. Nevertheless, this estimate may be useful in broad planning exercises.

Our estimate is based on collecting data at three locations, sampling 500 individuals, and three trips to Washington for planning and discussing results. Based on these parameters, we anticipate the pilot study requiring approximately 6 months and in the range of $250,000 to $350,000. Naturally, as various project parameters become more firm, the firmness of the cost estimate would increase as well.

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