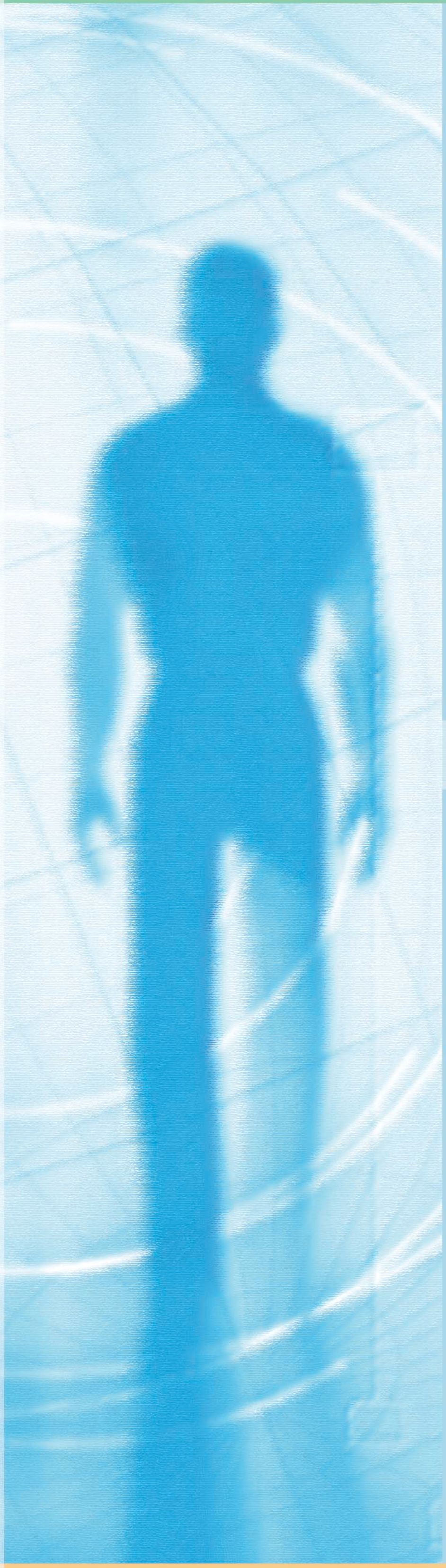
Guidelines for Using Anthropometric Data in Product Design

HFES 300 Committee



HFES INSTITUTE BEST PRACTICES SERIES

Published by the
Human Factors and Ergonomics Society

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Published by the
Human Factors and Ergonomics Society
P.O. Box 1369, Santa Monica, CA 90406-1369 USA
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Guidelines for Using Anthropometric Data in Product Design

HFES 300 Committee

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Submitted: November 2003

Preface

The Human Factors and Ergonomics Society formed the ANSI/HFES 300 "Anthropometry and Biomechanics" Committee in 1996. The committee's founding charge was to author an American standard for the application of anthropometric data to ergonomic design. The 300 Committee's inception coincided with revision of the ANSI 100 standard, "Human Factors Engineering of Visual Display Terminal Workstations", in order, among other things, to provide a foundation for statistical techniques used in the 100 standard. Over the course of development of this document, it was decided that publishing it as a HFES Best Practices publication would be more appropriate.

Chaired by Robin Herron from 1996-1998, by Claire C. Gordon from 1999-2002, and by Mark Strauss in 2003, the Committee at various times included Tom Albin, Marvin Dainoff, Claire Gordon, Robin Herron, Hongzheng "Cindy" Lu, Kristie Nemeth, Kathleen Robinette, and Mark Strauss. This diverse and talented committee often discussed the technical level at which the document should be targeted, given the complexity of the ergonomic design process and the relative novelty of statistical approaches required.

After much discussion, the committee concluded that there was so little published regarding the role and proper integration of sophisticated anthropometric methods within an ergonomic design framework that the initial target audience for this Best Practices document should be ourselves – professional ergonomists, engineers, and statisticians who apply anthropometry to product development. The decision to target a professional audience permitted the committee to address perceived knowledge gaps within our community and to produce a document that hopefully provokes both scientific discussion and greater application of anthropometric methods in product design. However, as most consumer products are neither designed nor tested by professional ergonomists, this document includes extensive examples, a glossary, and a bibliography for further reading.

In addition to the perseverance of the committee members, a number of people and institutions contributed directly and indirectly to the production of this document. Both Robert Beaton and Lynn Strother were instrumental in establishing and supporting the Committee. Marvin Dainoff served as the Committee's secretary throughout, recording and organizing meeting minutes and keeping copies of early drafts. The University of Illinois (thanks to Mark Strauss) provided server space and software guidance for electronic archiving and exchange of drafts among committee members. The U.S. Air Force (thanks to Kathleen Robinette) and Lucent Technologies (thanks to Hongzheng Lu) provided telephone conferencing facilities that permitted the committee to conduct many "meetings" at no cost to the Society. The U.S. Army (thanks to Claire Gordon) provided access to a professional editor, Marcia Lightbody, whose unique talents and extensive background in technical editing have substantially improved the clarity and readability our work. Respected members of HFES acted as reviewers and whose efforts enhanced the final product.

1. Introduction

An important purpose of all persons working in ergonomics is to design tools, workplaces and environments so that humans can function most effectively. In other words, we want to optimize human performance and well-being by achieving the best possible fit between the *human operator*, the *equipment*—hardware and software, and the working *environment*—physical and psychosocial. This fit is often referred to as "the human-machine interface." Anthropometry plays a major role in achieving thi s goal because variations in body shape and size affect the manner by people perform tasks, how efficiently the tasks are performed as well as the safety of the worker. Thus, anthropometry has an important influence on whether the human-machine interface is a good one.

1.1 Scope

This document is intended to aid the user in selecting, developing and applying anthropometric information for workstation and other product design, based on current scientific knowledge and best practices in ergonomics and human factors. The document is for anyone who is interested in using, or understanding the basis for using, anthropometry in design. The results should be workstations and other products that better fit their intended users.

1.2 Background

The breadth of opportunities for anthropometry to improve the human-machine interface is remarkably wide--including industrial equipment, clothing and furniture, surgical tools, farm implements, aircraft controls, and virtually every item in the environment with which humans interact. Over the years, engineers, designers, architects and others who design products have increasingly recognized the need for body measurement data on the users of their creations.

1.3 Defining the Design Problem

Of course, the type of anthropometric data required varies greatly from one product to another. The fit of a bathrobe, for example, can be quite loose and still serve its intended purpose. However a respirator for protection against breathing toxic fumes must conform closely to the geometry of the face in order to maintain adequate contact and prevent leakage. In the case of the bathrobe, data on the intended users' height and a few body girth measurements may be all the information needed to ensure adequate body coverage for a good interface. However, for the users of the respirators, it may be necessary to obtain detailed measurements of individual facial geometry to ensure a satisfactory fit. Thus, the function of a product not only influences our definition of "fit", but also determines what anthropometric information is needed to ensure an effective user-product interface.

Defining the design problem, including the concepts of fit and relevant body dimensions, is a critical first step in any ergonomic application of anthropometry in t he design process, and one that may call for considerable insight and analytical skill. This part of the ergonomic design process is taken up in Chapter 2 of these guidelines, Statement of the Design Problem.

1.4 Who Are the Users?

Another critical, but often overlooked, step in the ergonomic design process is determining "who" the product's intended users are. In this document, we will be referring to a product's intended users as the "target audience" or "target population". Target audiences can vary dramatically in their age, sex, racial/ethnic composition, and physical health characteristics, depending upon a product's function and the manufacturer's marketing strategy. All of these demographic and health-related factors influence the users' body size distributions, thus it is important to know as much as possible about the target audience in advance.

One would not, for example, find anthropometric data on men useful in the design of jogging bras for women. By the same token, standard anthropometric data may be virtually useless in the design of living spaces for those who use wheelchairs.

Apart from product function, marketing strategies can also influence target audiences and their body size distributions. A manufacturer may choose to fit only "tall" men, or "petite" women. Sometimes a particular design is intended for sale only in a particular country or geographical region – as is the case with many automobiles. Other products may have worldwide sales at the foundation of their marketing plan, and their designers need to consider worldwide anthropometric distributions. Failure of designers to consider the differences in body size distributions in fitting products to different target audiences is likely to be costly in terms of customer satisfaction, in sales, and production efficiency. The steps needed to define a product's target audience are thus discussed in Chapter 3, Defining the Target Population.

1.5 Using Anthropometric Databases

Once we know the design problem, its relevant body dimensions, and the target audience, a truly difficult third step faces the designer: identification of an appropriate anthropometric database. By anthropometric database, we mean a set of body dimensions measured on a sample of people. As discussed above, the ergonomic design process requires body dimensions relevant to the design's function and fit concept. However, these dimensions will only be helpful if they are measured on a sample that represents the body size variation to be expected in the target audience. It is a rare case indeed when a product designer can afford to measure exactly the dimensions needed on exactly the intended target audience, though we may all have had clothes altered. Thus, Chapter 4, Anthropometric Databases, discusses the decision-making processes, methodologies, and trade-offs that come with locating and using existing anthropometric databases.

Of course, having the right anthropometric database is really only the beginning of an ergonomic design solution. The designer must somehow use the information in the database to establish the design parameters of the product – its dimensions, its adjustment ranges, and whether more than one size will be needed. Although there are many different statistical approaches used to relate body size variation to product design decisions, they all share a common basis: a desire to know what the "average" and "worst-case" users' critical design dimensions are, and something about the variability of users in between.

1.6 Case Selection

Case selection is the process of choosing realistic combinations of body dimensions that must be accommodated simultaneously for a design to fit its target audience. A key aspect of case selection and application to design is that the critical body dimensions of each case must be accommodated *as a combination*. For example, if a case has a short eye-height sitting and a long leg-length, then a computer monitor must be positioned low enough so that the case's eye-height sitting is accommodated, and the desk/chair system must also give sufficient clearance for the case's long legs underneath the desk. Chapter 5, Representing Body Size Variability Using Cases, describes how body size variability in an anthropometric database can be represented by cases, and Chapter 6 describes how product designers and developers can use selected cases to guide the ergonomic design and evaluation process.

1.7 Information Distillation

As may be evident already, an ergonomic design process that uses anthropometric data is "front heavy". That is, there is a great investment of problem-oriented thought before one actually relates critical anthropometric cases to the design itself. In fact, ergonomic application of anthropometric data could be considered primarily a four-stage distillation process, such as described below and illustrated in Figure 1.

- State 0: we are at the initial state of information. At this state we are without a product concept or target audience, and virtually all body dimensions on anyone are potentially helpful.
- State 1: we address and state the problem, and we employ the product's concept of use and fit to restrict our attention to only those body dimensions critical to design success.
- State 2: we identify the target audience, and our attention focuses on only a subset of people in the world – the intended users of the product.
- State 3: we acquire a set of relevant body dimensions— or multivariate summary statistics — for a specific sample of people representing the body size variation of our target audience.
- State 4: we now can reduce our attention even further to selected cases with combinations of body dimensions that will drive the design and testing of the product.

It would be a mistake, however, to conclude that ergonomic design using anthropometric data is primarily an exercise in statistics. Indeed, we should use statistics to inform design choices, not to make design choices. Chapter 5, Representing Body Size Variability Using Cases, and Chapter 6, Transitioning Cases to Products, address the appropriate choice and application of statistical methods. At the end, Chapter 7, Anthropometry in Design: Examples and Summary, illustrates each stage of the process with concrete examples that emphasize the reasoning behind potential methodological alternatives. A Glossary and annotated Bibliography of related publications not cited in the chapters' references are provided at the end of the manuscript.

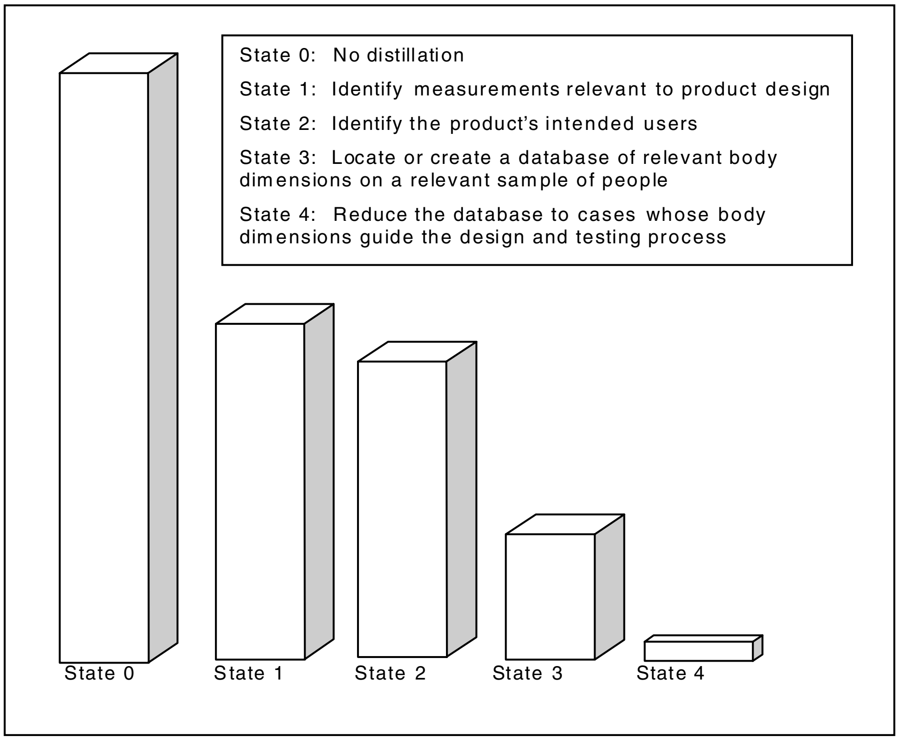

Figure 1. The information distillation process

1.8 Guidelines Contents

Table 1 below can be used to quickly identify which chapters of the document address particular stages in the ergonomic design process.

Table 1. Stages of the ergonomic design process by chapter

Stage	Chapter
Problem definition and relevant measures	2
Target audience definition	3
Database identification and considerations	4
Case selection	5
Application of cases in design	6
Anthropometry in Design: Examples	7
Glossary	
Bibliography	

2. Statement of the Design Problem

This chapter discusses basic concepts of ergonomic design. These concepts potentially apply to all people and all measurements. In later sections, the discussion becomes progressively more specific as we elaborate the nature of the design problem.

Broadly stated, we can conceptualize ergonomic product design as the design/organization/arrangement of various constraints so as to ensure an optimal fit between human operator, equipment, and the physical and psychosocial working environment. This chapter discusses the general nature of constraints on design, and how these constraints relate to fit as a design goal.

2.1 Constraints on Design

The human body can be considered a biomechanical system with multiple degrees-of-freedom. That is, in principle, each muscle-joint combination can be independently controlled by the brain-nervous system, resulting in a virtually infinite number of body postures. Each such posture represents an equilibrium state (balance of internal, applied, and reactive forces) acting against external forces. In practice, the large number of degrees-of-freedom is greatly reduced by a series of constraints. These constraints, as described below, can be categorized as task-, environmental- or human-based.

Task Constraints: The demands of each individual task naturally specify certain postural requirements. Consider, for example, a computer workstation. For those people who have use of their hands, a data-entry task requires that the fingers be in operational contact with a keyboard. For those people with vision, the copy and screen should be within the central field-of-vision. A lathe operator, on the other hand, usually maintains a standing posture such that his/her hands and arms are in appropriate relationship to the cutting tool and other controls. These task constraints significantly reduce the number of possible postural orientations that allow successful completion of the task.

Environmental Constraints: The number of possible postural orientations is further reduced by the design limitations of the objects, tools, or furniture within a user's environment. For an office environment, for example, the linear and angular dimensions, geometrical configuration, and degree of adjustability of chair, work surfaces, keyboards, etc., constrain operating postures. For the case of data entry, a standing user's workstation (e.g., airline reservation desk) allows a rather limited range of postural variations (slumping, bending, moving the legs). On the other hand, nonadjustable chairs and workstations allow a different but also limited range of postural shifts. Equipment maintenance and repair tasks that entail very precise orientation of tools (e.g., screwdrivers) often result in extremely limited postural options.

Other types of environmental constraints that are relevant to workstation design include temperature, humidity, noise, and lighting. The force of gravity is one of the most powerful environmental constraints, due to its impact on working posture.

Human Constraints: Finally, the personal characteristics, preferences and abilities of each individual determine the postures that can be seen in the workplace. These characteristics can be divided into two categories:

1. Physical: These constraints are anthropometric dimensions, strength, range of limb motion (relevant to operating controls), and somatic/physiological status (e.g., loss of sensation for persons with spinal cord trauma.)

2. Psychological: Such factors include current state of discomfort/fatigue, awareness of feedback signals from muscles and joints resulting from awkward posture, and willingness to shift body positions to relieve fatigue. Additionally, they include specific knowledge and skill related to the use of ergonomic aids, such as adjustability mechanisms on office chairs, or power-assisted lifts for materials handling. Finally, the question of the operator's intention and motivation is crucial. The operator is goal directed, embarking on a series of perception-action dialogues with her/her work-environment in which a continuous series of actions are performed in response to information about the world. In this context, the operator's knowledge of how ergonomic aids should be used and why their use is important must be combined with motivation to act if these adjustable mechanisms are to be used effectively.

2.2 Fit as an Ergonomic Goal

The concept of fit is most commonly associated with clothing. The expression "fits like a glove" conveys an intuitive sense of the meaning. A systematic analysis of fit with respect to clothing is helpful in generalizing this concept. Consider, for example, a surgical glove. This glove provides a "tight fit" to the user's hand in the sense that almost every movement or manipulation that can be carried out by combinations of fingers and thumbs when the glove is *not* present is also possible when the glove is worn. In a more abstract sense, the variability or available degrees-of-freedom present in the fingers and thumb are almost perfectly matched by those present with the glove's inherent flexibility. Thus, achieving appropriate fit between user and tool/environment can be characterized, in more general terms, as a problem of coordination among comparable sets of degrees-of-freedom. (This approach relies on the seminal work of N. Bernstein, 1967.)

Poor fit, or mismatches between comparable degrees-of-freedom, can be seen in the following example. If a shoe is too large, the foot can rotate within the shoe; if a helmet is too large, the helmet can rotate around the head. Each of these rotations is undesirable, representing a lack of correspondence between comparable degrees-of-freedom.

External constraints can heavily influence the definition of fit. In the example of surgery, task constraints require both the full range of manipulation of the fingers, and at the same time the protection of the open wound from possible contamination from those same fingers. A different set of task constraints, e.g., operating heavy machinery out-of-doors in an arctic environment, would dictate a mitten or glove with both insulation and limited but sufficient manipulation range. In a mitten, the four fingers are constrained to move essentially as a single unit. The advantage of this design is the reduction of surface area and the corresponding minimization of heat loss. The disadvantage, of course, is in restricting the number of hand postures that can be achieved. Accordingly, design of equipment for cold weather use needs to take gloved hand maneuverability into account. For some tasks, such as operating the trigger of a weapon, the use of a finger is typically required. A best fit is achieved by evaluating developments in fabric and insulation that afford movement of individual fingers while maintaining heat retention.

In general terms, fit can be conceptualized in terms of *compatibility* relationships among task, environmental and human constraints. (See Karwowski, 2000.) Compatibility implies the appropriate coordination of degrees-of-freedom among different constraints such that the user can accomplish effective performance.

2.3 Translating Ergonomic Concepts of Fit to Critical Design Dimensions

For the purpose of focus in this document, in the following sections, the primary human constraint will be anthropometric variation. The goal will be to relate the degrees-of-freedom associated with this variation with compatible workplace dimensions. It is assumed that reducing load associated with awkward postures will result in increased biomechanical efficiency. Biomechanical efficiency will lead to:

- reduced muscular fatigue;
- decreased perception of discomfort/pain;
- improved work performance.

A further assumption is that symptoms of perceived discomfort/pain can be precursors of musculoskeletal disorders. Comfort is herein conceptualized as the relative absence of discomfort/pain, though other factors arguably influence its perception. This is a complex concept, one that is simplified here only for the sake of maintaining clarity of the main discussion.

The term "awkward posture" may be broadly interpreted as postures or actions that increase the worker's energy expenditure, inhibit desired physiological functions, such as circulation, or place higher biomechanical loading on the body than is advisable. An awkward posture makes the worker work harder than necessary to accomplish the task. As there is no value added for this extra work, the product design is less efficient than it could (and should) be.

For example, some less-than-desirable working postures require long-term, static exertion of force. This exertion is commonly referred to as "static loading." Static muscle load places muscles into a constant state of contraction and should be avoided. Static muscle loading inhibits circulation and hastens muscle fatigue.

The discussion of task analysis allows us to refine the design problem to a point where we identify specific tools (environmental constraints) and processes (task constraints). We likewise refine the concept of fit to reflect appropriate postures that are the outcome of proper design of tools and procedures. It must be emphasized that although the following discussion presents a certain logical flow, in actuality, the process is highly iterative. Discovery of incompatibilities later in the design process may require revisiting earlier assumptions.

What Are We Designing? As in the earlier example of the fitting of gloves, the concept of fit between user and work environment (including tools) can be characterized in terms of the matching of corresponding degrees-of-freedom. The computer operator can translate his/her finger flexion/extension into vertical movements of keys. The equipment technician can translate his/her rotary grip movements via a screwdriver into helical motion of a screw. To the extent that the user can carry out these effector movements efficiently in terms of the overall postural orientation of the body (without excessive loading), these postures are permissible and fit is achieved.

The problem occurs when anthropometric variation enters the picture. If the keyboard is placed on a work surface of fixed height, some fraction of the user population will be unable to attain a working posture that is acceptable, because the working height will be too high for some people and too low for others. For these people, hands and wrists and arms will be in suboptimal (awkward) postures, resulting in less efficient execution of required keying movements. In the case of equipment repair, proper orientation of the tool is essential for successful completion. Awkward posture in this case can be a safety as well as a fatigue issue if, for example, the screwdriver slips and penetrates an adjacent hazard area (e.g., a high voltage source).

Satisfactory Fit And Individual Variability: The designer's challenge is to achieve satisfactory fit while accommodating individual variability. We can attain specific designs and specifications of workstation components and arrangements, in principle by combining "the envelope" of permissible environmentally constrained postures and the set of task constraints (determined above) with a set of specific individual physical constraints. A critical component of this process is that we characterize anthropometric variability among those body dimensions that are relevant to the task and environment under consideration.

However, at the same time, it is essential to keep separate the distinction between *body dimensions* and *object dimensions* (workstation/clothing, etc.). This distinction is captured in the concept of *affordance* (Gibson, 1979; Norman, 1988; Mark et al., 1991; Dainoff et al., 1999), which refers to attributes of the (physical) environment that have consequences for goal-directed actions of the person.

Take, for example, an ordinary kitchen chair. Let us look briefly at just one of the object dimensions- seat height. This dimension is not arbitrary, but bears some relationship to the lower leg lengths of the users for whom the chair was designed. This relationship is neatly conceptualized in the term affordance. Thus, the chair will afford a certain action–sitting–for a certain group of users, namely, adults. More precisely, the chair is an affordance for sitting in the sense that the user's buttocks are supported by the seat surface (seatpan) while the feet are supported by the floor. That same chair will not afford sitting for a *different* group of users, small children, whose lower leg lengths, as well as Seated Eye Height, are too small to use the ordinary kitchen chair *effectively*. For children seated on a kitchen chair, their feet are not supported and they would be unable to easily make eye contact with adults while seated at a kitchen table. To achieve the overall goal of allowing children to comfortably and effectively sit at the table with adults, a different kind of affordance–a highchair–must be designed. The highchair would not only raise the child up to the kitchen table surface, but could provide foot support to enhance comfort and torso stability. Hence, the concept of affordance allows us to understand that object and body dimensions are separate entities, which become matched through the design process. Simply put, what designers should design are affordances based on human-object compatibility relationships.

It is also important to realize that these relationships are not simply one-to-one. In the case of the kitchen chair, for example, seat height is a critical object dimension as it defines the capability (affordance) of allowing the legs to reach the floor while seated. A typical kitchen chair might have a seat height of 460 mm (ca. 18 inches). The corresponding relevant body dimension is lower leg length. That is, to a first approximation, fit can be defined in terms of the relationship between lower leg length and seat height. If we now identify an anthropometric database of adult users (e.g., Gordon et al., 1989), it can be seen that lower leg length is most closely approximated by the body measurement "Popliteal Height" (see Figure 2), though this neglects the use of slippers or other footwear.

Examining the distribution of Popliteal Height values in this database, we see that a person with a small Popliteal Height (5th percentile) is 351 mm while the corresponding value for a large Popliteal Height (95th percentile) is 476 mm. The relevant object dimension–seat height–is thus located within the range of variability of the corresponding body dimension–Popliteal Height.

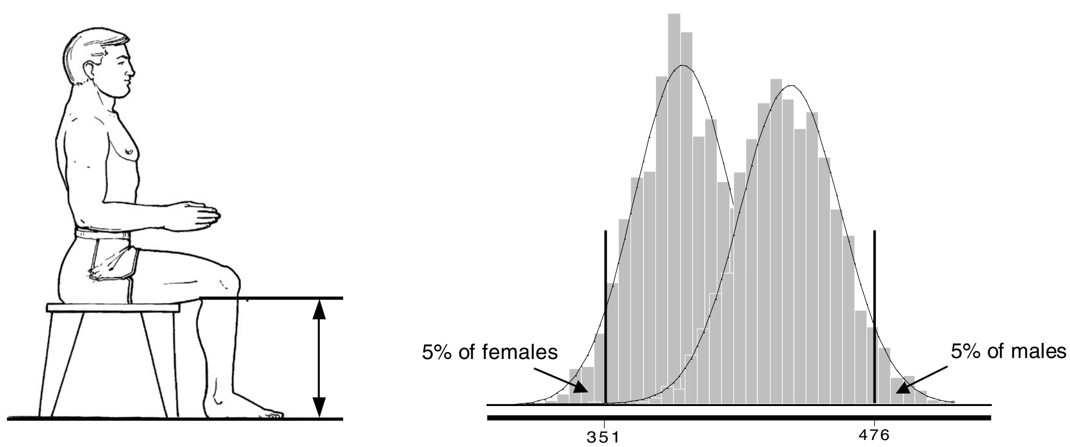

Figure 2. Popliteal height (in mm)

Consequently, fit, in this case, is only approximate. Even with footwear adding 25 mm, the small person's legs are too short to reach the floor. To use this chair comfortably, this person would need to either use some sort of footrest or wrap his/her legs around the chair supports. The large individual's legs are too long for sitting with legs perpendicular to the floor. This person may need to angle their legs either backward or forward to use the chair at a table. Notice that, in this particular case, the seat height is located more towards the upper end of the distribution depicted in Figure 2. For kitchen chairs, this may be a reasonable compromise in that it is easier for users with smaller legs to achieve a reasonably comfortable fit (add some sort of foot rest) than for those with longer legs.

The intent of this discussion is to emphasize the variable nature of the fit between object and body dimensions. Most users of the kitchen chair, as described above, would require some awkwardness of leg posture to sit in the chair, since the chair precisely fits only those with Popliteal Heights of 460 mm, assuming no footwear. However, this lack of precision in fit is not particularly bothersome given the overall goal-directed actions of most users of kitchen chairs, i.e., to sit for a relatively short period of time to eat a meal. (The 90 degree trunk-thigh angle depicted in Figure 2 is only meant for illustration of body dimensions and should be not be taken to be indicative of "proper" seated posture.)

If, on the other hand, the intention is to use the kitchen chair (and table) as a computer workstation for one's home office, the lack of affordance becomes more of an issue. Given that the duration of use increases dramatically (minutes to hours), the negative consequences of awkward posture correspondingly increase. What is now required is a different affordance–adjustability of the seat height–allowing for a greater correspondence between seat height and Popliteal Height (with and without footwear). In particular, we would require a chair whose seat height is adjustable throughout the range of variation of Popliteal Height. Other affordances related to appropriate working height of the keyboard and viewing angle of the display screen and copy also come into consideration. These issues are discussed in detail in subsequent sections.

Consequently, in the design process, it is essential that the designers clearly understand what product features are required and those that are only desired. Certain features are critical for the users to perform their tasks and other features may be considered luxuries. Having these prioritized is important when design trade-offs must be made due to space conflict or cost concerns. Realistic design solutions must also consider regulations, marketing issues, technology employed, safety and design conventions, among other factors.

2.4 Task Analysis

The logical first step in implementing a specific solution to the design problem is through the use of task analysis. While there are multiple approaches to task analysis (Vicente, 1999; Rasmussen et al., 1994; Meister, 1958), the following basic principles are common to all:

Step 1: The initial step of task analysis involves specification of goals and priorities in general terms. For example, a company wants to improve its order-entry process in which information about customers' orders is entered quickly and accurately into a database. Priorities associated with the goal include consideration of *time* to accomplish, *funding* available, *personnel*, *space* and *equipment* requirements.

Step 2: The next step is to describe the functional components of the task, ideally in technology-independent terms. In the order-entry task, these components include a source of customer information, a standardized repository for this information, and a method for translating the former into the latter.

Subsequent Steps: Once these functions are specified, a parallel set of decisions must be made to implement them. One set of decisions relates to the physical *tools* (supplies, equipment, work environments); the second set relates to *procedures* (tasks) to be accomplished by the human operator. Together, tools and tasks provide a specific implementation that will satisfy the functional requirements. In the order-entry case, the tools might consist of a standardized paper order form, a computerized database with predefined fields for information, and a computer workstation (display monitor, keyboard, mouse, copyholder). The associated procedures for data entry would require human operators with certain skills and abilities. Hence, we can begin to define the population of interest.

To attain a sense of the fine structure of the task, we decompose functional components into subtasks. At this level, we should describe the supporting tools and equipment.

Thus, the first subtask might be receiving a batch of paper order forms from a co-worker, and placing them on a copyholder. The second subtask might be keying data into the appropriate fields. This step might include screen navigation instructions and sources of help in ambiguous cases. The next subtask might be verification of critical information. The final subtask might be placing the paper form in a completed work tray.

2.5 Fit as Related to Workstation Design

In this section we apply a) the concept of fit as a relationship between corresponding task, environmental and human degrees-of-freedom, and b) affordance, as the design solution that achieves fit, to the case of workstation (product) design.

Consider an astronaut floating freely in zero gravity. With no task or environmental constraints, the number of postural orientations possible is enormous, limited only by the inherent biomechanical constraints of the human body. If the astronaut is assigned a task (e.g., operating a telescope), the number of working postures that allow him/her to satisfactorily complete the task is greatly reduced– although still probably larger than when gravity is present. Thus, one approach to conceptualizing fit is to start with the completely unconstrained human body (as in zero g) and then successively apply both task and environmental constraints.

Within these constraints, possible postural orientations can be considered permissible to the extent that they minimize biomechanical load on the musculoskeletal system (i.e., "awkward" postures) while allowing the person to accomplish the task in an efficient manner. Consequently, fit can now be interpreted more directly in terms of compatibility relationships between the combination of a) task constraints (e.g., procedures), and b) environmental constraints (e.g., required force to operate controls) with human constraints (e.g., variation in human characteristics including anthropometry), which leads to the determination of permissible postural orientations.

Certain task and environmental constraints afford greater degrees-of-freedom than others. In the data-entry example considered above, a well-designed workstation product will provide a reasonable fit for persons of the target population. The design may allow these people a relatively large range of permissible postures while doing the required tasks. On the other hand, data-entry work carried out by a person who has cerebral palsy, and who uses a mouthstick to type, requires a tightly linked keyboard-head-display-eye coupling, with a consequent reduction in the person's permissible postures.

2.6 Selection of Relevant Dimensions

It is imperative that the designer identifies the basic postures and movements necessary to complete the intended tasks, and how such postures and movements relate to the supporting tools and equipment. Understanding these relationships allows the selection of relevant anthropometric dimensions. It is helpful, in this process, to identify what Pheasant (1986) has called the cardinal anthropometric relationships between user action and objects in the environment: *reach, clearance, and strength***.**

Traditional ergonomic guidance for designers was that within the specified user population, accommodation could be achieved if the *smallest* person could reach (the desired object), the *largest* person could clear (any opening or aperture) and the *weakest* person could lift/operate (the target load/control). In general, all design solutions should follow the three principles of reach, clearance, and strength. Alternatively, we achieve design accommodation if the design affords reaching, clearance and lifting/operating by *all or a specified percentage of members of the target population*.

In the order-entry example, reach and clearance criteria are most relevant. Following the detailed task analysis described above, the permissible postures must include: a) reach capabilities for the hands, arms, shoulder and trunk such that the fingers can make contact with the keyboards, paper forms and other supplementary materials without excessive bending; b) reach capabilities for the legs and lower trunk such that the feet are able to rest firmly on the floor or footrest and the lower trunk can be firmly supported by the seat and backrest; and c) clearance for the legs so that the thighs are able to be placed under the work surface without encountering obstacles. Finally, the requirement to be able to view the monitor screen and copy while maintaining a reasonable head and neck posture can be considered an aspect of visual "reach". The design solution for the order-entry workstation entails that each of these criteria be accomplished through selection of appropriate critical body dimensions (with possible shoes or other clothing adjustments), which will, in turn, be used as a basis for workstation design dimensions (affordances).

Table 2 illustrates examples of the correspondence between affordance criteria and body dimensions for the order-entry workstation. This table is meant to be illustrative rather than exhaustive. A detailed discussion and example of workstation design is found in Chapter 7. More thorough discussions of ergonomic guidelines for workstation design may be found in the following references: American National Standards Institute (1988), Chaffin et al. (1999), Karwowski and Marras (1999), and Karwowski and Salvendy (1998).

Table 2. Correspondence between affordance criteria and body dimensions for an order-entry workstation

Affordance criteria for object dimensions	*Body dimensions*
Keyboard working height	Elbow Height, Seated
Seat height	Popliteal Height, Seated
Seat width	Hip Breadth, Seated
Seat depth	Buttock-Popliteal Distance, Seated
Clearance under the workstation	Thigh Height, Seated
	Knee Height, Seated
	Buttock-Knee Distance, Seated
Monitor viewing distance and angle	Eye Height, Seated

The next chapter discusses the start of the design process, where designers must decide and determine for whom they are designing.

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3. Defining the Target Population

It is costly to manufacture designs that poorly "fit" their users, and it is even more costly to retrofit designs that fail to accommodate their intended market. It is thus incumbent upon the designer to consider who the intended users of a design might be. Design optimization requires knowledge of user variation in such physical characteristics as body size and proportions, body strength and flexibility, reach capability, and endurance. Physical characteristics vary among people of different biological and cultural backgrounds, gender, age, and health; hence, it is essential both to define the intended market for a design, and to know as much as possible about its demographics.

3.1 Marketing Strategy

Definition of the "target population" for a design begins with consideration of a few simple questions. Who will be using the design? Where will the design be sold and/or used? Are there plans to expand the market in the future? In the case of a workstation, these questions might elicit responses as general as "the entire office furniture market in North America" or as specific as "American architects willing to spend more than $5000 for a personal workstation."

3.2 Demography of the Intended Market

Once we obtain a general description of the intended market, it is necessary to obtain more detailed information on characteristics that influence anthropometry. Nationality, race/ethnicity, gender, and age, for example, comprise the primary demographic variables that drive anthropometric distributions, and so we need these data to define a market for ergonomic design (Annis, 1978; Walker, 1993; Donelson & Gordon, 1996). Anthropometric distributions are also influenced by nutritional and epidemiological conditions, which impact growth (Eveleth & Tanner, 1976; Kouchi, 1983; Falkner & Tanner, 1986; Lasker & Mascie-Taylor, 1989). As a result, proxy variables—such as income or education level—are also sometimes included in market descriptions. Determination of the relative frequency of these demographic and market subgroups facilitates more accurate estimates of optimum anthropometric design values, and more intelligent design trade-off decisions.

Data on groups of people who comprise design markets are available from professional/occupational societies, U.S. Census publications (www.census.gov), the NHANES[1] data sets for U.S. civilian population (www.cdc.gov), or market surveys. Information on how to weight the samples to match the target demographics can also be found in these references. The prevalence of various disabilities among potential customers is another type of information important to defining the physical characteristics of the market for which we are designing.

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[1] The National Health and Nutrition Examination Surveys (NHANES), conducted by the National Center for Health Statistics, Centers for Disease Control (NCHS/CDC), are designed to assess the health and nutritional status of adults and children in the United States through interviews and direct physical examinations.

3.3 Application of Demographic Data in the Design Process

Knowing the relative frequencies of demographic subgroups in an intended market can inform designers about anthropometric aspects of the intended user. If no anthropometric data already exist that are appropriate to the design problem, demographic data are used to construct sampling strategies for new data collection (Botman et al., 2000; Robinette, 2000; Gordon et al., 1989; Donelson & Gordon, 1996). If some, albeit marginal, data exist, and time/resource considerations preclude a survey, then demographically-driven analytical and statistical adjustments to existing databases may provide adequate characterization of the intended user (Kinghorn & Bittner, 1995). If appropriate anthropometric data already exist, then we may be able to use the demographic data to statistically weight the subjects in existing databases in order to approximate best the distributions of physical characteristics in the intended market (Botman et. al., 2000, Donelson & Gordon, 1996; Gordon, 1996; Potter & Iannacchione, 1998). Details on the sampling and weighting of anthropometric databases appear in Chapter 4, Anthropometric Databases. In addition, demographic features of the intended design population can also be very helpful in selecting subjects to evaluate design prototypes and in planning and evaluating test marketing schemes (Chapter 6).

3.4 Defining the Target Population

It can be very difficult, and sometimes impossible, to achieve optimal fit in all features of a design for 100% of the intended market. Often in order to keep a design simple, easily manufactured, and moderate in price, we must tolerate less than optimal fit for some percentage of the intended market for some design features or tasks associated with the product.

When poor fit (and associated degradation in task completion and/or personal comfort) results in immediate or cumulative personal injury or risk to the user, we should seek maximum accommodation of the intended market. It is essential that full accommodation exist for life safety designs, such as an escape hatch being large enough so that the largest foreseeable user could pass through it.

When design limitations do not influence personal risk but may influence efficient completion of critical or primary product tasks, less than maximum accommodation of the intended market may be tolerable. When this situation arises, knowing the relative frequency of customers not accommodated by various compromises can be very helpful in evaluating the merits of design trade-offs.

Generally, when less than maximum accommodation of the intended design population is tolerable, some percentage of the population is targeted for optimal compatibility. In terms of anthropometric distributions, we might envision optimal fit for the central 90%-95% of the intended design population, with suboptimal fit tolerable on the "tails" of the body size/shape distributions where customer density is low and engineering costs to accommodate them are high (McConville & Churchill, 1976). Although criteria of this type have traditionally been quantified in terms of univariate percentiles, such as "5th-to-95th percentile accommodation," in practice this approach introduces serious ergonomic design deficiencies (Bittner, 1976; Robinette & McConville, 1982). It is better, instead, to define the target population as a minimal percentage to be accommodated. An example of a more appropriate statement might be, "The XYZ computer workstation shall accommodate 95% of all U.S. male and U.S. female computer programmers."

Once we define the target percentage to be accommodated, “cases” can be used to characterize this percentage of the population. Such methods are described in Chapter 5, Case Selection.

3.5 Population Subgroups with Unique Physical Characteristics

Designers should specifically consider the possibility that their markets may include substantial numbers of women, racial/ethnic minorities, and users with functional limitations (Fullerton, 1997; McNeil, 1997). Worldwide mobility and equal opportunity practices have promoted increasing diversity in the workforce, and medical advances have contributed to improved survival and therefore higher proportions of elderly and individuals with disabilities in the population in general.

Whenever a subgroup of the intended market possesses unique physical characteristics, as may be the case for women in predominantly male occupations, racial/ethnic minority groups, pregnant, ill, or users with disabilities, special considerations enter into the ergonomic design process. In some situations, these groups comprise the intended design population, and thus their “unique” physical characteristics are the primary design drivers, as is the case, for example, in the design of wheelchairs. However, unique subgroups are often a statistical minority of the intended market for a design, and their physical characteristics do not impact design parameters estimated from data on the intended market as a whole.

Design requirements calculated solely on a representative sample of the intended market may excessively disaccommodate minorities with unique physical characteristics. In Walker’s (1993) study, for example, univariate design ranges intended to capture 90% of all U.S. Army soldiers failed to capture 90% of Asian/Pacific Islanders for 109 of 132 body dimensions in males and 101 of 132 body dimensions in females. Walker’s results followed directly from the interaction of two phenomena: Asian/Pacific Islanders comprised less than 2% of the Army population at the time, and Asian/Pacific body size distributions are significantly different from those of Army majority groups. Similar results might be expected in civilian design problems, as Asian/Pacific Islanders comprise less than 4% of the American civilian population (Day, 1996).

Women in predominantly male occupations, such as the military, fire fighting, and construction trades are a common minority group that designers must consider. In a 1997 study, for example, Todd and coworkers reported that 88% of female soldiers were unable to be fit in mechanic’s coveralls, 66% could not reach the fuel flow valves on five-ton fuel tankers, and 26% experienced obstructed fields of view in forklifts. High rates of female disaccommodation in the crewstations of military aircraft designed for men have also been reported (Schopper & Cote, 1984; Rothwell & Pigeau, 1990; Zehner et al., 1999). Clothing that must fit closely to the body is a particularly serious problem for females in traditionally male occupations. These products were often originally designed for men, and it is common to simply “scale down” the male sizes in an attempt to fit women. However, since the body proportions (shapes) of women differ significantly from those of men (Robinette et al., 1979), scaling down products proportioned for men will not necessarily accommodate women and may exacerbate fitting problems (Gordon 1986, 1997; Reeps et al., 1990; Robinette, 1995).

Whenever a subgroup with unique physical characteristics is also a statistical minority of the intended market, we should estimate optimal design parameters separately for the subgroup and evaluate their impact on the design. If the design is sufficiently flexible, then we should expand its accommodation "envelope" to capture the extremes of the unique subgroup. Examples might be standing-user workstation heights and Asian/Pacific users, steering wheel tilt mechanisms and pregnant drivers, or workstation adjustments for wheelchair users. When this expansion is not possible, we should consider design options that make customized modifications as simple and cost effective as possible.

3.6 Verifying that the Design Fits the Intended Population

An important but often overlooked step in the ergonomic design process involves verification that the workstation prototype or final design actually fits the intended market. Methods for verification of prototype accommodation and empirical validation of final design envelopes are in Chapter 6. A key element in the validity of these tests, however, is the selection of test subjects that represent the full range of physical characteristics present in the intended design population. This selection means that testing the "average" consumer may not be as informative as testing consumers at the extremes of the design envelope when evaluating prototypes. And in validation of final designs and test marketing, the demographic profiles developed in this section should be utilized in sampling strategies to ensure that the results obtained are representative of those expected from the design population.

The next chapter discusses identifying relevant anthropometric variables and also databases from which to obtain anthropometric data.

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4. Anthropometric Databases

We have at this point identified relevant body measurements needed for our product design, and we should have a clear idea who the target audience for the product will be.

Once we are clear about the target audience and critical body measurements needed for a product, as designers we are still faced with a difficult task: identifying or creating an anthropometric database with relevant body measurements on a relevant sample of people. Occasionally, such an anthropometric database already exists; however, it is more likely that we will face using or modifying an existing database and/or collecting additional data.

This chapter outlines some common methods used to adapt existing anthropometric data to new problems and discusses the benefits and risks of these approaches. This chapter also reviews considerations underlying the need to collect new anthropometric data and provides a brief methodological overview of these situations.

4.1 What Is an Anthropometric Database?

An anthropometric database comprises a set of body measurements taken on a sample of people. A "good" database also has documentation (published or electronic) with details of its methods for sampling and measurement.

Sampling information should include how subjects were selected and describe the age, sex, race, and other pertinent demographic distributions of the people whose measurements are in the database. Measurement information should include a detailed description and photograph or illustration of each measurement. Measurement descriptions should include details regarding subject posture, anatomical landmarks that define measurement location, and the measuring instrument used. All instrument descriptions should include calibration protocols.

If traditional instruments are used (e.g. measuring tape and calipers), then many measurement definitions will also require additional details, such as whether firm or light contact with the subject is made with the instrument, and whether the measurement is made at the minimum, maximum or midpoint of the subject's breathing cycle. If measurement reading and recording are automated, then descriptions of the automated systems, their validation, and their calibration should be included directly or by reference. When 2-D or 3-D body scanning is used, the instrument description should include both scanning hardware and software. In addition, if measurements are extracted from the scans, the computer algorithms, methods for extraction, and validation of the accuracy of the extracted measurements are desirable.

4.2 Identifying Relevant Body Dimensions in an Anthropometric Database

The methodology underlying each body measurement in an anthropometric database is important because it determines whether the body measurement recorded in the database is relevant to a designer's problem. Sometimes the effect of body position on the design relevance of a measurement is obvious, as in the case of hip breadth and a seating problem. Clearly, hip breadth measured with the subject standing will underestimate the desired design parameter. The subject must be seated for the measurement to be useful in a seating problem.

At other times, determining whether the required measurement is in the database may require more in-depth thinking. Upper arm length, for example, could be measured as "acromion-radiale length", the distance between the lateral edge of the acromion process and the top of the radial styloid with the arm extended (Figure 3a), or as "shoulder-elbow length", the distance from the lateral edge of the acromion process to the bottom of the elbow with arm flexed at 90 degrees (Figure 3b). The former measurement is a useful estimate of link length for digital human models, the latter appropriate for use in the location of armrests. If acromion-radiale length were used for the armrest problem, it would *underestimate* upper arm length, resulting in armrests that are systematically too high; if shoulder-elbow length were used for the human model problem, it would *overestimate* the upper arm link, resulting in reach estimates that are systematically too high. Care clearly must be taken in selecting measurements for applications.

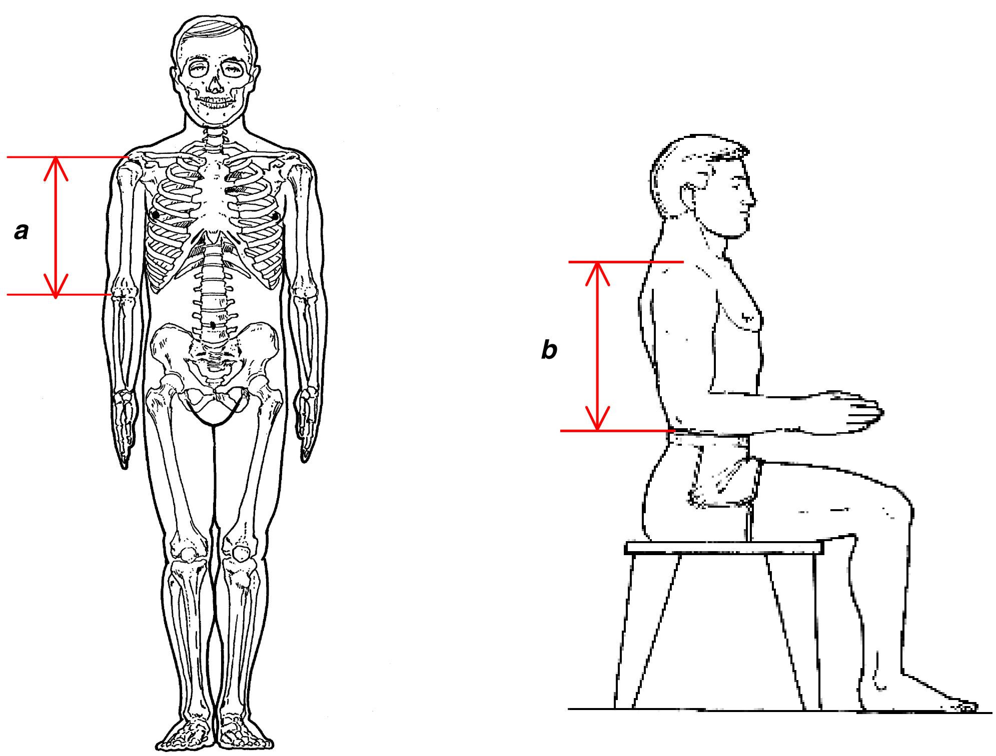

Figure 3. Two ways to measure upper arm length

4.3 Deriving Relevant Body Dimensions from an Existing Database

Sometimes a database lacks the desired body measurement but has others from which the needed measure can be derived algebraically. This situation often occurs with measurements useful for both seated and standing workstations. In Figure 4, for example, one can derive an estimate of seated eye height (d) if stature (a), standing eye height (b), and sitting height (c) have been measured. Similarly, one can derive an estimate of standing eye height if stature, seated eye height, and sitting height have been measured.

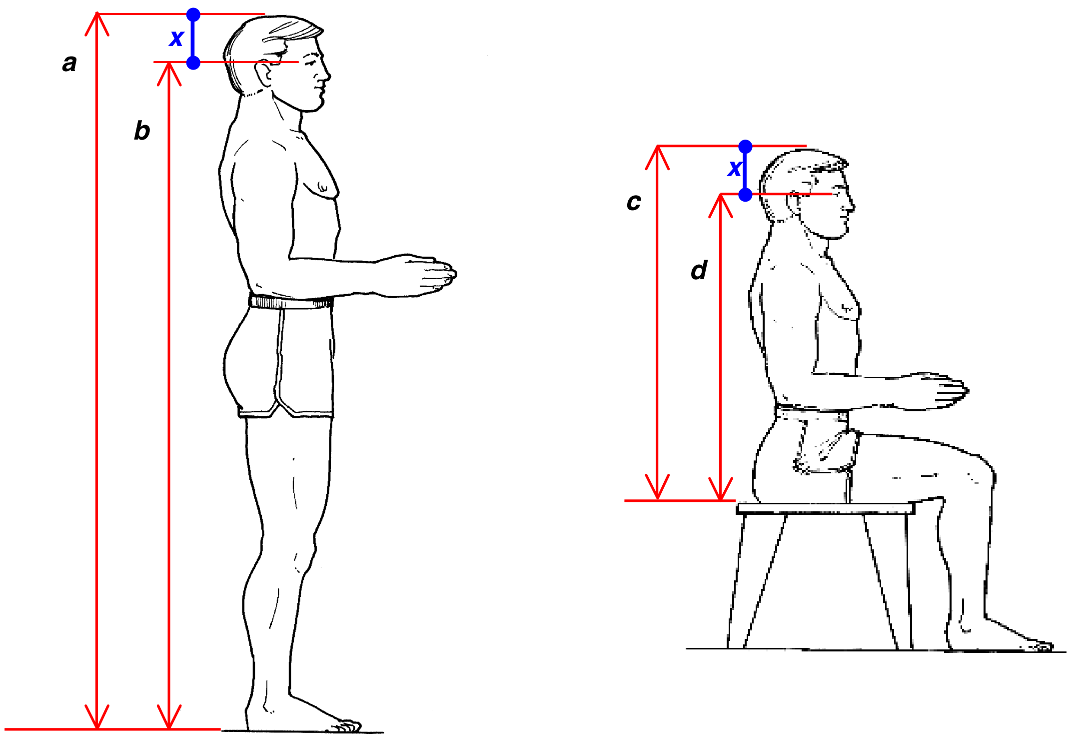

Figure 4. Deriving design variables

Standing Eye Height = (stature – x), where x = (sitting height – seated eye height)
Seated Eye Height = (sitting height – x), where x = (stature – standing eye height)

Cautions in Using Derived Measurements: Several cautions in the use of derived body measurements are appropriate. Firstly, the calculation of derived body measurements must be done on a subject-by-subject basis *before* further statistical analyses are undertaken in order to result in valid design parameters. The algebraic transformation should not be applied to summary statistics (such as means, variances, percentiles). Secondly, the designer should be aware that the observer error associated with each measurement in the equation is propagated in the derived body measurement. That is, when two or more measurements are used to derive a third, the observer error associated with the derived body measurement can be greater than that of either individual measurement (Gordon et al., 1989: 588-590). Finally, the landmarks associated with the origins and termini of the component measurements must exactly coincide with each other, and with the origin and terminus of the measurement the designer wants to derive. If not, then the derived body measurement will either underestimate or overestimate the design parameter of interest.

This final points bears further discussion. What if a particular design parameter is required for a product, but it doesn't already exist in a database, and it cannot be validly derived from measurements that are in that database? Two examples of this dilemma are illustrated below in Figure 5.

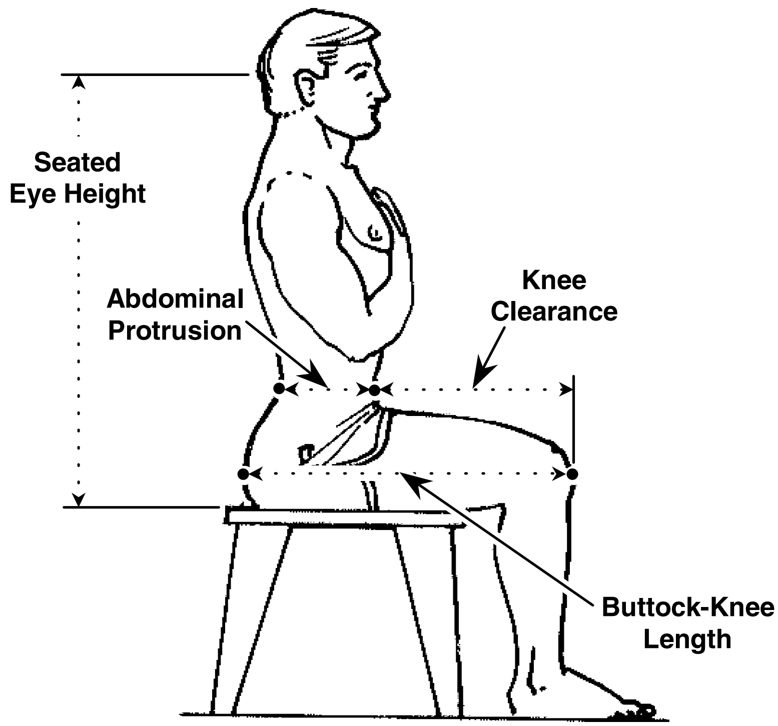

Figure 5. Some critical body dimensions for a seated workstation

The first problem illustrated in Figure 5 is that of the subject's erect sitting posture. This is not similar to the posture assumed by most people at a workstation. In fact, a standard anthropometric Sitting Eye Height dimension *overestimates* a relaxed seated eye height (Von Peters, 1969; Clauser et al., 1972; Pheasant, 1982). However, erect Sitting Eye Height data can still be useful to the designer if the information desired is an upper limit for adjustment of displays because the design parameter estimated will be *greater* than the true value, so the error will be in a "*conservative*" direction.

Another common design problem illustrated in Figure 5 is determining how much forward knee space should be designed under a workstation. This product design dimension can be called: knee clearance under a workstation. This specifically describes the depth needed under a desk or table when the seated workstation user pulls their chair fully forward until their abdomen touches the table edge. Because this dimension is one not readily available to look up in a database, the designer needs to derive this, or at least estimate it. In this case an estimate can be obtained from the two published body dimensions: Buttock-Knee Length and Abdominal Protrusion. As can be seen in Figure 5, the posterior terminus of the Abdominal Protrusion body measurement is often well forward of the posterior terminus of the Buttock-Knee Length body measurement. As a result, one cannot simply subtract the two to derive an exact knee clearance measure for use under the workstation. However, because buttocks generally protrude *more* than the posterior Abdominal Protrusion body measuremnet terminus, one can be sure that the difference between the Buttock-Knee Length body measurement and the Abdominal Protrusion body measurement is *greater* than the actual clearance required. Once again, this estimate will suffice if the designer requires only a “worst case” parameter estimate, but it may not be as useful if the goal is to optimize design efficiency, for example, by minimizing the “unused” depth of a workstation.

4.4 Estimating Relevant Body Dimensions Using Statistical Models

Even the most comprehensive anthropometric databases are often missing one or more critical body measurements required for a particular product’s design. When the missing body measurement cannot be derived and/or an optimal instead of “worst case” product design value is required, then the designer may choose to estimate the missing body dimension using a statistical model derived from another data source. Several such estimation methods are used by engineers (Roebuck, 1995), including linear regression (McConville & Churchill, 1976; Churchill 1978; Robinette & McConville, 1981) and ratio scaling (Pheasant, 1982, 1996).

In Figure 5, for example, we might locate another anthropometric study (database “B”), in which erect and relaxed seated eye heights are measured on the same subjects and use their statistical relationship to predict the missing relaxed eye height values in the database of interest (database “A”). Inherent in this approach, regardless of actual method, is the assumption that the statistical relationship between erect and relaxed seated eye height body dimensions observed in the subjects of database B is the *same* relationship as that actually present in the subjects of database A. However, a statistical model that fits one group well may not work well in another group. In general, the more different the two populations are in age, sex, racial/ethnic origin and body size, the greater the error in using a statistical model derived from one population to estimate a body measurement in another.

In addition, when statistical models are used to predict body dimensions, there is an associated prediction error which is generally smallest near the center and greatest at the extremes of the population distribution. This means that the body dimensions of subjects near the extremes are less accurately predicted than those at the center of the population distribution. Thus whenever the outer extremes of a population distribution are most important for a design problem, statistical estimates should be used cautiously and with an understanding of their error magnitudes.

4.5 Weighting Database Subjects to Match Target Population Demographics

Suppose there are relevant body dimensions available in an existing anthropometric database, but the database sample is not demographically representative of the design target population. Suppose, for example, that the intended users of an industrial workstation are primarily Hispanic, because the workstation is part of a manufacturing system located in Mexico. Or suppose that one is designing the "cockpit" of a luxury model automobile, and that the income needed to purchase such a car is primarily associated with older rather than younger age groups.

One way to use anthropometric data measured on a sample of people slightly different from the designer's target audience is to weight individuals within the database sample in proportion to their representation in the target audience. Earlier applied to estimating a Naval Aviation population (Bittner & Moroney, 1984), weighted parameter estimation has a long statistical history and is widely used in U.S. National Surveys (Bean, 1970; Botman et al., 2000; Potter & Iannacchione, 1998). Recent research has demonstrated this techniques value in estimating the anthropometric parameters of target audiences whose age, race, sex, height, and weight ranges are captured within the reference database to be weighted (Gordon, 2000). Subject weighting, however, cannot, be used to represent target audiences whose demographic and/or anthropometric ranges are outside that of the reference database. This fact poses a substantial restriction on the usefulness of military databases for civilian applications. For more information on sample weighting, see the U.S. Census publications (www.census.gov).

4.6 Propagation of Error

Subject weighting and body dimension estimation techniques both introduce some level of error into the derivation of product dimension design values. Even when the initial estimation error is of "acceptable" magnitude, propagation of error in subsequent algebraic manipulations can dramatically magnify error magnitude – for example, when one estimate is then "fed into" another statistical model.

Imagine, for example, having to use a subject weighting technique to match the demographics of the reference database to the target population, then suppose one must also apply a linear regression, ratio scaling technique, or algebraic derivation to estimate a body dimension not included in the reference database, *and* in addition, suppose one might need to adjust the result for estimated secular increases in body size that have occurred in the 10 to 15 years since the data were collected. Each step propagates the error of the measurements entered into it, and increases the magnitude of expected error in the next estimate. Sometimes this process is unavoidable when design issues are pressing (Kinghorn & Bittner, 1995). However, we should be aware of the error magnitudes incurred at each stage of the process so that we can appreciate the precision (or lack thereof) in the product design values that are derived from the anthropometric estimates. Cameron (1982) presents a short technical overview of means to estimate the magnitude of propagated errors.

4.7 Collecting New Anthropometric Data

If funds permit, it is always preferable to measure the exact body dimensions of interest on a representative sample of the design's target audience. In fact, for some specialized target populations (e.g., wheelchair users), there are little or no published anthropometric data, and so new data collection cannot be avoided. However, one should not underestimate the demands required for assembling technically valid anthropometric data on a statistically valid sample of subjects.

Standardized Anthropometric Dimensions: Although some relevant body dimensions may be unique to a particular design, many times there are standardized anthropometric dimensions already defined that are relevant to the product. Whenever appropriate to the design problem, standardized measuring protocols should be used because they have undergone rigorous evaluation for measurement validity and reliability (e.g., Garrett & Kennedy, 1971; Weiner & Lourie, 1969; Lohman et al., 1988; Clauser et al., 1988; ISO 7250, 1996). Using standardized protocols also offers the opportunity for valid comparison of new data collection results against those from previous studies.

Measurement Protocols and Measurer Training: Taking good (e.g., accurate and reliable) body measurements is deceptively difficult. One cannot simply read a protocol and expect to replicate faithfully the author's technique. Measurers should receive formal training from an anthropometric expert who measures *often* (Gordon and Bradtmiller, 1992). Anthropometric training should include the location of anatomical landmarks, positioning of subjects' bodies, and proper selection, use, and calibration of anthropometric instruments. If more than one measurer will be used to collect data, then these teammates should be trained together and they should periodically re-measure the same subjects to ensure that their techniques have not drifted apart. All details of measurement protocols and measurer training should be recorded and published with the study results.

Sample Sizes and Subject Acquisition: Study sample sizes and subject acquisition methods are equally critical to valid anthropometric data collection. The number of subjects required for a study is a function of the desired precision, the statistic(s) to be estimated from the data (e.g., means, percentiles, regression slopes), and the variability of the body measurement in the population of interest. Published power equations in reputable statistical texts should be used to establish the minimum sample sizes required in advance of data collection (e.g., Sokal & Rohlf, 1981; Snedecor & Cochran, 1980; Zar, 1984).

The validity of statistical power equations is based upon an assumption that subjects are randomly selected and representative of the target population to be described statistically. In practice, truly random subject selection is difficult to achieve. However, every effort should be made to obtain a representative sample through stratified random methods that address the major demographic and anthropometric features of the target population (ISO 15535, 2003). Sampling strata usually include age, sex, and race and *may* include other variables such as subject height, weight, and occupation.

4.8 Clothing Allowances

To maximize comparability and reliability, most measurers work on subjects wearing minimal clothing. Most people do not, however, work in minimal clothing! As a result, when designers require a product dimension that depends upon body clearance values or heights in shoes, it is critical to add a clothing allowance to whatever "semi-nude" body dimension is calculated. Recommended clothing allowances are published in several engineering guides and reported in a number of research reports (Hertzberg, 1972; Annis, 1978; Pheasant, 1996). Clothing allowances should be added to semi-nude design dimensions only *after* completing derivations and estimations, in order to ensure that the error/uncertainty associated with variations in clothing is not magnified through propagation of error.

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5. Representing Body Size Variability Using Cases

We have thus far defined: a) the problem, b) the population we are trying to accommodate, c) the relevant dimensions, and d) the sample we will use. This chapter will help us to characterize body size variability within the targeted user population through the definition of a limited number of anthropometric cases. This step is the last in the information distillation process (see Figure 1 in Chapter 1).

5.1 Definition of Cases

A case represents a set of body dimensions we plan to accommodate in design. A case may be the measurement from a particular human being, or they may be measurements generated to represent a combination that must be accommodated. Suppose that, for a given design problem, two body dimensions are relevant. In designing a certain kind of seating, for example, the relevant dimensions might be Popliteal Height and Hip Breadth. In this situation, a *case* is a single point in the two-dimensional space formed by the distributions of these two body dimensions (Figure 6).

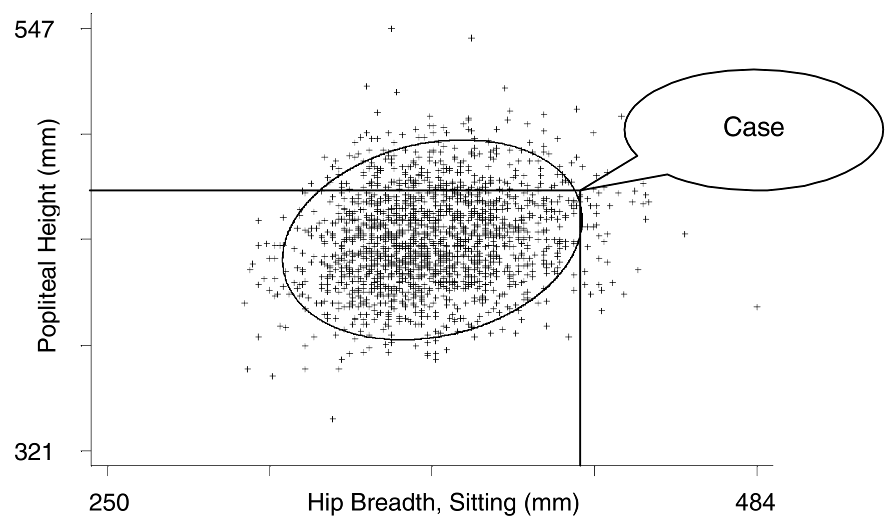


Figure 6. Case as a single point in 2 -D space

If we are designing the height of a doorway and only a single body dimension is relevant (e.g., Stature), a *case* is a point along the single axis representing the body dimension Stature (Figure 7). If 15 body dimensions are design relevant, a *case* is a point in a 15-dimensional space. One-dimensional cases are called univariate. Two-dimensional are called bivariate. Anything greater than one is a mult idimensional case. So a bivariate case is also a multidimensional case, but a multidimensional case generally refers to one that is three-dimensional or greater.

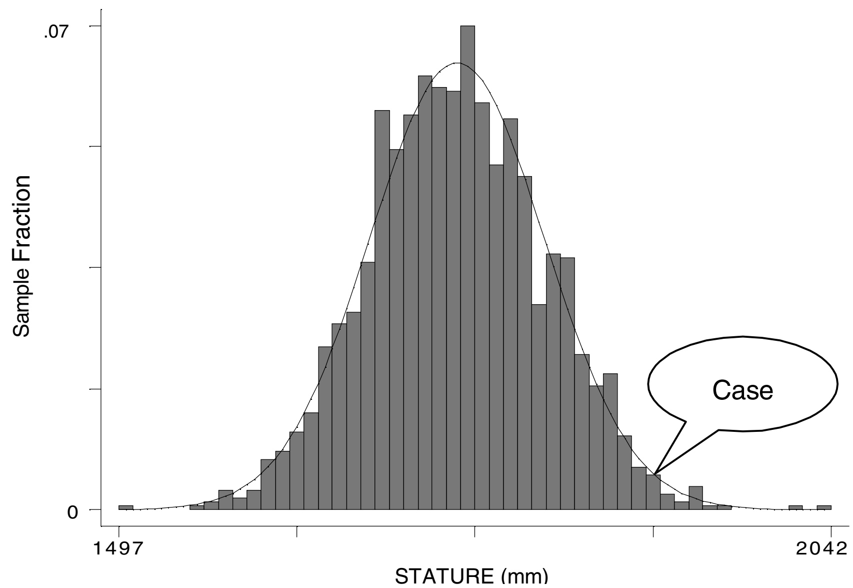


Figure 7. Case as a point along the distribution of a single body dimension

Each set of body dimensions represented by each case in the study, must be accommodated. For example, if a case is a point in the eye -height-sitting and leg-length distribution, then the combination of these dimensions for the case must be specified and accommodated. If the case has a short eye-height-sitting and a long leg-length, then it is not enough to accommodate the short eye-height-sitting and separately accommodate the long leg. Both conditions must be accommodated at the same time. For example, if a monitor is positioned on a desk low enough so the short eye-height-sitting is accommodated, the monitor must at the same time be high enough so that a case's long legs can be accommodated underneath the desk.

In addition to cases being represented directly in terms of univariate or multivariate distributions of body measurements, other design representations are possible. For example, a case can be a computer model comprising a combination of body measurements. Bittner and colleagues (1987), and Bittner (2000) derived sets of 17 virtual mannequins—each based on a combination of 19 body dimensions. Each of these mannequins (which Bittner called members of a cadre) could be considered a *case*. Robinette and Whitestone (1992) used the 3-D scans for eight cases to describe the variability of the human head for helmet design. Physical head forms were made from these cases and used for helmet mock-up and for helmet-mounted displays, such as night-vision goggles.

Thus, while cases are based on distributions of measurements of human beings, the points lying on those distributions that correspond to cases do not necessarily have to represent a specific human. On the other hand, a case can also be a particular human being with a specific combination of body measurements relevant to a given design problem. In fact, when live subjects are used to try out prototypes or adjust a design, the subjects can be considered cases as well.

There are essentially three types of cases (Robinette et al., 1998):

1. *Central cases* – These are located toward the center of the distribution of the body dimensions selected.
2. *Boundary cases* – These are located toward the outer boundaries of the body dimensions selected.
3. *Distributed cases* **–** These are spread throughout the distribution of body dimensions**.**

Central and boundary cases can be considered special types of a distributed case. They can also be used together to create a family of cases. Distributed cases need not include central or boundary cases. A random sample of subjects or a Monte Carlo sampling from a statistical distribution are types of distributed cases that do not require the inclusion of a center case or boundary cases.

The following text discusses the different types of cases, including which types are preferable for a given number of dimensions, as well as some advantages and limitations of each type. After that discussion is a section about how to decide which type of boundary case to use.

5.2 Central Cases

Central cases are points selected toward the middle of a distribution. Some common examples are the mean (average), the median (also called the 50^{th} percentile), and the mode. In addition, subjects who fall toward the center for some dimensions can be selected as central cases and these subjects' other dimensions are used no matter what they happen to be. This latter method is commonly used for apparel. A person is recruited who is near the center for a few key dimensions and that individual becomes the model for a basic size in a line of clothes. Sometimes more than one person is selected toward the center, each representing a different shape or "cut". For example, a coat can have a "European" cut or an "Athletic" cut.

Several central cases can be used in conjunction with boundary cases to fill in the region between the boundaries. When this is done, the set of cases exemplifies distributed cases.

5.2.1 Advantages of Central Cases

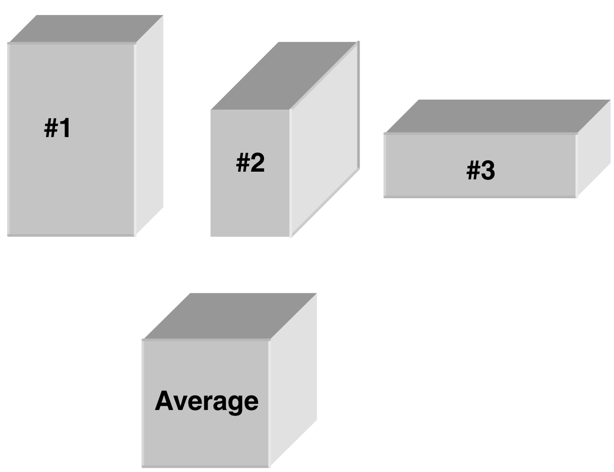
Central points are useful when there is a need to "center" something. For example, the height location of a mirror in the women's bathroom might be well represented by the average eye height for women. In this example, a univariate (or one-dimensional) central-point estimator is being used. The one dimension is eye-height.

It is also possible to have a multidimensional, single -point estimator, such as a multidimensional mean. A multidimensional mean is simply the mean value for every measurement or dimension. For example, the mean of Stature, Weight, Sitting Height, and Leg Length is a 4-dimensional mean. Another more practical multidimensional mean is the eye location in three-dimensional space. In this case there are three measurements, up-down, front-back, and left-right, to define the location of the average eye point.

Central cases can be used as starting points for scaling a design, a process that can simplify accommodation of the target population. The scaling factors can be arrived at by combining the central point proportions with boundary point or distributed point information. Again, this practice is common in the clothing industry. A pattern that fits the central model will be scaled using a process called "grading" to create the other sizes. The grading process is stopped when it reaches a boundary point. This fitting process can be much cheaper than creating a new pattern for each case along the scaling line.

5.2.2 Limitations of Central Cases

When a design problem has several dimensions, special care must be taken to ensure that either a real person exists whose combined body dimensions correspond to the central case, or that the absence of such a person will not matter to the design problem. As Daniels (1952) has pointed out, there is no average man or woman. In other words, there is no person who is average in every way. Each of us is a combination of small, medium and large dimensions. This fact means that averaging the dimensions of different people combines measurements in such a way that may not occur in nature and can smooth away the most important information. It is possible to design for the multidimensional average and accommodate no one. A simple explanation of the average man fallacy is illustrated in Figure 8 (Robinette et al, 1998).



	x	y	z
Subject #1	2	3	1
Subject #2	1	2	3
Subject #3	3	1	2

	x	y	z
Average	2	2	2

Figure 8. The average shape is different for all the subjects

Imagine you are designing a box within which the three "Subjects" (represented by rectangular objects with different proportions) were to fit. The criteria for fit are that the box can be larger by as much as 1 unit in any direction, but not smaller than the subject's proportions. If you average the dimensions of Subjects 1-3, you get a box with dimensions 2 x 2 x 2. This box is not shaped like any of the original subjects, and none of them would fit into it. Furthermore, if the average is scaled up to accommodate the subjects' largest dimensions, 3 x 3 x 3, it would be too large for each of the subjects on one dimension. The average does not help to solve the multidimensional problem.

Another limitation of central cases for design is the fact that central points alone do not characterize a range of variety of the population. Half the population may be smaller or larger. A door height at the mean value would require half of the population to stoop in order to enter. Therefore, central points used alone are generally not sufficient to ensure clearance or reach for a population, for example.

5.3 Boundary Cases

Boundary cases are points located toward the edges of the measurement distribution. Some examples include the minimum, the maximum, the 5th percentile, the 95th percentile, points around a 95% boundary ellipse, and points around a 95% boundary ellipsoid (a multidimensional elliptical shape). The minimums, maximums, 5th and 95th percentiles are examples of one-dimensional boundary cases. Points around an ellipse are examples of two-dimensional boundary cases, and points around an ellipsoid are examples of multidimensional cases.

A bivariate boundary is very similar to a univariate one. There are simply more than two points used to define the boundary. These points are selected from around an ellipse that encloses the desired percentage of a population to be accommodated by a design. An example of a distribution of two measurements is shown in Figure 9. In this figure, Sitting Height is plotted on the vertical axis, and Buttock-Knee Length on the horizontal axis. Individual subjects in the database are represented by dots at the point where their sitting height and buttock knee length intersect.

An ellipse can be imposed on the plot that includes any desired percentage of the population. The 90% ellipse in Figure 9 encloses 90% of the sample for these two measurements. Cases 1 and 2 (shown as circles) represent people who are small for both measures (1) and large for both measures (2). However, selecting only cases that are small or large for both dimensions does not describe the entire boundary. The ellipse also includes cases representing a short, long-legged person (3) and a tall, short-legged person (4) who are just as likely to occur in the population as any other individual along the perimeter of the ellipse. Furthermore, cases 3 and 4 can represent critical design dimension combinations that are just as important to accommodate as cases 1 and 2.

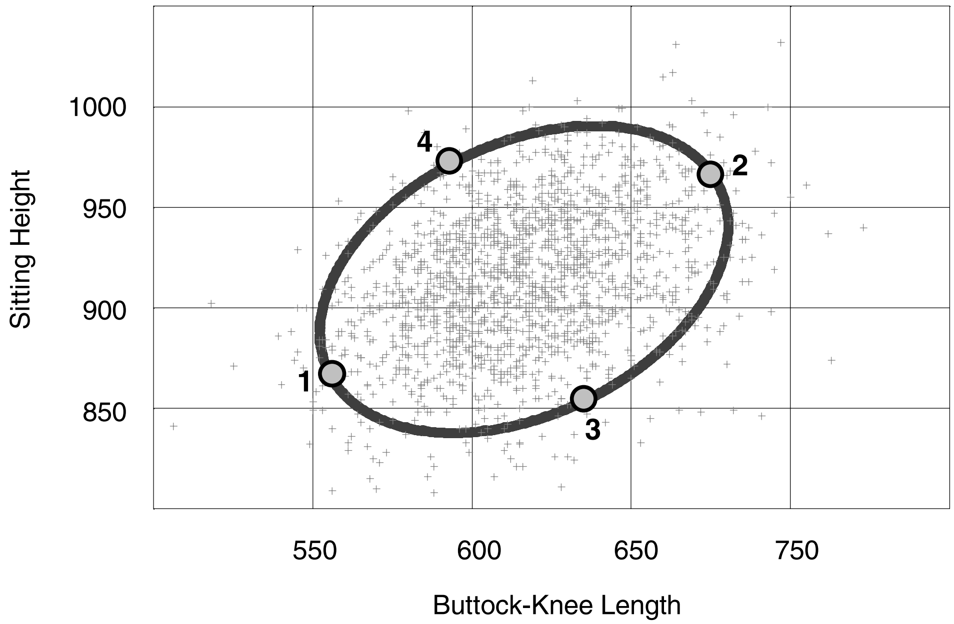


Figure 9. A 90% boundary ellipse (data in mm)

An ellipse, like a line, is continuous and, while the four points mentioned thus far (also referred to as cases), all fall on it, they do not fully describe it. To use this method, a decision must be made as to the minimal number of points needed to describe the boundary. As few as four or six points can be used to describe the boundary, if it is reasonable to assume that the people within the ellipse will be accommodated whenever the cases are accommodated. In Figure 9, one might be concerned that persons midway between the four cases might not be accommodated, and one could either choose more cases, or alternately pick four cases a bit further out to accommodate those within (Bittner, Glenn et al, 1987; Bittner, 2000). This decision process is referred to as choosing the resolution of the points or cases.

When the problem is a three-dimensional one, the ellipse becomes an ellipsoid, which might look something like an American football. Generally speaking, the three-dimensional ellipsoid requires more than four representative cases (points on the surface of the ellipsoid) to describe the various combinations of these measures.

Boundary cases are useful for problems where accommodating the ranges of measurements will accommodate the people who fall within the ranges. For example, the company who makes mirrors for the women's bathroom has to know how long to make the mirror so that most women, including women who use wheelchairs, can see into it when it is placed properly. In this case, the lower boundary selected for design might be the 5th percentile for Seated Eye Height and the upper boundary for design might be the 95th percentile for Standing Eye Height.

5.3.1 Advantages of Boundary Cases

If the points toward the center of the measurement distribution are not important to the problem, one of the advantages of boundary points is that a large range of accommodation can be achieved while using a relatively small number of cases. Bittner and colleagues (1987) demonstrated that in using only 17 cases (16 boundary and 1 centroid) they were able to achieve the same population accommodation rate as with a 400-subject distributed sample (400 cases).

If only the outer edges or boundaries are needed to solve the problem and the problem is one-dimensional, many of the statistics are readily available in the literature. This makes it easy to scan through statistics from populations around the world to select a boundary case. An example of an appropriate application is the overhead clearance through a doorway. If we place door height at the 95th percentile for stature, we have achieved fit for a specified population in the sense that at least 95% of the population can walk through the door without bending or banging their heads on the door.

5.3.2 Limitations of Boundary Cases

There are three major limitations to the use of boundary cases. Firstly, when there are more than three important measurements, boundary cases can be difficult to visualize and select effectively. Secondly, boundary cases give a false sense of a percentage accommodated when one or two-dimensional boundaries are used for a three- (or more) dimensional problem. Thirdly, if only boundary cases are used for design, and the assumption that the center will be accommodated when the boundaries are accommodated is wrong, the error affects the area of the population where subjects are concentrated.

Visualizing and Selecting Boundary Cases: With regard to the first limitation, in order to pick good boundary points, some feel it necessary to be able to "see the boundaries." There are many 3-D displays available now so it is possible to visualize a 3-D ellipsoid, but it is, for the most part, not possible to simultaneously view 4-D distributions in a single display. Also, as each additional measurement is added to the design, an additional dimension or level of complexity is added to the analysis with the accompanying geometrical expansion of the number of representative cases, which must be considered in the design. This dimensionality problem can become unworkable very quickly.

There are several ways to help resolve this problem. Pilot studies can be used with similar products or prototypes to narrow down the number of important combinations. Some sort of multivariate statistical technique, such as principal component analysis (PCA) can be used to reduce the dimensionality of the problem (cf. Bittner, 2000). The correlation structure can be examined to determine if a combination of three or four dimensions has a high correlation ($r = .9$ or higher) with the other important dimensions. Also, some boundaries can be eliminated from consideration if, for example, only an upper boundary is necessary for one or more of the important measurements. Zehner (1996) used the maximum values for some dimensions, such as shoulder breadth, for example, and then defined cases with combinations for the other relevant dimensions.

Understating the Dimensionality of the Problem: The second limitation is really a misapplication of the boundary method, the most common example of which is the use of univariate percentiles for a multidimensional problem. Using two-dimensional boundaries for a three or more dimensional problem can be just as problematic, however. In a seated workstation, for example, it is possible to accommodate 99% of the population for Sitting Hheight and Buttock-Knee Length, but fit few people in the workstation because thigh depth and stomach depth are not accommodated.

Percentiles, minimums, and maximums are one-dimensional points. It has become common for them to be used for multidimensional problems, but it is inappropriate and dangerous to do so. Multidimensional combinations of percentiles do *not* always exist in reality, and they often do *not* exist mathematically as well. In other words, there are people with 95^{th} percentile statures, but there is no such thing as a 95^{th} percentile person (McConville and Churchill, 1976). As with the use of the one-dimensional central case points in multidimensional problems, when the problem has several dimensions, special care must be taken to ensure that the case is one that actually exists, or that it will not matter to the problem if there is a person who is that size for all dimensions.

If there is an interactive effect between dimensions in the multidimensional problem (i.e., combinations of small and large values are important to design), then percentiles will not be appropriate and extending the range will not improve the accommodation for these combinations. Many design problems fall into this category.

Many automobile manufacturers, for example, have designed manually operated driver’s seats to move along an incline such that adjustment of the seat closer to the steering wheel also causes seat elevation to increase. Thus, an example of an interactive effect between design dimensions is the effect of Eye Height Sitting and Leg Length in an automobile. Both Eye Height Sitting and Leg Length are important and the size of one affects the position and size needs of the other. In order to be able to see over the dashboard or car hood, a person's eyes need to be at a certain height or higher. That height is different depending on how close the person sits to the dashboard, which is a function of leg length needed for operating the pedals.

A similar interaction, and the impact of inappropriately using percentiles, was demonstrated in the proposed design for the T-1 aircraft (Zehner, 1996). The pre-production mock-up cockpit layout was designed for the “1st and 99th percentile” pilot. When the mock-up was tested it was found that 30% of white male pilots, 80% of black male pilots, and 90% of female pilots would not be able to fly the aircraft due to an interference of the yoke (similar to the steering wheel in a car) with their thighs. The combinations that caused the fit problems were short Eye Height Sitting and long legs, or short Eye Height Sitting and fat thighs. The former occurred most often in black males, and the latter in females. People with a short Eye Height Sitting needed to have the seat all the way up so they could see over the nose. If they also had long legs or large thighs, this additional factor pushed them up into the yoke so they couldn’t turn it.

Most problems are not really one dimensional and, as Searle and Haslegrave (1969) discovered, using one-dimensional statistics such as percentiles can really cause havoc if the problem is multidimensional. First of all, percentiles are not additive (McConville & Churchill, 1976; Churchill, 1978; Robinette & Churchill, 1979). Robinette and McConville (1982) demonstrated that adding 5th percentile values for just seven body segments resulted in an error for stature of 156.1 mm (6.14 in.). This error is 19% larger than the average difference between U.S. Army men and women (126.4 mm; Gordon et al., 1989), and approximately 50% larger than the average difference between men of North Europe and men of Iberia (Jurgens et al. 1989).

Secondly, percentiles do not accurately estimate the actual proportion of the population accommodated for multidimensional problems. With each additional dimension, an additional proportion of the population is disaccommodated (Moroney & Smith, 1972). An example from a report by Zehner and colleagues (1993) is illustrated below in Figure 10:

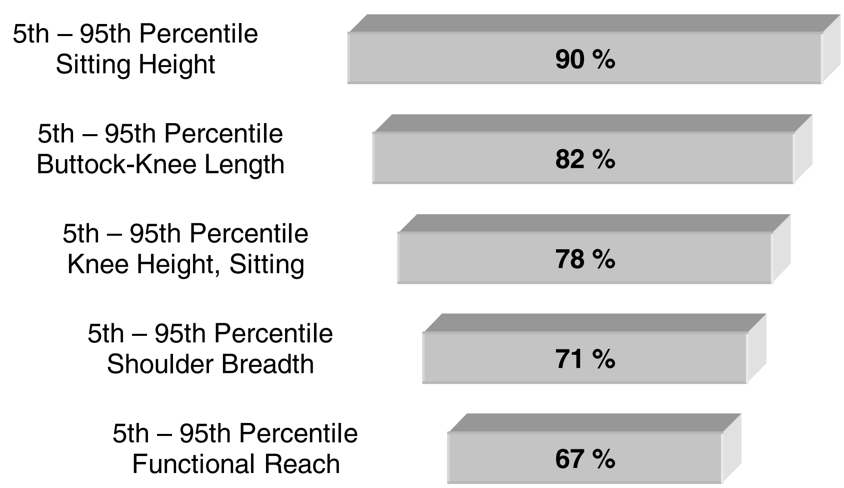


Figure 10. Diminishing accommodation with each subsequent variable

Instead of the desired 90% accommodation, only 67% of Zehner's(1993) sample are captured by the 5^{th} and 95^{th} percentile values of all five dimensions. When more variables are used, there is less accommodation.

Assuming that Accommodation of Boundaries Always Ensures Accommodation of Interior Points: With respect to the last limitation, boundary methods alone should not be used if it cannot be assumed that accommodating the outside points or boundaries will ensure accommodation of the points within the boundaries. Hendy (1990) demonstrated that there are times when it may seem this assumption is valid when it isn't. In fact, this assumption is *rarely* valid when a design has predrilled stops for seat, worktable, or other adjustments that are far apart. This fact can be costly in terms of accommodation.

For example, in the case of the mirror length for restrooms, the points between the top and the bottom are covered by a continuous mirror surface; therefore, points at either end of the range are all that is needed. If, however, the design was a seat height and there were only two adjustment options, all the way down and all the way up with no positions between, the smallest and the largest people might find an acceptable height while many people falling between would not. Since the highest density of the population is in the middle, it is possible that such a system could accommodate very few people.

5.4 Distributed Cases

A distributed method is one in which points are selected that are spread (or distributed) throughout the region of desired accommodation. Two simple examples are: a) a random sample from a population and b) the single variable case where the points or cases would be distributed in increments from a lower boundary point to an upper one. For example, Eye Height range for a population might be divided into ½-inch increments from the minimum to the maximum values, or from a small to a large percentile, to design the vertical adjustability of a viewing device.

Another type of distributed approach is a combination of boundary and central points. An elliptical boundary combined with a point in the middle is one example (e.g., Bittner, 2000). Still another starts with ellipsoidal boundaries and uses cases evenly spaced within the boundaries.

Distributed approaches require either a decision about the number of subjects for a random sample or a decision regarding the resolution of the cases. In other words, how close should cases be in order to assume safely that people between them will be accommodated? It is possible to have cases too far apart with the result people can "fall through the cracks."

If the problem involves simply one dimension and there is some prior knowledge of the needed resolution, then an even distribution of points between two boundaries, such as the Eye Height example above, will be effective. All the Eye Height observations between the boundaries could also be used. However, since body measurements are normally distributed, this process would involve testing lots of points that fall near the center, which are not very different from each other. This effort increases costs and may not add much accommodation information. Also, the evenly distributed cases can be derived from published statistical sources as long as they contain both mean and standard deviation.

If the problem involves more than one dimension and the dimensions are related, then elliptical or ellipsoidal boundaries should be used for the same reasons described in the boundary section, but the even distribution of the cases within the boundaries can still be used. Again this approach uses fewer cases than the total sample but as long as the resolution is deemed good enough, it will not waste time and money on cases that are very close together. We can devise this method from published documentation as well, as long as all means, standard deviations, and correlation or covariance matrices are included.

5.4.1 Advantages of Distributed Cases

There are many advantages to using a distributed approach. With cases spread throughout the distribution, there is less risk of missing a key area. If a random sample is used, we don't have to "know" the key measurements up front. With this method, there are statistical tests for proportions that can be used to estimate the accuracy of the percentage-accommodated estimates.

What if the dimensionality of the sample cannot be reduced to something manageable? Then the only feasible option may be a random sample (which can be a Monte Carlo sample generated from the multivariate distribution) *or* the use of all subjects in the sample (assuming the sample selected is sufficient to represent the target population previously defined in Chapter 3).

If the dimensionality is small or can be reduced to something meaningful and manageable, then some of the other distributed approaches can be cheaper than using all subjects but still very effective.

5.4.2 Limitations of Distributed Cases

This method generally requires using many cases, which can be time-consuming and expensive. This method also requires evaluating more points than if we use boundary points alone, which can make it a more difficult method to implement. In addition, when the design is complex and multidimensional, distributed methods can have some of the same limitations as boundary point methods. When there are more than three important measurements, for example, incrementally distributed cases can be just as difficult to visualize and select as boundary cases. Furthermore, incrementally distributed cases can give a false sense of the percentage of target population accommodated when one- or two-dimensional cases are used for a three- or more dimensional problem. This false sense is not an issue with randomly distributed cases because their geometric locations need not be visualized in order to select them. Distributed cases, however chosen, may be readily handled when there are good computer models of accommodation for the problem of interest.

5.5 Selecting Cases

The number of dimensions used to define a case is an important factor in the case selection process for several reasons. First of all, statistical combinations of dimensions, such as the mean or the 95th percentile, can be good in a one-dimensional case, but such combinations may not be good in a multidimensional case. Secondly, if a large number of measurements are deemed relevant to a problem, that fact can make it difficult to select a small number of cases to represent the population well. Thirdly, it may be difficult to find cases if live human subjects are needed to represent extreme boundary cases.

As the number of relevant measurements increases, the complexity of the problem increases and the types of cases used must change to accommodate the complexity. Generally, it also means that the number of cases must be increased. There are advanced multivariate statistical tools, such as Principal Component Analysis (PCA), which have been used in some instances to reduce the dimensionality of the measurement space and consequently the number of cases required (Bittner, 2000;

Bittner, Glenn et al., 1987; Zehner et al., 1993; Zehner, 1996; Gordon et al., 1997). However, PCA methods require considerable statistical sophistication on the part of the user (see Harris, 1975; Reyment et al., 1984; Grimm & Yarnold, 1995; Johnson & Wichern, 1982), and the application of PCA to case selection is beyond the scope of this document.

To help in arriving at a decision as to which is the best statistical method to use to obtain valid anthropometric cases, a decision tree is shown in Figure 11.

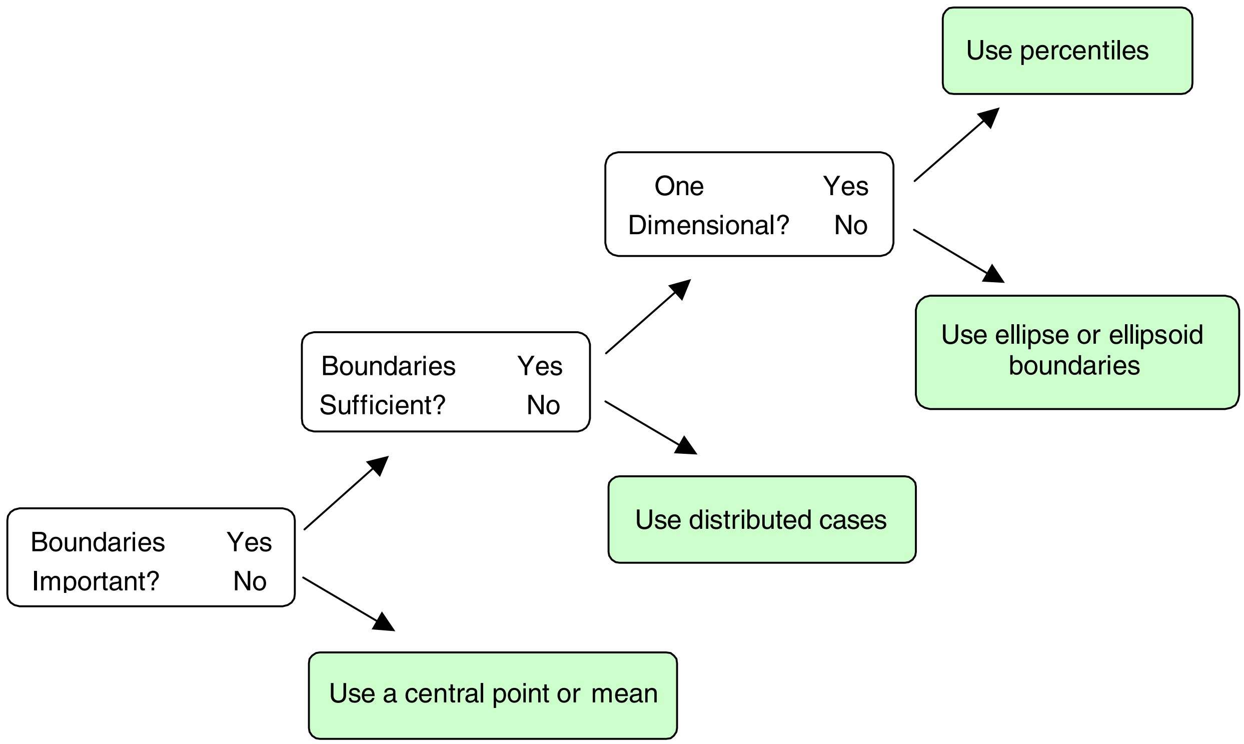


Figure 11. Decision tree for case selection methods

In this tree, the first step is to determine the importance of boundaries to the design problem. If boundaries are not important, then only the center of the distribution is important to the design. When boundaries are important, then we must decide whether knowing the dimensions of boundary cases is sufficient for the design problem. If boundaries are not sufficient, we need to use cases distributed within the boundaries. When boundary cases are sufficient, then our case selection method depends upon the number of dimensions that are critical to the design problem. If only one dimension is important, percentiles will suffice. When more than one dimension is important, however, ellipses or ellipsoids are necessary to define boundary cases. As noted previously, when a product is complex and large numbers of body dimensions are critical to its design, no single statistical definition of cases may be appropriate. This difficult situation may require a randomly distributed sample of cases and a good computer aided design model for evaluating accommodation.

This chapter has discussed the selection of combinations of body dimensions (cases) to use in defining the design criteria of products. The following chapter will discuss how to use these cases to develop a physical design.

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6. Transitioning Cases to Products

At this point we have the information distilled down to its smallest unit, the cases. We have defined: a) the problem, b) the population we are trying to accommodate, c) the relevant dimensions, d) the sample we will use and e) the cases we will use from it. All distillation stages are complete. This chapter explains how to use the cases we have selected in the design and evaluation of products.

6.1 Using Cases in Design and Evaluation

In practice, the ergonomic design process is often an iterative loop of design concepts and functional evaluations so closely integrated that it is sometimes difficult to separate design from evaluation. In the context of anthropometry, the goals of testing and evaluation are to ensure that the product adequately fits the targeted user population and facilitates performance of the functions intended. To achieve these goals, fit testing is necessary to examine the match between product dimensions and related body measurements, strength, flexibility and postures of the users. The fit testing may also examine the adjustability of the product and required clearance.

Even when anthropometric data and case selection are optimized, fit failures may occur due to one or more of the following design constraints:

1. Mathematical relationships between the body dimensions of users and the design dimensions of their clothing or workspaces are *approximations*, and thus subject to some error.
2. Most human-machine systems involve simultaneous accommodation of multiple, somewhat independent variables whose interactions may not be fully predictable in advance.
3. Standard anthropometric dimensions and/or those of a human model derived from body segment measurements may not reflect variations in the clothing worn and body postures assumed by real people engaged in real tasks.
4. Some designs or product concepts are simply ineffective, and therefore not acceptable to the targeted population. It may not be possible to achieve a good fit with some designs, no matter how they are sized or shaped. Some designs may not be comfortable for people no matter what is done.

Quantitative data on fit-test outcomes are used to adjust product dimensions in the next design cycle. However, even when designs have been iteratively optimized, there may still be imperfect fits between the design and some users for some tasks. These occur because there are inevitable engineering trade-offs to be made between system complexity, cost, weight and the relative importance of some tasks vs. others.

It should be noted that the cases selected for design may be different than those used for evaluation. Central cases, for example, are often utilized for developing initial design concepts and for early component integration testing, whereas distributed or boundary cases are useful in determining the extent of adjustment or scaling required to accommodate the full range of variability in the target population; distributed cases are usually required for final design verification and validation. Functional verification and validation of a final design are important components of the ergonomic design process. Verification testing ensures that the design meets the design specifications. Validation testing makes sure that the design serves the intended functional purpose for the intended target audience.

This chapter discusses how to use cases in the design concept and fit evaluation. As discussed previously in Chapter 5: a) designs should accommodate all of the selected cases, b) in functional systems, all components together should accommodate all selected cases, and c) each case must be accommodated as a combination. In other words, if a case has a short eye height seated and a long leg length, then it is not enough to accommodate the short eye height and separately accommodate the long leg. Both conditions must be accommodated at the same time. For example, if a monitor is positioned on a desk low enough so that a case with short eye height (sitting) is accommodated, it must at the same time be high enough so that their long legs can be accommodated underneath the desk.

There are several ways to represent the cases in a design: a) use real people, b) use computer models, c) use physical forms, and d) measure the computer or physical mockups of the design when they are adjusted to accommodate each case. Sometimes more than one of these methods is used. Each of them is discussed briefly below.

6.2 Real People Representing Cases

Both physical mock-ups and human test subjects are costly; thus, the use of real people as cases is often best suited for the latter part of the design process, when a design concept has been "frozen" for evaluation. Design changes or adjustments can then be determined by testing the prototype with people representing the cases. Dotson and co-workers (1995) provided an example of this for the F-22 aircraft cockpit. They tested a mockup with females representing one of seven cases. The other cases were male cases that presumably had already been accommodated by the prototype design.

Although use of human subjects is usually reserved for later in the design process, when a design problem is difficult and a preexisting product can be used as a "straw-man" prototype, then testing with people representing cases can yield important engineering data early in the design process.

Finding real people that match the physical characteristics of boundary cases can be problematic. Boundaries represent extremes in a population, which means there aren't very many people who have those proportions. However, it isn't always necessary to find people who match the cases exactly as long as the dimension combinations that aren't matched can be simulated or measured in some other way. Kennedy and Zehner (1995) describe the simulation of a subject with different shoulder heights in an aircraft cockpit:

> …In selecting subjects to be representative of those who will potentially experience difficulty in reaching controls, it is necessary to target the uppermost seat position – that is, to examine subjects in the full-up seat, or simulated full-up seat. Because of the above relationships, then, a subject with a sitting shoulder height of 22 inches in the seat adjusted to 2 inches down from full-up can simulate the subject with a 20 inch sitting shoulder height in the full-up seat. This eases the persistent and impossible problem of finding subjects who are of the exact sizes needed for the examination of reach…

For final validation of a design it is important that real people be used in a physical mock-up because the models, forms, and constructs used in developing a design usually require assumptions about posture, apparel, comfort, fit, etc., that are understandably imperfect representations of reality. It is valuable to use distributed subjects in these final test panels because validation testing involves determining whom the design fits and whom it doesn't fit, and thus establishing the design's limits, cut-off point, or margin of fit. This validation may also require many subjects with body dimensions at or near the design's accommodation limits where fit degrades.

6.3 Computer Models Representing Cases

Products are frequently designed and built within computer-aided-design and three-dimensional modeling computer programs. These two- or three-dimensional prototypes need to be tested against a set of computerized human figures (computer mannequins) generated to characterize the body dimension combinations of the cases to be accommodated. For fit testing, a mannequin selected to represent a case - with a predetermined posture - is placed within the design region of the prototype. The fit between the mannequin and the prototype can then be observed, measured, and analyzed. The process is repeated for all the body postures and/or tasks and all the selected mannequins.

The advantage of computer prototype testing is that the testing and evaluation can be performed quickly – especially if the software has the ability to let the tester manipulate the prototype and mannequin easily. One limitation is that a computer mannequin is a simplified model of a human body that may not accurately represent real people. Likewise, the computer mannequin may also not adequately characterize other factors such as clothing, strength, flexibility and abnormal body weight distributions. A second limitation is that the postures manipulated on the computer may not accurately represent the wide range of postures that real users will use. A third limitation is that computer prototype testing cannot assess the extra space that may be required by the user for comfort or preference when interacting with the product or system. (See: Verification and validation of human modeling systems, Oudenhuijzen et al., 2002.) For these reasons, computer prototype testing is most often used early and iteratively in the design process, to catch and correct gross problems in the human-system interface. Testing with actual human subjects is necessary to ensure accommodation.

6.4 Physical Forms Representing Cases

The design or evaluation can be performed using physical forms (also called dummies or physical mannequins) representing the cases. As with live human subjects, it must be possible to create the design around the forms or have a prototype to evaluate with them. A physical form typically is placed into the prototype with various predetermined body postures and the match between the product dimensions and the body dimensions can be observed, measured, and analyzed.

One of the advantages to using forms over human subjects is that they usually don't object to being used for long periods of time and repeatedly asked to test the same prototypes over and over. Another advantage is they generally don't change in size and shape over time. Finally, they can be subjected to hazardous crash forces or other dangerous environments, and provide standardized results.

The disadvantages to using forms are much the same as those of computer models discussed above. Essentially they are simplified models of people and may not accurately represent real people. Posture, tissue deformation, painful pressures or forces, fatigue, and strength in marginal reach zones are among the items that are estimated, simplified, or ignored in models. Again, testing with actual human subjects is useful to ensure accommodation, though generally, only physical dummies or models should be used when situations are hazardous.

6.5 Mathematical Constructs Representing Cases

Utilizing a computer or physical mockup of the design, it is possible to directly evaluate the assumptions about the relationship between the body measurements and the product to evaluate and/or modify a design. For example, imagine it has been assumed that the monitor height should be one-inch lower than a person's seated eye height and the desk should be one-inch higher than a person's knee height. In this instance, the designer need only measure the design concept to ensure that these conditions are simultaneously met for each and every one of the cases. The suitability of this method depends upon the confidence that can be placed in the assumptions about these relationships. Certainly this is a good place to start if one already has a design concept in mind and a good understanding of the mathematical relationships between design affordances and human body dimensions. Testing the product with real people is almost always required to fully ensure user accommodation.

6.6 Summary

Cases can be used at several points in the design process. Different types of representations for the cases are generally best for the development of the first concept or prototype than for the final accommodation assessment. Usually it is best to use real people toward the latter part of the process to ensure accommodation, especially when subject safety during testing is not an issue.

The cases selected can also differ depending upon the part of the process for which they will be used. In other words, even if the cases selected are boundary cases for the design concept or the development of the first prototype, often it is best to select distributed cases for evaluation of a design. In an evaluation it is usually important to know how close the design is to accommodating the boundary cases. If they are not accommodated, this information can be used to determine changes necessary to achieve the accommodation goals.

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7. *Anthropometry in Design: Examples and Summary*

At this point we have discussed all of the stages of applying anthropometry in the design process. This chapter presents four examples of the process. Each instance highlights a different aspect and each example begins with an explanation of the purpose, the techniques used and why.

When problems have been intentionally simplified for illustrative purposes, these details are noted in the text. As in most ergonomic problems, there may be more than one approach that leads to a satisfactory solution. The approaches outlined in this Chapter were chosen for their pedagogical value. Some alternate methods that lead to valid (and sometimes invalid) solutions are included in the example discussions.

To facilitate use of this chapter, Table 3 outlines the contents of each example, proceeding from the most simple to the most complex.

Table 3. Chapter 7 examples and their contents

	Example 7.1	**Example 7.2**	**Example 7.3**
Problem	Work Surface Height--for a standing workstation	Fire Retardant Gloves	Workstation Seating
Key Variables	One	Two	Many
Statistics	Percentiles	Ellipse	PCA/Ellipsoid
Case Selection	Boundaries	Distributed	Boundaries and Distributed
Illustrates	· Database Selection · Derived Dimensions · Subject Weighting · Clothing Allowance	· Minority Subgroup · Estimated Dimensions · Multiple Sizes · Cases for Fit Testing	· Database Selection · Clothing Allowances · Mathematical Models

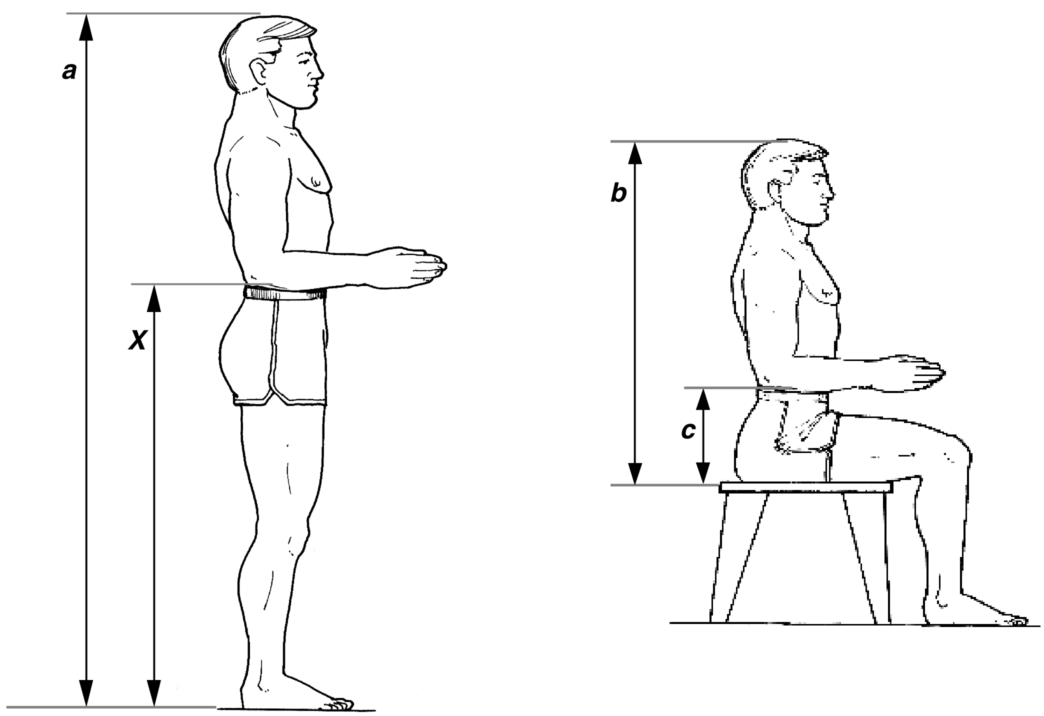
7.1 *Example 1:* Keyboard Height for a Standing Workstation

The purpose of this example is to illustrate the anthropometric design process in one of its simplest forms, when critical design parameters depend upon a single body dimension. This example also illustrates database selection considerations, dimension derivation methods, subject weighting methods, and the proper definition of single dimension boundary cases.

7.1.1 Statement of the Design Problem

A workstation is needed for airline check-in, with an adjustable writing and keyboard work surface. The airline employee will ordinarily work while standing, and the workstation must allow the operator to complete writing and data entry tasks quickly, while at the same time being comfortable. In this example, we will assume that the adjustment mechanism affords continuous variation of the work-surface height between the adjustment limits. The designer needs to know the upper and lower vertical limits of adjustment required to fit the users.

One approximation for standing work surface height is Elbow Rest Height, Standing.[1] This measurement can be done directly (see ***X*** in Figure 12), but is more often derived from separate measurements of Stature, Sitting Height, and (Seated) Elbow Rest Height (see ***a***, ***b***, and ***c***, respectively, in Figure 12).



Elbow Rest Height, Standing = Stature – Sitting Height + Elbow Rest Height
(*X* = *a* – *b* +*c*)

Figure 12. Direct and derived measurements of elbow rest height, standing

7.1.2 Defining the Target Population

If we define our primary market as U.S. airlines and airports, the resulting target population is the group of people who work for these airlines at U.S. airports. As we are unable to locate specific data on the demographics and anthropometrics of these

[1] This does not include footwear (heel height) but this will be considered later.

airline check-in employees, we assume that they are similar to those of American adults in general. We decide in advance that we want our design to fit at least 90% of this target population (See Section 3.4.)

7.1.3 Selecting an Anthropometric Database

General body size data on the American population (such as Height, Weight, Sitting Height, Biacromial Breadth, and Shoulder-Elbow Length) can be found in the National Health and Nutritional Examination Surveys (NHANES), whose comprehensive sampling plans make them an excellent reference[2]. However, the NHANES databases do not contain many body dimensions relevant to product design, and in particular, they do not contain Standing Elbow Height or dimensions from which it could be derived.

The most recent anthropometric database on American adults with the required dimensions is the 1988 U.S. Army Anthropometric Survey (Gordon et al., 1989). However, the 1988 Army database (ANSUR) contains measurements made on active duty military personnel – not civilians, so we need to consider whether or not the ANSUR sample can be used to adequately represent Standing Elbow Rest heights of civilians.

Several issues enter into this decision. Firstly, we know that military Height, Weight, and body fat standards restrict the anthropometric distributions of military personnel relative to civilians. However, height standards are so broad for the Army that they eliminate less than 2% of the civilian population (Gordon & Friedl, 1994), and as can be seen in Table 4, the military and civilian Height distributions are not very different, except at their tails.

Table 4. Comparison: military and civilian stature (height) distributions, NHANES III and ANSUR databases

STATURE (cm)	min	p5*	mean	sd	p95*	max
NHANES III males	142.3	164.4	176.2	7.1	188.1	200.0
ANSUR males	149.7	164.7	175.6	6.7	186.7	204.2
NHANES III females	131.7	151.9	163.1	6.7	174.3	183.1
ANSUR females	142.8	152.8	162.9	6.4	173.7	187.0

* 5th and 95th percentile values

Thus for body dimensions closely related to Stature, the ANSUR database may be useful for civilian applications *when no civilian data are available*. In addition, we know that Standing Elbow Rest Height is highly correlated with Stature; $r = .93$ in Army males, and $r = .94$ in Army females (Cheverud et al., 1990). As a result, if the Army database captures 98% of civilian variation in Stature, it is also likely to capture

[2] Databases cited in this standard were publicly available as of December 2003. Mention of a particular database should not be construed as endorsement, however, as new sources of anthropometric data become available every year, whereas standards are updated only periodically.

most of the civilian variation in Standing Elbow Height. With this in mind, we conclude that use of the ANSUR database to estimate civilian Elbow Heights involves an acceptable level of risk, where risk means the chance that a military approximation to civilians is so poor that the resulting design will not fit the target population well. Any risk associated with this decision can be further reduced during testing by including test subjects whose Heights are outside military limitations, but within a 5th – 95th percentile range for US civilian Heights, such as might be obtained using data from the National Center for Health Statistics (http://www.cdc.gov/nchs/nhanes.htm).

7.1.4 Case Selection

The designer of this standing workstation needs to know the upper and lower limits of an adjustment range that accommodates 90% of the targeted population. We note that upper and lower limits are a boundary problem, and because the designer's mechanism provides continuous adjustment between its limits, we can assume that if the design accommodates upper and lower boundary cases, it will also accommodate any cases in between. Finally, we note that the height requirement can be estimated using the variation of a single body dimension–Elbow Rest Height, Standing. Referring to Figure 11 in Chapter 5, we conclude that percentiles are appropriate statistical estimators for the upper and lower boundary cases required in this design problem.

Calculating the Percentiles. There are three steps in calculating the percentiles for this example. Firstly, to obtain statistics describing the distribution of a derived dimension such as Elbow Rest Height, Standing, we must first calculate the derived dimension for *each and every* subject in the database using the equation in Figure 12. Secondly, because we don't know the actual proportions of males and females working at airline check-in counters, we decide to give male and female subjects equal weight in the estimation of percentiles. Since the ANSUR database has 2208 females and 1774 males, the proportion of females in the database is 2208/3982 or 0.5545; the proportion of males in the database is 1774/3982 or 0.4455. The proportional contribution desired for each sex is 0.5. Thus the weight for each male in the database will be p(target)/p(database) = .5/.4455, and the weight for each female in the database will be p(target)/p(database) = .5/.5545. In the final step, percentiles are calculated for the weighted distribution of males and females. The results are shown below in Figure 13.

Verifying Theoretical Accommodation Rates: No matter how simple an estimation problem, it is always wise to check one's answer before implementing cases in a design. In this boundary problem one simply codes each subject in the database as captured if his/her standing elbow rest height is between 942 and 1135 mm, and the proportion of captured subjects is calculated and compared with the targeted accommodation rate. In this example, our boundary cases capture 90.2% of all subjects in the ANSUR database; 90.5% of the females and 89.8% of the males. These are acceptable results since the targeted accommodation rate is 90% of users. The capture rates recorded here are referred to as *theoretical* accommodation rates because the design has not been completed and tested with real people. The *actual* accommodation rates achieved by a product depend on a plethora of assumptions about the relationships between body dimensions and the design, design functionality, body postures of users, and relevance of the database to the targeted population (see Chapter 6, Section 6.1).

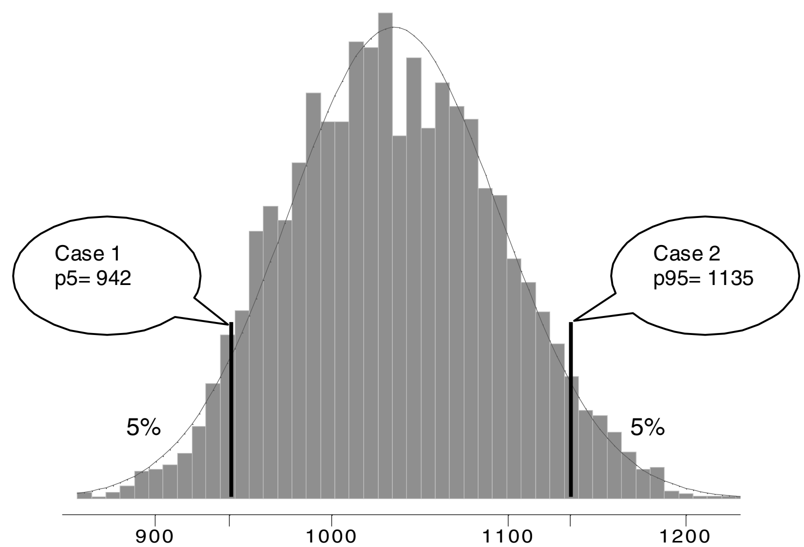


Figure 13. Distribution of the derived dimension, elbow rest height, standing (in mm)

7.1.5 Transitioning Cases To Product

The cases above describe a "close to ideal standing work surface height" for the shortest and tallest people we plan to accommodate (not including footwear or anti-fatigue mats). The cases can be applied to the design of the airline check-in counter using any of the methods described in Chapter 6 or a combination thereof. If real people are used to represent cases, then they should wear the kind of footwear normally worn by airline employees when their Elbow Heights are used to set the design's adjustment limits; anti-fatigue mats or any other artifact which might change Elbow Height should be included in testing. If mathematical constructs or CAD models are used to represent cases, we will need to add a "heel height" adjustment to the elbow heights for our cases, because the anthropometric data were recorded on subjects in bare feet. Although heel heights vary, Pheasant (1996: 29) notes that 25 mm is a typical heel height for ordinary men's shoes and women's flats, so we add 25 mm to the elbow heights of both cases before using them to define the work-surface adjustment limits.

7.1.6 Product Testing and Validation

As discussed previously, it is always advisable to mock up the design and test that it will actually perform as expected. In this stage of the design process, real people are required. If the test subjects are also members of the user community, their usual work clothing, working postures, and knowledge of common tasks will contribute to more realistic test results.

In this problem we have used a military database to approximate the distributions of a civilian workforce knowing that at least 2% of the smallest and largest American civilians are probably not represented in the military sample. To ensure that this approximation has been a good one, we could use a distributed (random) sample of airline counter employees, and record the number of successful trials to test whether the work-surface adjustment accommodates 90% or more of the random sample. In addition, we also record the sex and critical body dimensions (e.g. clothed Stature and Standing Elbow Rest Height) of the test subjects, so that the mathematical relationships between body dimensions and accommodation success/failure can be established and used to modify the design if necessary. Alternately, to focus on extremes, we could pre-screen users to identify the upper and lower boundary case values. This would efficiently focus our evaluation on only those likely to be most challenged by the design.

7.1.7 Discussion

Some readers may wonder why the standing workstation height adjustment range was not directly taken from tabled (Gordon et al., 1989:374) values of male and female percentiles of Elbow Rest Height Standing: 10^{th} percentile female to 90^{th} percentile male, for a 90% accommodation target. This approach, however, captures the expected proportion of users *only* when two conditions are met: 1) the "small female" percentile value must be smaller than the minimum male value in the sample, *and* 2) the "large male" percentile value must be larger than the maximum female value in the sample.

In the case of Elbow Rest Height, Standing, the conditions required for the sex-specific percentile approach are nearly, though not exactly, met. The 10^{th} percentile value for females is 942 mm, and only 6 of 1774 male values are smaller; the 90^{th} percentile value for males is 1135 mm, and only 2 of 2208 females are larger. In fact, in this case, the results (recorded to the nearest mm) are identical to those achieved by taking percentiles from the weighted joint sex distribution. Most of us would consider results to the nearest mm more than "close enough" to merit the trade-off between accuracy and convenience, which is why this approach is often recommended in the human factors engineering literature.

Unfortunately, male body measurements are not always larger than comparable female body measurements (see Robinette 1995, for example), the situation that enabled the "shortcut" above to work. Consider a body measurement often used for seating design: Hip Breadth, Sitting. Figure 14 compares its distribution to that of Elbow Rest Height, Standing for U.S. Army personnel (Gordon et al., 1989).

Figure 14. Male and female distributions of hip breadth, sitting

To use the same sex-specific percentile approach that captured approximately 90% of the target population in the case of Elbow Rest Height, we choose the 10th female and 90th male percentile values of Hip Breadth Sitting: 351 mm and 401 mm, respectively (Gordon et al., 1989:204). However, when we apply the 10th female to 90th male percentile range to each subject in the ANSUR database, we find that these boundary cases capture only 63% of the males and females in the database, when we intended to capture 90%. Even if we choose the 5th percentile value for females and the 95th percentile value for males (342 – 412 mm), we still capture only 79% of subjects. These results arise because the female distribution of Hip Breadth has generally larger values than the male distribution, even though they overlap. As a result, there are many males with smaller Hip Breadths than the "small female" percentile value, and many females with larger Hip Breadths than the "large male" percentile value.

It is noteworthy that the only way to be certain that a "small female – large male" percentile approach is valid, is to look closely at the individual male and female distributions and verify the number of subjects captured if sex-specific percentiles are used. However, since many statistical reports of anthropometric data do not include minimums and maximums, and even fewer present cumulative frequency distribution data, one will most often need access to the original data to be sure the sex-specific percentile approach is valid. Additionally, if we will require access to individual subject data anyway, we might as well use a method that gives the correct result *every* time: weight the data for equal male and female contributions, and then utilize the percentiles of the resulting distribution. This may be done either with individual subject data, as herein, or by mathematical representations of such distributions (e.g., Bittner, 1978).

7.2 *Example 2:* Fire Retardant Gloves

The purpose of this example is to illustrate the anthropometric design process when there are two critical design parameters, and one cannot assume that accommodation of boundary cases is sufficient to ensure accommodation of cases within the boundaries. This example also illustrates the handling of minority subgroups, case dimension estimation, and case selection for the design and testing of products that come in more than one size.

7.2.1 Statement of the Design Problem

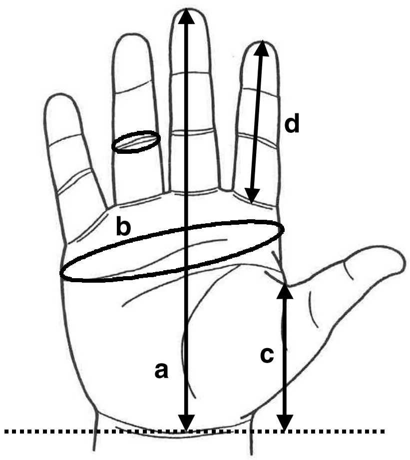
Fire retardant gloves are required to protect Army personnel from flame exposure during flash fires in and near aircraft and armored vehicles. Personnel must be able to operate vehicle navigation, communication, and weapons systems while wearing the gloves, so a close fit is required to ensure that dexterity is not compromised. Textile engineers on the product team have identified a stretchy material for the gloves, and a prototype design that avoids seams on the fingertips. The product team needs to know how many sizes of gloves they should make, and what the dimensions of each glove size should be.

7.2.2 Defining the Target Population

The users of these gloves are US Army personnel, both men and women. The glove sizing system is intended to accommodate at least the central 90% of the combined user population.[3]

7.2.3 Selecting an Anthropometric Database

In order to maximize dexterity, gloves must settle onto fingertips and into finger crotches with a minimum of excessive fabric around the fingers and palm. We will thus need measurements that describe overall hand size and some details about finger lengths, finger crotch heights, and finger circumferences. Some of these measurements are illustrated below in Figure 15.



a. *Hand Length*
b. *Hand Circumference*
c. *Crotch 1 Height*
d. *Digit 2 Length*
e. *Digit 4 Proximal Interphalangeal Circumference*

Figure 15. Some hand dimensions for glove design

Fortunately, all the necessary measurements are available from the 1988 U.S. Army Anthropometric Survey, which included an extensive series of digitized hand dimensions. Greiner (1991) reports statistics for 72 hand and finger measurements on a representative sample of Army personnel (1304 females and 1003 males).

7.2.4 Case Selection

Although there are many hand and finger dimensions that could be useful in this problem, we note that the correlation coefficients reported by Greiner (1991) between Hand Length and Finger Lengths/Crotch Heights are high (r = .81 - .94), and the correlation coefficients between Hand and Digit Circumferences are also high (r = .86 -

[3] We presume that the other 10% can be accommodated by custom fitting or other means; from an ethical point of view, critical safety and survival clothing and equipment should be provided for all at hazard.

.88). Thus, we decide to focus case selection for our glove sizing system on two critical variables: Hand Length and Hand Circumference.[4]

The boundaries of our target population are important to visualize since they show us the limits of fit for the glove sizing system as a whole. Referring to Figure 11 in Chapter 5, we see that an ellipse is an appropriate method to visualize a bivariate boundary. However, boundary cases alone do not usually provide sufficient information for sizing system design, since the distribution of size categories within the boundaries influences accommodation rates, and since we will need cases from within the boundaries to serve as models for each size category.

Figure 16 illustrates the bivariate distribution of Hand Length and Hand Circumference for male and female soldiers. The Army target population is overwhelmingly male (>85%). However, if we weighted the database to match this sex ratio, female data would have virtually no impact on the design criteria, and the result would be a product that fits men well but fails to accommodate women. To avoid this unacceptable outcome we analyze the male and female hand data separately.

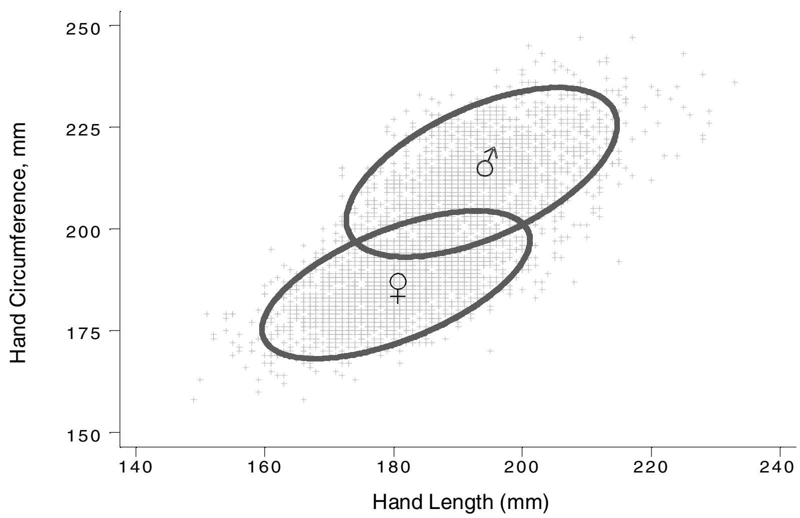


Figure 16. Hand size distributions of Army men and women.

The design team knows that the material chosen will stretch substantially in a horizontal direction to accommodate Hand and Finger Circumferences, and considerably less in the vertical direction associated with Hand and Finger Lengths. They also know from previous experience that close-fitting Finger Lengths and Crotch Heights are extremely important in maximizing scores on gloved dexterity tests. The team concludes that the gloves should come in multiple lengths. (Information on dexterity tests can be obtained from: Ervin, 1987; Robinette et al., 1986a; Robinette et al., 1986b.)

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[4] This methodology carries a small risk as the variance for those other variables, predicated on Hand Length and Circumference, is generally a factor of r^2 of the actual population variance. This risk is ameliorated by the later test fitting of users.

The team knows that manufacturing tolerances for commercial gloves of similar design and materials are in the 10 mm range, so specifying glove sizes that differ in length by 10 mm or less would not be practical. However, if a glove length were situated in the approximate center of the male and female Hand Length distributions (see Figure 17), then glove lengths distributed every 14 mm along the Hand Length axis would capture the 90% target boundaries (located approximately between 160 and 220 mm) with a five-length system. Because the glove materials stretch to fit circumferentially, the team assumes initially that a single glove width can be used for each glove length and locates a case centrally within each length category to guide glove design, as illustrated in Figure 17. Note that 12 mm length intervals could have been chosen instead of 14 mm intervals, but would have required at least 6 glove sizes to cover the 90% target audience. Such trade-off decisions between closeness of fit and the cost/benefit of additional sizes are common in clothing design problems. In this case, because the glove material was stretchy, the 2 mm closer fit was not deemed of sufficient functional importance to warrant the cost of carrying 6 sizes in the system.

7.2.5 Transitioning Cases To Product

Case locations in Figure 17 provide model Hand Lengths and Circumferences for five glove sizes. To actually manufacture the glove, the team also needs to know Finger Lengths, Circumferences and Crotch Heights. As indicated in section 7.2.4, these dimensions are highly correlated with Hand Length and Circumference, so regression equations employing Hand Length and/or Hand Circumference to predict Finger Lengths, Circumferences and Crotch Heights are used to estimate finger dimensions and Crotch Heights for each case. No “allowances” are added to the nude hand dimensions, since the product will be made of a stretchy material.

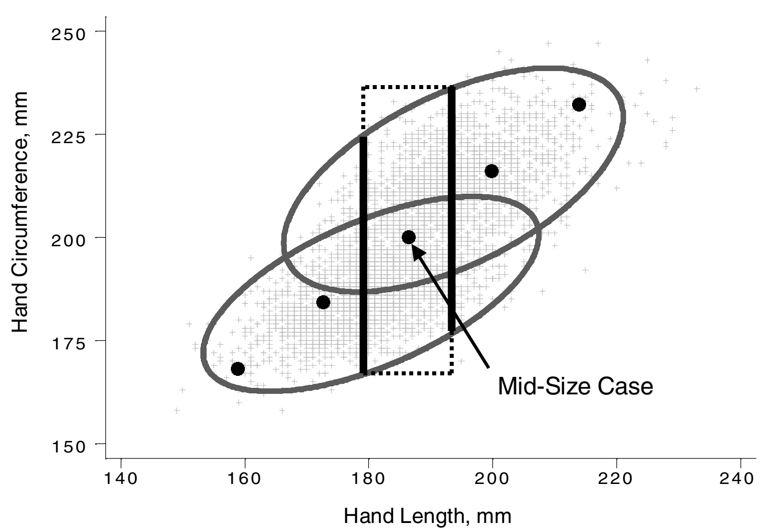


Figure 17. Case selection for a five size design

7.2.6 Product Testing and Validation

Before a full range of sizes is manufactured, mid-sized prototypes are created for testing. This step is very important since we have assumed, but do not yet know, that the gloves will stretch sufficiently to accommodate the wide range of hand circumferences associated with each glove length. In addition, we need to verify that the finger proportions are correct, since they were estimated from regression equations. And finally, mid-size prototype testing with a wide range of subjects can help to establish the true limits of fit for each size of the product by providing data on how different a subject's hand dimensions can be from the case model before a degradation in fit, comfort, or dexterity is noticeable.

At the minimum, test subjects for the mid-sized prototype should include people on the theoretical boundaries of the size category (see Figure 17), and distributed randomly throughout the size category. It is also wise to test subjects *outside* the theoretical limits of a size category, because if they can also achieve satisfactory fit, the number of sizes required to accommodate the target population can sometimes be reduced.

Once the mid-size prototype has been finalized, other sizes of the glove are manufactured and tested using the cases as size models. Once again, testing requires subjects representing hand dimensions distributed both on the boundaries and randomly within the boundaries of the sizing system. Subjective assessments of fit and comfort are recorded, and standardized dexterity tests (both nude hand and gloved) are used to measure functionality of fit. The test battery also contains several functional dexterity tests meant to mimic tasks required to operate aircraft and ground vehicles. Hand and finger measurements and measurements of glove stand-off distance at the fingertips and finger crotches are also made on each test subject so that mathematical models relating hand and glove dimensions can be created for future use.

In this example, laboratory testing of subjects demonstrated that the five-size glove system successfully accommodated hand lengths and circumferences covering more than 95% of users although the original goal was only 90%. This probably occurred because of the stretchy nature of the fabric used, and some designers might want to consider repeating the exercise with a wider than 14mm length interval to see if production costs could be reduced by using a 4 size system without affecting fit and dexterity. In any case, after lab tests are completed, a large number of gloves should be manufactured for operational testing by actual users. This final test is necessary to ensure that the glove design is fully compatible with all equipment and tasks that might be encountered in an operational environment, and to ensure that the new item will be well received by actual users.

7.2.7 Discussion

The reader should note that the density of distributed cases used for sizing system problems varies as a function of several factors *in addition to* anthropometric variation in the target population. Product design, materials, and required closeness of fit all influence the range of body sizes that can be accommodated within a single size category, and these limits of fit in turn influence case density.

Figure 18 illustrates a dress skirt sizing system derived by Robinette and co-workers (1990) for use by US Navy females. In Robinette's approach, the design team first established the limits throught fit testing for one skirt size of the desired design and materials (see Mellian et al., 1990). The ranges of Waist Circumference and Hip Circumference that were successfully accommodated by that prototype then determined the density of sizes required to successfully accommodate the target population as a whole.

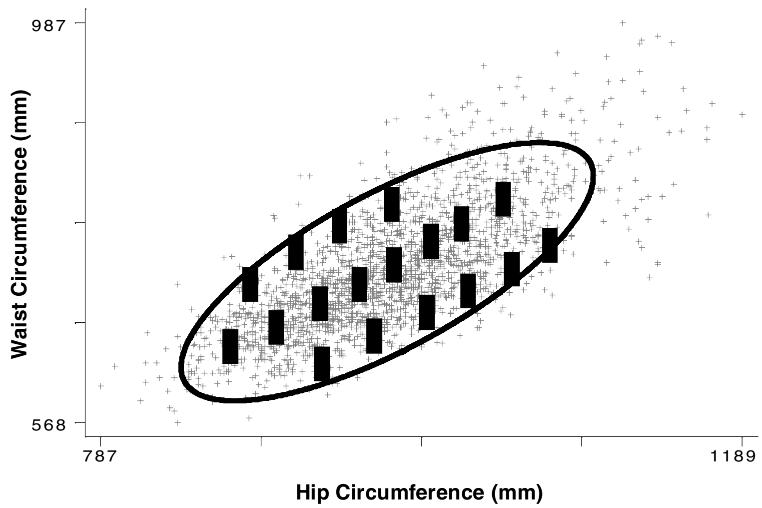


Figure 18. Case distribution for dress-skirt sizing (adapted from Robinette et al., 1990)

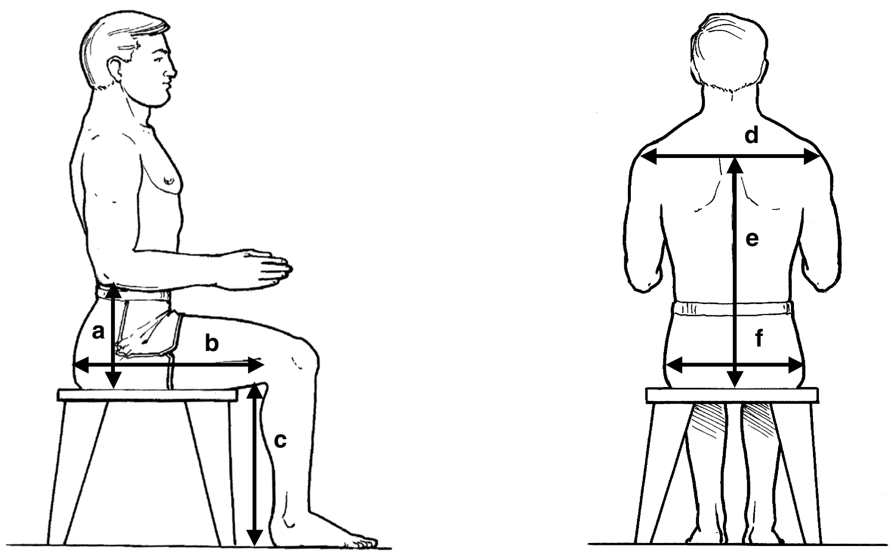
7.3 *Example 3:* Workstation Seating

The purpose of this example is to illustrate the anthropometric design process when there are many critical design parameters that must be simultaneously satisfied though they may be poorly correlated with one another. This example also illustrates database selection methods, the use of mathematical models, and clothing allowances.

7.3.1 Statement of the Design Problem

A chair is needed for use at a seated computer workstation or desk. The chair will offer seat, back, and elbow rest height adjustments in order to support a variety of comfortable working postures for users. For simplicity, seat pan depth and width will be fixed, as will seat pan angle (0 degrees). For further simplicity, this example does not consider seat cushion compressibility. However, one could establish the mathematical relationship between user weight and the compressed height of a particular cushion material and design, and include that in the analyses described below.

Much has been written about seating design (see, for example, Dainoff, 1998; Pheasant, 1996; Kroemer et al., 1994; Roebuck, 1995). Some relevant body dimensions and their relationships to seat design parameters are illustrated in Figure 19, and described in BRS/HFES 100 (which is a revision of ANSI/HFES 100.)



	Body Dimension	Design Parameter
a.	Elbow Rest Height	armrest height range
b.	Buttock-Popliteal Length	maximum seat pan depth
c.	Popliteal Height	seat pan height range
d.	Biacromial Breadth	minimum seat back width
e.	Acromion Height, Seated	seat back height range
f.	Hip Breadth, Seated	armrest clearance minimum seat pan width

Figure 19. Some body dimensions useful in seating design

7.3.2 Defining the Target Population

The target population for this office chair includes American men and women. The manufacturers of this design will not market it to school children or to people who may be unable to sit unassisted for extended periods of time.

7.3.3 Selecting an Anthropometric Database

As was the case in example 7.1, the best available data on American adult height and weight distributions is from the NHANES surveys. However, body dimensions for seating design were not all included in NHANES, so we must assess the risk of using a military database to approximate civilian distributions.

Marras and Kim (1993) reported nine body dimensions measured on 384 male and 124 female factory workers, comparing these against the 1988 US Army data (Gordon et al., 1989). Male factory workers were significantly larger than military males for weight and abdominal dimensions, and the civilian body dimension distributions of both sexes appeared to be more variable than their military counterparts. These results are not surprising when one considers military and civilian population ellipses for 90% capture of height and weight (Gordon, 2000).

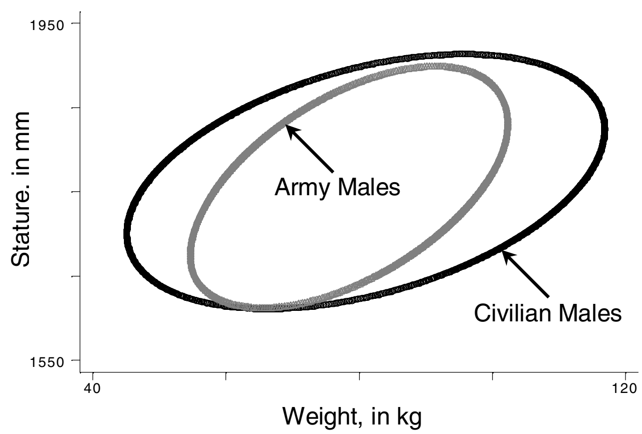


Figure 20. Ninety-percent ellipses comparing military and civilian males

Whereas Stature (height) variation is similar for Army and civilian populations, Figure 20 clearly illustrates the much wider civilian variation in weight for males, and the same is true for females. We conclude that civilian extremes of body dimensions closely related to weight may be underestimated (at both tails) by military data. For seating design, this primarily affects Seated Hip Breadth, which is closely correlated with weight: $r = .87$ males; $r = .81$ females (Cheverud et al., 1990). For purposes of the present illustration, and in the absence of a directly applicable database, we elect to use the Army database, and can address likely underestimation of civilian Hip Breadth in two ways. Firstly Seated Hip Breadth can be measured in a small sample of civilians whose weights are outside the military range but inside the 90% envelope for civilian heights/weights, and seat pan width design values revised upwards if necessary. Secondly, the resulting seat can be tested using civilian subjects whose weights range throughout the 90% civilian distribution as defined by a large-scale probability sample such as that obtained in the NHANES surveys.

7.3.4 Case Selection

The mathematical relationships between seat design parameters and their corresponding body dimensions (Figure 19) all require boundary case estimates. Six body dimensions must be accommodated simultaneously in the design geometry to ensure 90% accommodation of the target audience. Referring to Figure 11 in Chapter 5, we conclude that a 90% ellipsoid is appropriate for case definition. The proposed design calls for *independent* and *continuous* adjustment mechanisms for seat height, back height, and arm rest height, so in this example we can assume that cases inside the ellipsoid will be accommodated if the boundaries are accommodated. Other situations in which this assumption would be inappropriate are discussed in section 7.3.7.

We need to capture the extremes of 6 variables simultaneously in order to achieve 90% accommodation of the target audience. A six dimensional ellipsoid, however, is simply too complex for practical application. Instead, we utilize Principal Components Analysis (PCA) on the correlation matrix in order to reduce the dimensionality of the problem before fitting 90% ellipsoids to the multivariate distribution of male and female subjects.

Principal Components Analysis: The following body dimensions were submitted to PCA: Buttock-Popliteal Length, Popliteal Height, Hip Breadth Seated, Elbow Rest Height, Acromion Height Seated, and Biacromial Breadth, (see Figure 19).

Preliminary results indicated that separate male and female PCA's yielded comparable results, and so a joint PCA with males and females weighted for equal contribution is shown here in order to keep this example simple. Even for this example, separate analyses might be necessary in many situations such as when a different sample, or a different set of measurements is used. See section 7.3.7 for a discussion that explains the need for separate male and female analyses in many situations.

Table 5. Principal components analysis of six seating design dimensions*

Component	Eigenvalue	Difference	Proportion	Cumulative
1	2.79990	1.27120	0.4667	0.4667
2	1.52870	0.46282	0.2548	0.7214
3	1.06588	0.63603	0.1776	0.8991
4	0.42985	0.30215	0.0716	0.9707
5	0.12770	0.07974	0.0213	0.9920
6	0.04796	.	0.0080	1.0000

	Eigenvectors		
Variable	PC 1	PC 2	PC 3
Buttock-Popliteal Length	0.44745	-0.33407	0.36897
Popliteal Height	0.52265	-0.29279	-0.13978
Hip Breadth, Sitting	0.07831	0.28116	0.88415
Elbow Rest Height	0.19473	0.73913	-0.16739
Acromion Height, Sitting	0.49733	0.40071	-0.14408
Biacromial Breadth	0.48500	-0.12934	-0.11757

* n=3982 soldiers, males and females weighted for equal contribution

Table 5 reports the results of the PCA. The first three Principal Components accounted for 90% of the variation present in the original 6 variables. The first PC (accounting for 47% of the variation) reflects skeletal frame size. The second PC (25% of the variation) describes primarily Elbow Rest Height and Seated Shoulder Height, contrasting these dimensions with lower limb lengths – Buttock Popliteal Length and Popliteal Height. The third PC (18% of the variation) describes primarily Seated Hip Breadth and Buttock Popliteal Breadth, and presumably would most be influenced by any underestimation of civilian body fat by a military database such as ANSUR.

Fitting ellipsoids to the PC scores: Each subject in the ANSUR database was scored using their original body dimensions and the PC eigenvectors in Table 5. These results were plotted in 3-D "PCA" space, with the x-axis representing PC1, the y-axis representing PC2, and the z-axis representing PC3. A 3-D ellipsoid capturing 90% of the population can then be fit to the population scatter, as is shown in Figure 21.

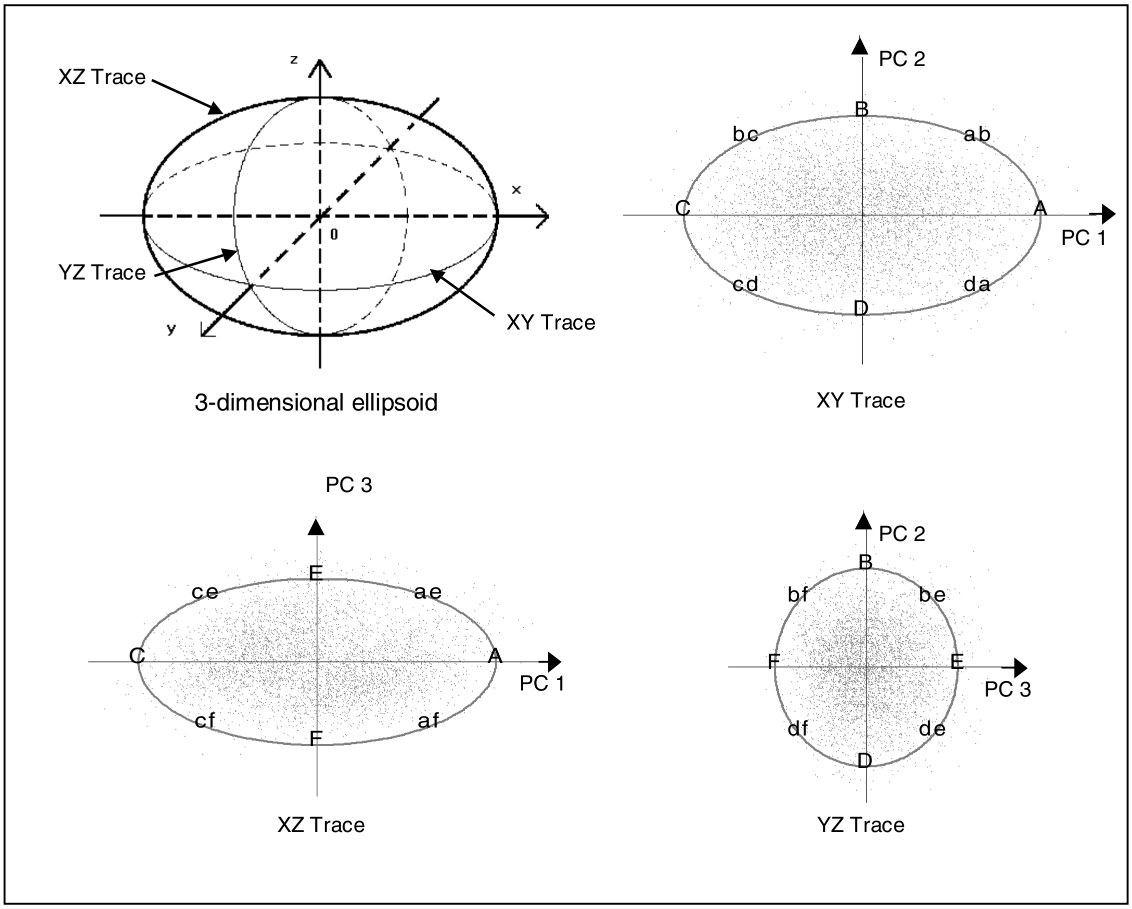


Figure 21. A 90% ellipsoid capturing variation in three principal components (cases are identified by letter)

Boundary Cases: To describe the extremes and combinations of extreme body dimensions represented by the 90% ellipsoid, 26 boundary cases were located on the ellipsoid surface at major axis intersections and at intermediate points. Theoretical body dimensions for each of the 26 cases can be calculated from their xyz coordinates and/or by using the body dimensions of subjects whose PCA scores place them in a localized neighborhood of each case. In this problem, we have calculated theoretical body dimensions for the cases using their xyz coordinates, the PCA eigenvectors, and means and standard deviations of each dimension.

7.3.5 Transitioning Cases to Product

With a central case and 26 boundary cases to accommodate, the design team chooses to use a computer aided design approach, and generates virtual human models with the same critical body dimensions as those of their design cases and with appropriate clothing allowances derived from textbooks (e.g. Pheasant, 1996) or from small scale studies of the clothing worn by intended users. Central cases are particularly helpful in deciding where to establish the center of adjustment ranges such as those for armrest height; boundary cases can then be used to establish the range of continuous adjustment needed on either side of the center point. By using continuous adjustment mechanisms and all 26 boundary cases to establish user maxima/minima and extreme proportional combinations for the design parameters in Figure 19, the CAD designer can be reasonably sure that his virtual seating solution is sufficiently close to ideal and that investment in prototyping and testing is warranted. To ensure that seat pan width is not underestimated by use of military data, additional CAD models with Hip Breadths derived from a small scale study of civilians (described in 7.3.3) may be included in the iterative CAD design process.

7.3.6 Product Testing and Validation

As in other examples, we will need to test our design with real subjects representing the full range of variation in our intended users. It will be particularly important to ensure that test subjects for this design are distributed throughout the *civilian* range of body weight; not just the military range. In addition, we will need to be sure that subjects wear the kinds of clothing and shoes they would choose for office tasks, so that assumptions about clothing allowances can be tested. Finally, the seat should be tested with a variety of office workstation components, including desks and workstations with both fixed and adjustable worksurfaces and display heights to be sure that the seat design is compatible with other elements required in office task scenarios.

7.3.7 Discussion

The methodological details behind Principal Components Analysis, ellipsoid fitting, and multivariate case selection are well beyond the scope of this document. The example provided here was selected specifically for its simplicity, and several aspects of it merit discussion.

Firstly, ellipse and ellipsoid methods assume that observations are from bivariate or multivariate normal distributions. The normality assumption is particularly easy to violate if one pools males and females (or any other demographic subgroups) with quite different anthropometric distributions for analysis. Relationships among torso dimensions differ significantly among men and women for example. Fitting a single ellipse or ellipsoid to the pooled sex sample would be inappropriate and the resulting accommodation boundary would have been ineffective (Gordon et al., 1997:23). An example of this is illustrated in Figure 22.

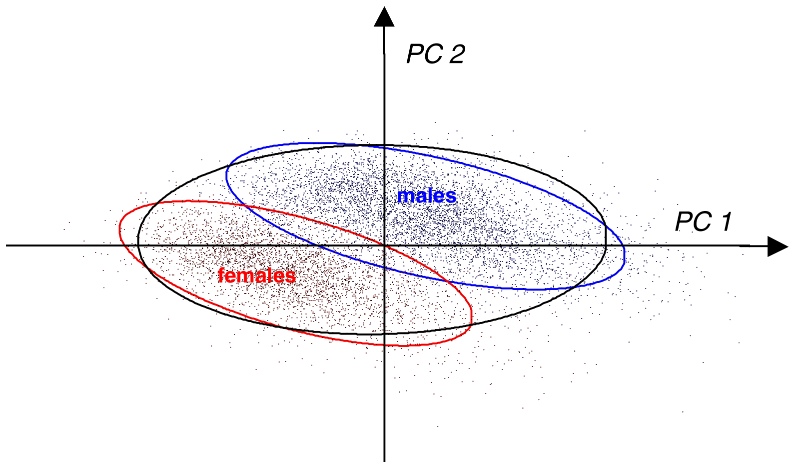


Figure 22. Joint sex ellipsoids may not capture individual sex boundaries.

In Figure 22, PC1 represents overall torso size. PC2 represents a contrast in shoulder and hip dimensions, with positive values of PC2 having large shoulders and small hips, and negative values of PC2 having small shoulders and large hips. As can be seen above, there is very little overlap between male and female distributions, and when an ellipse is fit to the joint distribution (which is bimodal), it describes the accommodation envelope of neither sex well. In this situation, completely separate analyses should always be conducted, and cases representing both male and female extremes should be selected for use in estimating design parameters.

The fact that boundary cases sufficed for the seat design problem is also worthy of discussion. We recall that the design called for *continuous* adjustment mechanisms for seat pan height, seat back height, and elbow rest height. Had the adjustment mechanism(s) been discontinuous (with large stops pre-set by the manufacturer), we could not have assumed that accommodation of boundary cases would ensure accommodation of cases within the boundaries. Instead, a distributed case method would have been required, and the design solution would have included determining the resolution of cases required to ensure that the pre-set stops captured everyone inside the targeted accommodation envelope.

7.4 Summary

The use of anthropometric data is very dependent upon the particular design problem. Every solution requires the designer to make choices. The data and the statistics available are tools to help in the decision process. However, it is generally not advisable to let the data and statistics make the decisions. There is no solution th at is appropriate for all problems.

This document explains the design process, and how to use anthropometric data to resolve a variety of design challenges. It discusses how to determine the population of interest, select a sample, find relevant measurements, and reduce the amount of information down to something manageable. It explains some of the pitfalls and uses some examples to illustrate each step of the process given different requirements and situations.

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Appendix A

Glossary[1]

accommodation - when a particular design fits the user in such a way that the user can perform intended tasks safely, efficiently, and comfortably

accommodation region - the range, area, or volume in anthropometric space throughout which users are accommodated by a particular design

accommodation boundary, accommodation envelope - the anthropometric limits of accommodation for a particular design. These can be either empirically defined through testing of an existing design, or represent the intended limits of accommodation for a new design.

affordance - attributes of product design that have consequences for goal-directed actions by users

ANSUR - an acronym for the 1988 Anthropometric Survey of US Army Personnel

anthropometry - the study of human body measurements

anthropometric space - a Euclidean space (e.g., graph) whose axes either directly represent body dimensions or are derived from body dimensions

awkward posture - the position of a joint or joints that imposes excessive or inappropriate demands on the musculoskeletal system

body posture - the position of the body or body parts relative to a reference system used to define positions and movements in space

boundary - the outer edges of a specified interval, area or volume

clearance - room needed for the body and its parts to function without interference (from controls, structural elements, or other objects)

comfort - a subjective state wherein stresses on the body are perceived as being within an acceptable range and the individual feels at ease

constraints, environmental - limitations in the design of objects, tools, instruments, etc., with which the user must interact in performing a task

[1] This glossary is informational, not normative.

***constraints, human* -** personal characteristics (including physical, psychological and cultural factors) or abilities that limit an individual's posture or performance in the workplace

***constraints, task* -** demands associated with a specific job application

***correlation* -** a measure of the degree to which two variables are associated

***covariance* -** a measure of the degree to which two variables are linearly associated

***demography* -** the study of human populations, their characteristics and their vital statistics

***design optimization* -** a design process that maximizes user accommodation and system effectiveness within relevant engineering constraints (e.g., cost, time, etc.)

***dimension* -** a scale of measurement along which data may vary

***distributed method* -** a method, which utilizes selected points or cases spread throughout the region of desired accommodation

***ellipse* -** a two-dimensional boundary estimator for bivariate normal data

***ellipsoid* -** a three or more dimensional boundary estimator for multivariate normal data

***empirical testing* -** use of observation and experimentation with live subjects

***endurance* -** the ability to exert force over time

***equilibrium state* -** a state of balance

***ergonomic design* -** a design, which incorporates the principles of ergonomics

***ergonomics* -** the scientific study of human work

***fit* -** the relationship between a user and environmental components associated with the performance of a task

***fit testing* -** a process for evaluating fit

***functional components* -** the elemental activities involved in performing a task

***human factors* -** a body of information about human abilities, human limitations, and other human characteristics that are relevant to design

human factors engineering - application of human factors information to the design of tools, machines, systems, tasks, jobs, and environments for safe, comfortable and effective human use

human-machine interface - the common boundary between equipment and a user through which the human interacts with the system

human-machine system - a system in which a human (or humans) and a machine (or machines) work together to complete a task

mode - the most frequently occurring value in a set of measurements

mean - the average value of a set of measurements, computed as the sum of the values divided by the number of measurements.

median - the middle value in a set of measurements that are ordered from lowest to highest

multivariate - involving more than one variable

NHANES – an acronym for The National Health and Nutrition Examination Surveys anthropometric datasets, conducted by the National Center for Health Statistics, Centers for Disease Control (NCHS/CDC)

normal distribution - a continuous, mathematically-defined distribution with a bell-shaped frequency curve; it closely approximates many human body measurement distributions

parameter - a specific variable (e.g. measurement or statistic) of interest

percentile - a statistic describing the position of a value in an ordered set of measurements; the "*n*th" percentile is the value having *n* percent of measurements in the set smaller, and (100-*n*) percent of the measurements in the set larger. Note that the median is by definition the 50^{th} percentile.

point estimator, central - a single point estimator near the center of a measurement distribution or accommodation region, such as the mean, median, or 50^{th} percentile

point estimators, boundary - estimators of the outer edges of a measurement distribution or accommodation region

point estimators, distributed - estimators representing selected points distributed throughout the region of desired accommodation

principal components analysis - a statistical procedure for reducing the dimensionality of a problem by using (relatively few) linear combinations of the original variables to represent the patterns of variation present in the original data

prototype - *a* physical or virtual rendition of a design concept

reach - the ability to extend the body parts so as to grasp and operate controls

resolution - the distance between points in a distribution

sample - a subset of individuals taken from a larger population

stand-off distance - the distance between a garment and the skin surface of the body wearing it

standard deviation - a widely used measure of variability computed as the square root of the sample variance

static load - sustained muscular contraction

strength - the human capacity to generate, apply or resist force

target population, target audience - the group of people for which a design, product or process is intended; the intended market

task - an activity required to achieve a goal or objective

task analysis - a detailed, step-by-step, description of an operator's task, in terms of its components, to specify the human activities involved, and their functional and temporal relationships

variable - a characteristic or measurement that can vary in an i ndividual, sample or population

work equipment - machinery, tools, vehicles, devices, furniture, installations and other components used in the work system

working environment - the physical, chemical, biological, organizational, psychosocial, and cultural factors surrounding a person in his or her workspace

workstation - the combination of work equipment in a workspace and the surrounding work environment

worst case(s) - the most extreme combination(s) of physical characteristics in a target population; the most difficult combination(s) of physical characteristics to accommodate in a design.

Appendix B

Bibliography of Related Publications

Chapanis, A. (1996). *Human Factors in Systems Engineering*. New York: John Wiley & Sons Inc.

Broad in scope, this book describes the full cycle of design using the systems engineering process.

Gordon, C.C., Bradtmiller, B., Churchill, T., Clauser, C.E., McConville, J.T., Tebbetts, I., & Walker, R.A. (1989). 1988 Anthropometric Survey of U.S. Army Personnel: Methods and Summary Statistics. Technical Report NATICK/TR-89/044. Natick, MA: U.S. Army Natick Research, Development, & Engineering Center. (AD A209 600).[1]

This report includes protocols, illustrations, and statistics for 260 engineering body dimensions. Appendices address observer error, applications, and comparability to other surveys.

Grimm, L. G. and Yarnold, P.R. (1995). *Reading and Understanding Multivariate Statistics.* Washington DC: American Psychological Association.

This is an easy to understand textbook written for an audience without formal exposure to multivariate statistics. It would be useful to anyone who has a design problem that involves more than 3 measurements.

Human Factors and Ergonomics Society (2002). *Human Factors Engineering of Computer Workstation.* (BRS/HFES 100) Draft Standard for Trial User. Santa Monica, CA: Human Factors and Ergonomics Society.

This document is the first revision of ANSI-HFES 100-1988, American National Standard for Human Factors Engineering of Visual Display Terminal Workstations. The anthropometric approach used in this revision is described in detail in an appendix. This approach works well for the specific design requirements covered in this revision, but would not be considered a general approach and might not be appropriate for other workstation applications.

Kroemer, K.H.E. (1989). Engineering anthropometry. *Ergonomics* 32(7):767-784.

This article provides a comprehensive and concise review of the field.

National Center for Health Statistics (1994). Plan and Operation of the Third National Health and Nutrition Examination Survey, 1988-94. Vital and Health Statistics, Series 1 No 32. DHHS Publication No. (PHS) 94-1308. Hyattsville, MD: National Center for Health Statistics.[2]

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[1] To obtain copies of this and other DOD reports cited, use the Defense Technical Information Center (DTIC) Scientific and Technical Information Network web site (http://stinet.dtic.mil/).

[2] To obtain copies of NHANES III reports and data, consult the National Center for Health Statistics web site (http://www.cdc.gov/nchs/).

This report documents some important logistical aspects of conducting a large survey, including subject weighting and statistical estimation methodology.

Pheasant, S. (1996). *Bodyspace: Anthropometry, Ergonomics and the Design of Work*, 2nd Edition. London: Taylor & Francis.

Bodyspace is a comprehensive treatise that integrates anthropometric issues in the wider realm of ergonomics.

Roebuck, J.A. (1995). *Anthropometric Methods: Designing to Fit the Human Body*. Santa Monica, CA: Human Factors and Ergonomics Society.

Intended for use by practitioners and students, this 194 pp. monograph addresses engineering anthropometry for workstations and clothing design.

Vanderheiden, G.C. (1997). Design for people with functional limitations resulting from disability, aging, or circumstance. In: Salvendy, G. (Ed): *Handbook of Human Factors and Ergonomics*, 2nd Edition, 2010-2052. New York: John Wiley & Sons, Inc.

This book chapter describes the concept of design for universal access, and includes an extensive bibliography of literature and other resources on the topic.

Webb Associates. (1978). *Anthropometric Source Book*. Volume I: *Anthropometry for Designers*. Volume II: *A Handbook of Anthropometric Data*. NASA Reference Publication 1024. Washington DC: National Aeronautics and Space Administration.

Although somewhat dated, these volumes still represent one of the most comprehensive references available on anthropometry in design. Volume I addresses methods and applications, including an article focused specifically on statistics for design written by Edmund Churchill. Volume II provides definitions, illustrations, and worldwide comparative data on 294 body dimensions from 91 surveys between 1940 and 1974.

Zehner, G.F., Meindl, R.S., and Hudson, J.A. (1993). A Multivariate Anthropometric Method for Crew Stations Design: Abridged. Technical Report AL-TR-1992-0164. Wright Patterson Air Force Base, OH: Armstrong Laboratory, Air Force Systems Command.

This report describes the application of Principal Components Analysis (PCA) in the development of cases for aircraft crew station design criteria.